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Entraîner le contrôle attentionnel chez la personne âgée : Perspective comportementale et cérébrale

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Résumé

L'objectif principal de cette thèse est d'évaluer l'effet des interventions cognitives sur le contrôle attentionnel en faisant appel à des mesures comportementales et à des mesures d'imagerie par résonance magnétique fonctionnelle (IRMf). La thèse comprend cinq articles empiriques.

L'objectif de la première étude (Chapitre II) était d'examiner la source des différences reliées à l'âge au niveau du contrôle attentionnel. Les résultats suggèrent que les participants âgés présentent plus de difficultés que les jeunes adultes à varier le niveau d'attention à allouer à chacune des tâches selon la consigne d'emphase attentionnelle, reflétant un problème de contrôle attentionnel. La deuxième étude (Chapitre III) visait à comparer l'efficacité de trois types d'entraînement attentionnels chez la personne âgée. Les résultats montrent des effets spécifiques selon l'entraînement reçu. Seuls les participants âgés ayant suivi un entraînement à priorité VARIABLE, dans lequel ils étaient appelés à varier le niveau d'attention à allouer à chacune des tâches à travers plusieurs blocs, améliorent leurs capacités de contrôle attentionnel suite à l'entraînement. Cette amélioration ne peut être expliquée par la pratique aux tâches en attention focalisée, ni la pratique en double-tâche sans modulation attentionnelle. L'objectif de la troisième étude (Chapitre IV) était d'examiner si les bénéfices d'un entraînement à priorité VARIABLE pouvaient se transférer sur des tâches similaires à celles entraînées et sur des tâches plus représentatives du quotidien, à l'aide d'un paradigme de double-tâche immersive en réalité virtuelle (RV). Les résultats montrent qu'un entraînement à priorité VARIABLE améliore les capacités de contrôle attentionnel et, pour la première fois, que les effets bénéfiques de cet entraînement peuvent se transférer à un paradigme de double-tâche en RV chez une population âgée. De plus, nous montrons que les âgés bénéficient autant, voire même plus que les jeunes adultes, d'une intervention visant le contrôle attentionnel et que l'âge n'influence pas les effets de transfert obtenus. La quatrième étude (Chapitre V) examinait l'impact des entraînements attentionnels sur les changements d'activation en IRMf. Les résultats suggèrent que le cerveau est hautement plastique, même à un âge avancé, et que les changements d'activation obtenus diffèrent selon le type d'intervention reçu. Un entraînement à priorité VARIABLE, visant l'apprentissage de stratégies de contrôle attentionnel et les capacités métacognitives, est le seul qui produit des augmentations d'activation dans une région frontale impliquée dans la coordination multitâche et le contrôle attentionnel. Un entraînement visant la pratique répétée de tâche en attention focalisée produit plutôt des diminutions d'activation dans les régions préalablement recrutées. Enfin, l'objectif de la cinquième étude (Chapitre VI) était d'évaluer le décours temporel des changements d'activation à l'aide de trois séances en IRMf. On observe une augmentation d'activation suivie d'un plateau dans des régions reliées aux stratégies apprises pour l'entraînement à priorité VARIABLE, alors que les changements d'activation suite à un entraînement en pratique répétée sont caractérisés par une courbe en U-Inversée. Les résultats de cette dernière étude montrent que les changements d'activation sont non linéaires au cours de l'entraînement et, de façon similaire aux résultats obtenus dans la quatrième étude, modulés par le type d'intervention donné.

Mots-clés : Vieillissement normal, Entraînement cognitif, Contrôle attentionnel, Imagerie par résonance magnétique fonctionnelle

Abstract

The main objective of this thesis was to evaluate the effect of cognitive interventions on attentional control using behavioral measures and functional magnetic resonance imaging (fMRI). The thesis comprises five empirical articles.

The aim of the first study (Chapter II) was to examine the cause of age-related differences in attentional control. The results suggest that, compared to younger adults, older participants have more difficulty varying the level of attention to be allocated to each task according to the attentional focus that is required, reflecting a difficulty with attentional control. The second study (Chapter III) aimed to compare the effectiveness of three types of computerized attentionnal training in older adults. The results show specific effects depending on the type of training received. Only the older participants who followed the VARIABLE-priority training, in which they had to vary the level of attention allocated to each task across several blocks, showed improvement in their attentional control skills following training. This improvement cannot be explained by repeated practice in the tasks under focused attention or in the dual-task condition without attentional variation. The aim of the third study (Chapter IV) was to assess whether the benefits of VARIABLE-priority training could transfer to tasks similar to those trained and to tasks that are more representative of everyday life, using an immersive dual-task paradigm in virtual reality (VR). The results show that VARIABLE-priority training improves attentional control abilities and, for the first time, that the beneficial effects of this training can be transferred to a dual-task paradigm in VR in older adults. Furthermore, we show that older adults benefit as much, if not more than younger adults, from an intervention aiming to improve attentional control, and that age does not have an effect on the transfer effects observed. The fourth study assessed (Chapter V) the impact of attentional training on changes in fMRI activation. The results suggest that the brain is highly plastic, even in old age, and that the changes in activation are different depending on the type of intervention. VARIABLE-priority training, which aims to teach attentional control strategies and metacognitive abilities, is the only one that produces increases in activation in a frontal region involved in multitasking and attentional control. Repeated practice of a task under focused attention, on the other hand, causes decreases in activation in regions that were previously recruited. Finally, the aim of the fifth study (Chapter VI) was to evaluate the time course of activation changes across three fMRI sessions. An increase in activation followed by a plateau in regions related to the strategies learned for the VARIABLE-priority training is observed, while the activation changes following repeated practice are characterized by an inverse U-shape function. The results of the latter study show that activation changes are non-linear during training and, similarly to the results obtained in the fourth study, are modulated by the type of intervention followed.

Keywords: Normal aging, cognitive training, attentional control, functional magnetic resonance imaging

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En français :

IRMf : Imagerie par résonance magnétique fonctionnelle

AVQ : Activités de la vie quotidienne

CCA : Cortex cingulaire antérieur

CPF : Cortex préfrontal

CPFDL : Cortex préfrontal dorsolatéral

CPFV : Cortex préfontral ventral

TEP : Tomographie par émission de positons

TCL : Trouble cognitif léger

En anglais :

ACTIVE: Advanced Cognitive Training for Independent and Vital Elderly

BOLD: Blood-Oxygen-Level Dependent

CFQ : Cognitive Failure Questionnaire

DAQ : Divided attention questionnaire

UFOV : Useful Field of View

À Laurette et Lidia,
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Chapitre I : Contexte théorique

1. Introduction générale

Le vieillissement de la population canadienne représente un tournant majeur sur le plan démographique. Depuis le début du siècle dernier, l'espérance de vie s'est accrue de façon importante, si bien qu'en 2015, l'Organisme mondial de la Santé estimait que l'espérance de vie atteignait 80 ans pour les Canadiens et 84 pour les Canadiennes. Puisque les personnes âgées représentent une proportion grandissante de la population, il est capital de s'intéresser aux changements psychologiques, physiques et cognitifs associés au vieillissement. Une meilleure connaissance du vieillissement normal est l'une des premières étapes dans la compréhension des maladies qui lui sont associées. Parmi les changements qui s'opèrent dans le vieillissement, le déclin cognitif représente une préoccupation importante chez la personne âgée. Une étude menée par Tannenbaum, Mayo & Ducharme (2005), auprès de femmes âgées canadiennes, soulève que la cognition se situe au premier rang de leurs priorités en termes de soins de santé. Pourtant, ces femmes ont aussi rapporté que cette préoccupation semblait être peu considérée par les professionnels de la santé. Il importe donc de mieux arrimer nos pratiques aux besoins de la population vieillissante en termes de santé cognitive. En effet, il semble essentiel de s'intéresser davantage à comment se modifie la cognition chez la personne âgée saine et plus particulièrement de trouver les facteurs qui permettent d'améliorer le fonctionnement cognitif et ultimement favoriser leur autonomie.

Il est bien connu que certaines fonctions cognitives tendent à décliner avec l'avancée en âge. Parmi celles-ci, le contrôle attentionnel semble être particulièrement sensible aux effets du vieillissement. Les difficultés de contrôle attentionnel peuvent avoir des répercussions importantes sur plusieurs activités de la vie quotidienne comme la marche (Gaspar, Neider, &

Kramer, 2013; Li, Lindenberger, Freund & Baltes, 2001) et la conduite automobile (Daigneault, Joly & Frigon, 2002). Il est important de savoir si les capacités de contrôle attentionnel peuvent être améliorées à l'aide d'interventions cognitives ciblées et quels sont les impacts de ces interventions au niveau comportemental, mais aussi sur le cerveau. Plus important encore, les personnes âgées bénéficient-elles autant de ces interventions que les jeunes adultes et peuvent-elles transférer leurs acquis obtenus en laboratoire aux tâches du quotidien ?

L'objectif principal de la thèse est d'évaluer l'effet des interventions cognitives sur le contrôle attentionnel en faisant appel à des mesures comportementales et à des mesures d'imagerie par résonance magnétique fonctionnelle (IRMf). La thèse comprend cinq articles. Puisque les interventions doivent être guidées par une connaissance fine des atteintes et capacités résiduelles, nous évaluerons d'abord, la source des différences reliées à l'âge au niveau du contrôle attentionnel (Article 1). Puis nous évaluerons s'il est possible d'améliorer le contrôle attentionnel chez la personne âgée à l'aide de différents types d'entraînement attentionnel (Article 2). Ensuite, nous examinerons si les bénéfices de ces interventions montrent des effets de transfert sur des tâches similaires à celles entraînées et sur des tâches plus représentatives du quotidien et si le transfert varie selon l'âge ou le type d'intervention (Article 3). Finalement, nous évaluerons les changements d'activation associés à différents types d'entraînement attentionnel (Article 4) et leur décours temporel au cours de l'entraînement (Article 5).

L'introduction présentera la littérature relative aux principaux éléments qui ont motivé ce travail. La première partie de l'introduction porte sur le contrôle attentionnel dans le vieillissement normal. Elle présentera différents modèles de contrôle attentionnel et l'impact du vieillissement normal sur cette composante cognitive. La deuxième partie traitera des interventions cognitives et des façons d'améliorer le contrôle attentionnel dans le vieillissement, via des entraînements cognitifs ciblés. La troisième partie traitera de la notion de transfert et des effets de transfert suite aux entraînements attentionnels. La quatrième partie portera sur les substrats neuronaux du contrôle attentionnel. La cinquième partie présentera les études en neuroimagerie ayant évalué l'impact des interventions cognitives sur les changements cérébraux dans le vieillissement. Seront ensuite présentés les objectifs généraux de la thèse ainsi que les objectifs et hypothèses rattachés à chacune des cinq études.

2. L'attention et le contrôle attentionnel

L'attention est une fonction cognitive complexe qui est impliquée dans la plupart des activités cognitives. Elle fait référence à un ensemble de capacités ou de processus qui permet à l'organisme d'être réceptif ou non à certains stimuli internes ou externes et qui permet de les traiter de façon optimale (Parasuraman, 1998). Il existe plusieurs types d'attention. L'attention sélective, ou focalisée, réfère à la capacité de porter attention à un stimulus, ou à un attribut particulier, en inhibant les stimuli ou attributs non pertinents. En revanche, l'attention divisée, ou partagée, consiste à tenir compte de plusieurs sources d'information en même temps. Elle réfère à la capacité de partager les ressources attentionnelles entre deux tâches réalisées de façon concurrente (Joyce & Hrin, 2015; Kramer, Wiegmann & Kirlik, 2007; Maquestiaux, Lemaire & Insingrini, 2013). Par exemple, lorsqu'un individu conduit une voiture tout en poursuivant une conversation avec le passager, il doit partager ses ressources attentionnelles entre les informations et actions relatives à la conduite automobile (accélérer ou freiner ; informations visuelles sur la route) et celles relatives à la conversation (encoder le message de l'interlocuteur ; lui répondre). Par ailleurs, il peut s'avérer nécessaire de modifier l'allocation ou l'emphase des ressources attentionnelles en fonction de contraintes ou contingences externes ou internes, par exemple lorsqu'un enfant traverse soudainement la rue. Dans ce cas, le conducteur automobile se devra de prioriser l'activité de conduite automobile plutôt que la conversation et ainsi rediriger l'emphase attentionnelle vers la tâche à prioriser. Il est ici question du contrôle attentionnel (Milham et al., 2002). Cette flexibilité dans la redistribution des ressources attentionnelles nécessite l'intervention d'un système de contrôle attentionnel permettant d'adapter son comportement correctement en réponse aux demandes extérieures. Cette composante attentionnelle constitue l'objet de la présente thèse et sera décrite plus en détail dans la section suivante.

2.1. Modèles du contrôle attentionnel

Le contrôle attentionnel est une composante ou un processus exécutif de haut niveau qui survient dans des conditions où les demandes attentionnelles sont élevées, par exemple lorsque l'on doit réaliser deux tâches de façon concurrente et qui permet l'exécution et la coordination de comportements complexes orientés vers un but (Braver et al., 2001; Milham et al., 2002). Différents modèles théoriques intègrent le contrôle attentionnel comme une composante centrale du fonctionnement cognitif (Baddeley & Hitch, 1975; Braver & West, 2008; Norman & Shallice, 1986). Nous décrirons ici les modèles qui nous apparaissent les plus pertinents pour l'étude du vieillissement cognitif.

2.1.1. Le contrôle attentionnel dans le modèle de Baddeley (1986)

Un des modèles les plus connus est celui de la mémoire de travail de Baddeley (1986; Baddeley & Hitch, 1975) qui postule trois systèmes à capacité limitée opérant en interaction. Parmi ces systèmes, deux sous-systèmes esclaves, soit la boucle phonologique et le registre visuospatial, se spécialisent dans le maintien temporaire du matériel verbal ou non verbal. Le troisième système, l'administrateur central, est conceptualisé comme étant responsable du contrôle attentionnel et permettrait de coordonner l'information issue des deux sous-systèmes esclaves et celles issues de la mémoire à long terme (Baddeley, 1992; Engle, 2002). L'administrateur central régulerait la portion active de la mémoire et serait fractionné en différents sous-processus exécutifs, tels que la division de l'attention, l'alternance (p.ex., alterner entre différentes stratégies de récupération en mémoire) et la mise à jour (Baddeley, 1996; Baddeley, 1998). Le contrôle attentionnel serait donc impliqué dans le *monitoring*, la régulation de différents processus cognitifs et dans la gestion et la réorganisation des informations provenant de plusieurs sources externes (Luszcz, 2011). Selon Baddeley et al., (2002 ; 2007) le fonctionnement de l'administrateur central pourrait être similaire à celui du système superviseur attentionnel (SAS) proposé par (Norman & Shallice, 1986) dans leur modèle du contrôle de l'action.

2.1.2. Système superviseur attentionnel, Norman & Shallice (1986)

Norman & Shallice (1986) ont proposé un modèle de contrôle de l'action, qui distingue l'intervention des processus cognitifs selon que les situations sont routinières (habituelles) ou nouvelles (inhabituelles ou complexes). Ce modèle est basé sur les schémas-type de réponses. Un schéma est associé à chacune des situations dites routinières. Ces dernières seraient traitées de façon plus automatique, via l'activation de schémas sur-appris ou mémorisés. Lors de situations nouvelles, les schémas sur-appris se retrouvent en concurrence et nécessitent l'intervention volontaire et contrôlée du SAS. Le SAS est décrit comme une unité de contrôle actif qui sélectionne les actions appropriées en focalisant et alternant l'attention par le biais de processus d'activation et d'inhibition des schémas. Ce système permettrait donc de faire face à des situations nouvelles et complexes.

2.1.3. Le contrôle attentionnel dans le modèle de Braver (2001 ; 2008)

Le modèle proposé par Braver et al., (2001), suggère que le maintien d'un but (*goal maintenance*) est un mécanisme clé et central du contrôle cognitif ou contrôle attentionnel. Dans ce modèle, le contrôle attentionnel permettrait d'assurer une performance réussie et optimale dans un grand nombre de tâches cognitives. Le maintien d'un but serait donc nécessaire pour soutenir et sélectionner les actions nécessaires aux comportements complexes et ainsi favoriser une performance optimale. Par exemple, lorsqu'un individu reçoit l'instruction de réaliser deux tâches de façon concurrente, les buts doivent être représentés et maintenus de manière active afin d'influencer l'attribution de l'attention et la sélection de la réponse vers un comportement adéquat. L'intérêt de ce modèle pour notre travail est qu'il souligne plus particulièrement le rôle du contrôle attentionnel en contexte de double-tâche. Braver et al., (2001) et Braver & West, (2008) suggèrent en effet que le contrôle attentionnel est important dans les situations qui présentent une forte concurrence quant à la sélection de réponses, et que cela est particulièrement vrai pour les paradigmes de double-tâche. En effet, dans ce type de paradigme, plusieurs tâches doivent être gérées en concurrence nécessitant parfois la priorisation d'une tâche plutôt qu'une autre. L'hypothèse d'un apport du contrôle attentionnel en condition de double-tâche est soutenue empiriquement par des études utilisant des techniques d'analyse factorielle (Engle, Tuholski, Laughlin & Conway, 1999; Miyake et al., 2000) qui montrent que le contrôle attentionnel est en grande partie impliqué dans des situations complexes à forte concurrence ou conflictuelles.

2.1.4. Résumé des modèles et choix du paradigme expérimental

En résumé, plusieurs modèles soulignent le rôle important du contrôle attentionnel dans la réalisation de tâches ou de situations complexes ou conflictuelles. Le contrôle attentionnel permettrait d'adapter son comportement, via la sélection d'actions appropriées, en réponse aux demandes extérieures. Les paradigmes de double-tâche semblent être intéressants pour évaluer le contrôle attentionnel, car ce sont des situations complexes qui font appel à la fois aux capacités de coordination, au traitement simultané de différents flux d'informations et à la capacité d'alterner entre différentes tâches à prioriser. Plusieurs situations de double-tâche que nous effectuons dans la vie de tous les jours nécessitent d'adapter son comportement afin de répondre aux demandes de l'environnement. Cela peut se produire lorsque nous devons prioriser une tâche plutôt qu'une autre. Par exemple, lorsque nous traversons une rue achalandée tout en ayant une conversation téléphonique, ou lorsque nous préparons un plat tout en discutant avec nos invités. Au niveau expérimental, il est possible de reproduire ce type de situations en demandant aux participants de réaliser deux tâches conjointement tout en faisant varier le niveau d'attention porté à chacune d'elles. Par exemple, dans une situation de double tâche, une instruction est donnée au participant lui indiquant qu'il doit porter 80 % de son attention sur une tâche et 20 % sur l'autre et vice versa (Gopher et al., 1996 ; Kramer, Larish & Strayer, 1995). Ce type de paradigme expérimental est au cœur de la présente thèse et les études l'ayant utilisé seront abordées dans la section 3.1.

Nous avons donc vu que le contrôle attentionnel est une composante exécutive de haut niveau qui est sollicitée dans des conditions où les demandes attentionnelles sont élevées et qui interviendrait dans l'exécution et la coordination de comportements complexes en réponse aux demandes extérieures. La plupart des études décrites dans cette section ont porté sur des personnes jeunes. Dans la prochaine section, nous nous intéresserons aux modifications des capacités de contrôle attentionnel avec l'âge.

2.2. Vieillissement normal et contrôle attentionnel

Les personnes âgées se plaignent spontanément de difficultés à réaliser deux tâches simultanément et à diviser leur attention (Langlois & Belleville, 2013; Weaver, Maruff, Collie, Shafiq-Antonacci & Masters, 2007). De nombreuses études empiriques confirment la présence de ces difficultés chez les ainés (Bherer et al., 2005, 2008; Craik, 1977; Crossley & Hiscock, 1992; Hahn et al., 2008; Hartley, Jonides & Sylvester, 2011; Li et al., 2001; Vaportzis, Georgiou-Karistianis & Stout, 2013, 2014; Verhaeghen, 2011; Verhaeghen & Cerella, 2002; Whiting & Smith, 1997). Parmi celles-ci, une méta-analyse menée par Verhaeghen et al., (2003) sur l'effet du vieillissement sur les performances aux tâches d'attention divisée, conclu à un effet de l'âge pour les temps de réponse suggérant un coût attentionnel deux fois plus important chez les âgés que chez les jeunes adultes. Plus récemment, une revue de méta-analyses menée par le même auteur (Verhaeghen, 2011) a montré que les tâches impliquant les capacités de coordination, comme la double tâche, montrent davantage de différences liées à l'âge, lorsque comparées à d'autres tâches de nature exécutive, comme celles mesurant la résistance à l'interférence (p.ex. tâche de Stroop). De plus, Verhaeghen (2011) rapporte que, parmi les mesures exécutives répertoriées, seul le déclin de la performance aux épreuves de double-tâche est spécifique au vieillissement normal et qu'il n'est pas attribuable à un ralentissement général (McDowd & Shaw, 2000; Verhaeghen & Cerella, 2002; Verhaeghen et al., 2003). L'attention divisée serait donc particulièrement sensible au vieillissement normal.

Des différences liées à l'âge seraient aussi présentes en ce qui a trait au contrôle attentionnel (Braver et al., 2001; Braver & West, 2008; Reuter-Lorenz, Festini & Jantz, 2016; Salthouse, Rogan & Prill, 1984; Verhaeghen, 2011). Braver & West (2008) ont proposé que le vieillissement est associé à une détérioration de la capacité à contrôler adéquatement le traitement stratégique descendant ou *top-down*, qui est nécessaire dans les tâches impliquant des demandes contradictoires au niveau perceptuel ou de la réponse, par exemple, lors de situations en attention divisée. La présence ou non de difficultés de contrôle attentionnel en condition d'attention divisée reste toutefois à être élucidée puisque les données empiriques sont contradictoires.

Dans une série de trois études réalisées par Salthouse, Rogan & Prill (1984), des participants jeunes et âgés devaient réaliser conjointement deux tâches de mémoire visuelle (mémoriser une série de lettres et une série de chiffres), en modifiant l'emphase attentionnelle portée à l'une ou l'autre des deux tâches. Dans ce type de paradigme, un problème de contrôle attentionnel devrait se manifester par un pourcentage de bonnes réponses plus faible sur la tâche qui est à prioriser. Par exemple, si l'on demande au participant de porter 75 % de son attention sur la tâche de mémoire de lettres et 25 % sur la tâche de mémoire de chiffres, le nombre de bonnes réponses attendues devrait être supérieur pour la tâche de mémoire de lettres. Dans l'une des trois études, les auteurs montrent une interaction Age x Emphase se traduisant par des difficultés accrues pour les participants âgés à gérer l'allocation des ressources attentionnelles en fonction de l'emphase (i.e. la quantité d'attention à allouer à une tâche). Par contre, les auteurs n'ont pas retrouvés cette interaction dans les deux autres études, bien que les âgés présentaient une performance globale plus faible en attention divisée (Salthouse et al., 1984). Les tâches expérimentales utilisées dans les deux dernières études étaient moins exigeantes que celles utilisées dans la première, ce qui aurait pu faciliter leur coordination. Pour expliquer ces résultats, les auteurs soulèvent l'hypothèse que les difficultés d'allocation attentionnelle, observées dans l'étude 1, pourraient être liées à une diminution des ressources disponibles avec l'âge, plutôt qu'à des difficultés de contrôle attentionnel. Selon cette hypothèse, plus le niveau de difficulté de la tâche augmente plus les ressources disponibles pour la traiter diminuent, ne permettant pas de réaliser la tâche de façon optimale. Cette diminution des ressources attentionnelles disponibles serait donc étroitement liée à l'augmentation du niveau de difficulté de la tâche et serait caractéristique du vieillissement cognitif.

En résumé, le vieillissement se caractérise par des difficultés à réaliser deux tâches de façon simultanée. Ces difficultés pourraient s'expliquer par un trouble du contrôle attentionnel ou par une baisse des ressources attentionnelles disponibles avec l'âge. L'article 1 vise à mieux comprendre l'atteinte attentionnelle dans le vieillissement. Cette démarche est importante puisque les interventions cognitives doivent reposer sur une connaissance précise des atteintes et des fonctions préservées dans le vieillissement. Dans la prochaine section, nous nous intéresserons aux interventions cognitives dans le vieillissement.

3. Les interventions cognitives dans le vieillissement

Plusieurs études ont tenté de vérifier si les capacités cognitives des personnes âgées pouvaient s'améliorer via des interventions cognitives ciblées (Mowszowski, Batchelor & Naismith, 2010). Il existe différents types d'interventions cognitives. Parmi celles-ci, les interventions de type *stratégique* ont largement été utilisées dans la littérature. Ce type d'intervention cible l'apprentissage de nouvelles méthodes ou techniques permettant de favoriser la performance à une tâche donnée. La vaste majorité des études portant sur l'entraînement *stratégique* chez la personne âgée ont visé à améliorer les capacités mnésiques, par exemple, via l'apprentissage de techniques d'imagerie mentale (Belleville et al., 2006; Gross et al., 2014; Rebok et al., 2013). Certaines études ont aussi porté sur les capacités de raisonnement et de résolution de problèmes (Payne et al., 2011; Willis & Caskie, 2013; Willis et al., 2006). Un autre grand type d'intervention cognitive porte sur l'entrainement des *processus* via la pratique répétée. Ces interventions sont souvent adaptatives et varient le niveau de difficulté de la tâche au cours de l'entraînement. De nombreuses fonctions cognitives ont été visées par ce type d'entraînement : vitesse de traitement de l'information (Ball et al., 2002; Edwards et al., 2005), attention sélective (Fisk, Hertzog, Lee, Rogers & Anderson-Garlach, 1994; Ho & Scialfa, 2002; Jenkins & Hoyer, 2000), mémoire de travail (Dahlin, Neely, Larsson, Bäckman & Nyberg, 2008), alternance (Kramer, Hahn & Gopher, 1999; Kray & Eppinger, 2006) et attention divisée (Bherer et al., 2005, 2008; Kramer et al., 1999; Kramer et al., 1995). Dans le domaine attentionnel, tant les entrainements de stratégies que la pratique répétée ont été utilisés.

3.1. Entraînement attentionnel et entraînement à priorité variable

Les interventions cognitives utilisées visant les processus attentionnels ont porté entre autres sur l'attention visuelle (Ball et al., 2002; Willis et al., 2006), l'attention auditive (Anderson, White-Schwoch, Parbery-Clark & Kraus, 2013; Mahncke et al., 2006) ou les capacités de double-tâche (Bherer et al., 2005; Kramer et al., 1995).

Dans l'étude ACTIVE (*Advanced Cognitive Training for Independent and Vital Elderly*), Ball et al., (2002) ont évalué l'effet de trois types d'entraînements cognitifs sur les capacités cognitives. Les participants bénéficiaient pendant 5 à 6 semaines d'un entraînement cognitif qui portait soit sur la mémoire épisodique, la capacité de raisonnement ou l'attention visuelle. Dans ce dernier, les participants étaient entraînés en contexte de double-tâche à l'aide du test *Useful Field of View* (UFOV ; Edwards, Wadley, Vance, Roenker & Ball, 2005) dans lequel le participant devait identifier une cible au centre de l'écran et simultanément, repérer une cible en périphérie, et ce à différents niveaux de difficulté (ajout du nombre de distracteurs ; variation de la vitesse d'apparition des stimuli). 87 % des participants ayant reçu l'entrainement attentionnel ont montré une amélioration de leurs performances au post-test.

Au niveau de l'attention auditive, Mahncke et al., (2006) ont montré des améliorations significatives sur un score global de mémoire suite à un programme d'entraînement attentionnel adaptatif (Brain Fitness Cognitive Training: Posit Science) visant la discrimination et l'identification de stimuli acoustiques (p.ex. sons de différentes fréquences, syllabes, courtes histoires).

Pour ce qui est des capacités de double tâche, plusieurs études ont fait appel à des techniques de modulation de la proportion d'attention à allouer à chacune des tâches (priorité variable) et ont porté de façon plus spécifique sur l'entraînement du contrôle attentionnel (Bherer et al., 2005; Gagnon & Belleville, 2012; Gopher, 2007; Kramer et al., 1995). Ces entraînements supportent l'apprentissage de stratégies d'allocation des ressources attentionnelles. Les techniques de contrôle attentionnel sont pratiqués alternativement ou successivement dans un contexte intégré et adaptatif. L'étude de Kramer et al., (1995) a été l'une des premières à faire appel à un paradigme d'entrainement à priorité variable pour réduire les difficultés attentionnelles associées au vieillissement. Pour ce faire, les auteurs ont comparé deux types d'entraînements attentionnels : 1) un entraînement à *priorité variable*, dans lequel le participant devait combiner les deux mêmes tâches tout en variant le niveau d'attention alloué à chacune à travers plusieurs blocs et 2) un entraînement à *priorité fixe*, faisant office de groupe contrôle actif, dans lequel le participant devait combiner deux tâches, une tâche de monitoring où il devait surveiller et remettre à jour une jauge et une tâche d'équation alphanumérique de type « G – 1 = ? » et 2). Dans l'entraînement à *priorité variable*, une rétroaction sur les performances était donnée aux participants afin de les amener à exercer un contrôle actif sur leur attention. Chaque entraînement était composé de trois séances d'environ une heure. Dans cette étude, la variable cible était une tâche d'attention divisée dans laquelle les participants réalisaient deux tâches conjointement (tâche de mémoire de paires de mots et de planification) en y portant le même niveau d'attention. Kramer et al., (1995) rapportent une amélioration de l'attention divisée pour les deux groupes d'entraînement, mais un gain plus important pour les participants entraînés en *priorité variable*.

Gagnon & Belleville (2012) ont comparé l'efficacité d'un entraînement à *priorité fixe* vs un entrainement à *priorité variable* chez des participants âgés avec un trouble cognitif léger (TCL). Les interventions étaient offertes pendant 6 séances d'une heure chacune et la variable cible portait sur les capacités d'attention divisée et consistait à réaliser deux tâches (équation alphanumérique et tâche de détection visuelle) conjointement en portant le même niveau d'attention aux deux tâches. Contrairement à l'étude de Kramer et al., (1995), l'entraînement à *priorité variable* impliquait une stratégie d'autorégulation afin de favoriser les capacités de métacognition, dans laquelle les participants devaient faire une auto-évaluation de leurs performances suivie d'une rétroaction. L'entraînement à *priorité fixe* servait de groupe contrôle actif. Les auteurs ont montré une réduction du coût attentionnel en attention divisée pour les participants ayant suivi l'entraînement à *priorité variable* (Gagnon & Belleville, 2012), mais pas pour ceux ayant reçu l'entraînement à *priorité fixe*. L'efficacité d'un entraînement à *priorité* *variable* a aussi été montrée auprès de jeunes adultes dans un contexte de jeu vidéo (Lee et al., 2012; Voss et al., 2012) se traduisant par une meilleure acquisition et maitrise des techniques de jeu.

Par ailleurs, d'autres études observent au contraire que les deux types d'entraînement peuvent mener à une amélioration équivalente des capacités d'attention divisée (Bherer et al., 2005 ; 2008). Par exemple, Bherer et al., (2005) ont comparé un entraînement à *priorité fixe* et à *priorité variable* à l'aide d'un paradigme de double-tâche combinant une tâche de discrimination visuelle (i.e. déterminer si la lettre présentée à l'écran est un B ou un C) et sonore (i.e. déterminer si le son est aigu ou grave). Comme pour la majorité des études précédemment décrites la variable cible portait sur les capacités d'attention divisée sans demande de modulation attentionnelle. Cependant, l'étude de Bherer et al (2005) est la seule à avoir comparé les deux groupes d'entraînements à un groupe contrôle « sans contact » qui n'effectuait que les séances pré et post-entraînement. Bherer et al. (2005) rapportent donc une amélioration équivalente des deux groupes entraînés en contexte de double-tâche et aucune amélioration pour le groupe contrôle sans contact. Le fait qu'ils n'aient pas trouvé de différence entre les deux types d'entraînements pourrait provenir du fait que le paradigme utilisé nécessitait moins de capacité de coordination, les tâches utilisées étant relativement simples.

Bien que plusieurs études aient évalué l'efficacité d'un entraînement à *priorité variable* chez la personne âgée, certaines questions restent à être élucidées. D'abord, on ne sait pas jusqu'à quel point la pratique sur chaque tâche réalisée individuellement peut contribuer à l'effet obtenu. En effet, les groupes contrôles dans ces études étaient soient des groupes contrôles actifs (*entraînement à priorité fixe*) pour contrôler l'effet de la pratique aux tâches en attention divisée, ou un groupe sans contact qui ne suivait aucun entraînement. Aucune étude n'a donc inclus de groupe contrôle actif visant à isoler l'effet de la pratique aux tâches simples. Ces études ne permettent donc pas d'exclure que l'amélioration en attention divisée puisse provenir en partie du fait que chaque tâche était mieux réalisée séparément et donc plus facile à combiner avec la seconde. Ensuite, l'effet de l'entrainement était évalué sur un paradigme de double-tâche où les participants devaient accorder le même niveau d'attention aux deux tâches. Il est donc difficile de déterminer l'effet de ces entraînements sur les capacités de contrôle attentionnel, c'est à dire sur l'habileté des participants à varier le niveau d'attention alloué à l'une ou l'autre des tâches.

En résumé, les résultats des études décrits plus haut semblent suggérer que les personnes âgées avec ou sans TCL peuvent améliorer leur capacité d'attention divisée. Toutefois, il n'est pas clair si l'entraînement à *priorité variable* est plus efficace que l'entraînement à *priorité fixe*. De plus, l'apport de la pratique aux tâches simples sur les performances en attention divisée ainsi qu'une mesure plus précise de l'impact d'un entraînement à *priorité variable* sur les capacités de contrôle attentionnel reste à être évalué. Ces questions seront abordées dans l'article 2 de la présente thèse.

On ne sait pas non plus si ces interventions permettent d'améliorer le fonctionnement cognitif au quotidien des personnes âgées. Cette question fera l'objet de la prochaine section.

4. Transfert

4.1. L'importance du transfert

L'objectif ultime des interventions cognitives est de soutenir la personne âgée pour qu'elle puisse rester indépendante et autonome plus longtemps. Sur le plan clinique, le transfert des bénéfices des interventions cognitives au-delà des tâches entraînées en laboratoire est primordial si l'on souhaite utiliser ces entraînements pour améliorer le fonctionnement cognitif dans la vie quotidienne des aînés. Cependant, les mécanismes sous-tendant les effets de transfert sont encore peu connus et de nombreuses questions restent à être élucidées.

Tel qu'abordé dans la section précédente les interventions attentionnelles peuvent mener à des effets positifs sur les capacités cognitives des personnes âgées. Cependant, quand est-il du transfert de ces gains vers des tâches nouvelles non entraînées ? Est-ce possible de transférer ces acquis aux activités de la vie quotidienne et est-ce que les personnes âgées peuvent autant bénéficier des effets de transfert que les jeunes adultes ? La définition du transfert ainsi qu'une revue de la littérature sur les effets de transfert suite aux interventions attentionnelles et sur l'effet d'âge sur les capacités de transfert seront présentées dans les sous-sections suivantes.

4.2. Définition du transfert

Le transfert est une notion ancienne puisque déjà en 1906, Thorndike proposait la théorie des éléments communs (*common elements theory*) suggérant que l'entrainement à un type d'activité ne pourrait être transféré que si les activités sollicitées par la tâche de transfert partagent des éléments communs avec la phase d'entraînement. De cette théorie découle la notion de transfert proximal (*near transfer*) et distal (*far transfer*) (Barnett & Ceci, 2002). On parle de transfert proximal quand la tâche de transfert et celle entraînée partagent plusieurs éléments en communs. Le transfert distal, quant à lui, réfère au transfert entre des tâches qui partagent moins d'éléments. Bien que cette conceptualisation du transfert soit largement utilisée dans la littérature, elle reste relativement vague en raison de l'absence de critères stricts sur ce qui est considéré comme proximal ou distal et son opérationnalisation diffère d'une étude à l'autre (Noack, Lövdén & Schmiedek, 2014). Par exemple, certaines études utilisent le terme de transfert distal pour décrire les effets de transfert mesurés à l'aide de questionnaires auto-rapportés portant sur les capacités fonctionnelles au quotidien, alors que d'autres utilisent ce terme pour désigner des tâches expérimentales utilisant des modalités différentes à celle de la tâche entraînée (p.ex., utiliser une tâche de discrimination visuelle plutôt qu'auditive). Ces deux tâches diffèrent toutefois considérablement en termes du nombre d'éléments communs partagé avec la tâche entraînée.

D'autres modèles plus récents ont proposé une taxonomie des différentes formes de transfert. Ainsi Barnett & Ceci (2002), proposent une définition multidimensionnelle du transfert qui distingue entre autres la notion de transfert de *contenu* et de *contexte* (Barnett & Ceci, 2002). Le transfert de *contenu* survient lorsque l'apprentissage d'une habileté mène à l'amélioration d'une nouvelle habileté, tâche ou fonction cognitive non directement visée par l'entraînement (Austin, 2009; Butterfield & Nelson, 1991; Mayer & Wittrock, 1996; Noack, Lövdén, Schmiedek & Lindenberger, 2009). Par exemple, un entraînement sur une double-tâche améliore les performances dans une situation de double-tâche utilisant des tâches des natures différentes. En revanche, le transfert de *contexte* survient lorsqu'un comportement ou une stratégie apprise dans un contexte est appliqué avec succès dans un contexte différent de celui entraîné (Bransford, Brown & Cocking, 2000; Lobato, 2006; Perkins & Salomon, 1992). Par exemple, on parle de transfert de *contexte* quand on mesure si l'apprentissage de stratégies mnésiques diminue le nombre d'oublis rapporté par les participants dans leur quotidien, ou encore si un entraînement en attention divisée fait à l'ordinateur améliore les capacités de conduite mesurée sur la route. Le transfert de *contenu* est généralement mesuré à l'aide de tâches expérimentales conçues pour évaluer des processus cognitifs qui se rapprochent des tâches cognitives entraînées, par exemple en modifiant la modalité de présentation des tâches ou la nature de celle-ci. Le transfert de *contexte* est quant à lui plus souvent mesuré à l'aide de questionnaires qui reflètent la cognition dans le fonctionnement de la vie de tous les jours ou des tâches en contexte réel mesurant certaines aptitudes du quotidien (conduite automobile à l'aide d'un simulateur). Dans le cadre de cette thèse, nous nous intéresserons particulièrement à la capacité des entrainements attentionnels à produire un transfert de *contenu* vs un transfert de *contexte*.

4.3. Transfert des entrainements attentionnels

Notons que les études ayant évalué les effets de transfert suite aux entraînements attentionnels ont porté pour la plupart sur le transfert de *contenu* (Bherer et al., 2005; Kramer et al., 1995; Lussier, Bugaiska & Bherer, 2016; Lussier, Gagnon & Bherer, 2012) et peu sur le transfert de *contexte* (Boot et al., 2010; Gopher, Weil & Bareket, 1994; Hart & Battiste, 1992). Ainsi, Kramer et al., (1995) montrent une amélioration plus importante pour le groupe entraîné en *priorité variable,* lorsque comparée au groupe entraîné en *priorité fixe,* à la fois sur le paradigme de double-tâche entraîné (tâches de *monitoring* et de mémoire de travail) et sur un paradigme de transfert similaire (tâche de mémoire de paires de mots et de planification). Des résultats similaires sont rapportés par Lussier et al., (2016) qui ont comparé les effets de transfert des deux types d'entraînements (*priorité variable* ; *priorité fixe*) chez la personne âgée saine. Le paradigme de double-tâche utilisé combinait deux tâches de discriminations visuelles simples (chiffres et formes). Les auteurs montrent une amélioration plus importante du coût de la performance en double-tâche sur les tâches de transfert (tâches de discrimination visuelles et auditives) pour le groupe entraîné en *priorité variable*. En contradiction avec ces études, certains auteurs ont montré soit des effets de transfert similaires pour les deux types d'entraînement

(Bherer et al., 2005) ou aucun effet de transfert (Bherer et al., 2008). Bherer et al., (2005) ont entraîné des participants jeunes et âgés à exécuter une double tâche composée d'une tâche visuomotrice (identification de lettres) et d'une tâche auditivomotrice (identification d'un son). Les tâches de transfert utilisaient les mêmes modalités que la tâche entraînée, soit une tâche visuomotrice (identification de chiffres) combinée à une tâche auditivomotrice (identification de sons) ou combinaient deux tâches visuelles (identification de chiffre et de formes). En résultante, les auteurs montrent une diminution du coût de performance en double-tâche pour les participants jeunes et âgés, et ce pour les deux tâches de transfert utilisées, peu importe le type d'entraînement (*priorité variable* ; *priorité fixe*).

Bien que plusieurs études montrent un bénéfice d'un entraînement à *priorité variable* sur des mesures de transfert de *contenu*, elles ne permettent pas de clairement supporter les effets de transfert dans un environnement plus proche de la vie quotidienne (*transfert de contexte*). Seules quelques études ont évalué l'impact d'un entraînement attentionnel sur des mesures de *transfert de contexte*.

Parmi les études ayant utilisées des tâches de transfert de *contexte* chez la personne âgée, l'étude ACTIVE rapporte des effets de transfert positifs suite à un entraînement attentionnel en condition de double-tâche via l'utilisation de questionnaires auto-rapportés (Rebok et al., 2014). Ces questionnaires permettent de mesurer les difficultés avec lesquelles les participants effectuent leurs activités de la vie quotidienne (AVQ) (Rebok et al., 2014 ; Willis et al., 2006). L'entraînement en attention visuelle (UFOV) engendrait un déclin moins important des AVQ lors d'un suivi 10 ans plus tard lorsque comparé à un entraînement mnésique (Rebok et al., 2014). Les effets positifs de cet entraînement ont aussi été montré via l'amélioration des performances à une tâche en simulation de conduite, ainsi qu'une diminution de l'occurrence de comportements dangereux lors d'un exercice de conduite réelle (Roenker, Cissell, Ball, Wadley & Edwards, 2003).

En ce qui concerne le contrôle attentionnel, Gagnon & Belleville (2012) ont utilisé un questionnaire auto-rapporté, le *Divided Attention Questionnaire* (DAQ), pour évaluer les effets de transfert d'un entraînement à *priorité variable* et à *priorité fixe* chez des participants âgés avec TCL. Le DAQ évalue les difficultés des participants à réaliser des tâches de façon concurrente dans la vie quotidienne (p.ex. parler à quelqu'un tout en conduisant ; écouter la radio tout en travaillant). Les auteurs ne montrent aucun effet de transfert sur cette mesure suite aux entraînements.

Chez le jeune adulte, quelques études ont utilisé des situations en contexte réel ou des tâches complexes plus « réalistes » pour évaluer le transfert d'un entraînement à *priorité variable* (Boot et al., 2010; Gopher et al., 1994; Hart & Battiste, 1992). Gopher et al., (1994) ont montré des effets de transferts positifs d'un entraînement à *priorité variable* réalisé dans un contexte de jeu vidéo interactif (Space Fortress) sur la performance de vol en situation réelle (manœuvre de vol simple et complexe) chez un groupe de cadet de l'armée israélienne. Lors de l'entraînement, les participants devaient contrôler le vaisseau tout en essayant de diriger des missiles pour détruire la forteresse. Boot et al., (2010) ont aussi montré des effets de transfert positifs à l'aide d'un simulateur de tâches complexes (contrôle aérien et simulateur de vol). L'entraînement à *priorité variable* améliorait les performances en double-tâche sur ces deux mesures.

En résumé, un entraînement à *priorité variable* semble montrer des effets de transfert prometteur sur des tâches expérimentales similaires à celles entraînées. Cependant, malgré son efficacité peu d'études ont évalué ses effets sur des tâches plus représentatives du fonctionnement quotidien. Les études l'ayant fait ont porté pour la plupart sur des groupes de jeunes adultes, ce qui rend difficile l'interprétation chez la personne âgée. D'autres études ont fait appel à des questionnaires auto-rapportées. Ces questionnaires ont comme désavantage d'être subjectifs et de dépendre des capacités métacognitives des participants qui peuvent parfois être limitées (Zanardo, De Beni & Mo, 2006). Aussi, il est possible que les participants soient plus à l'affut de leurs difficultés cognitives suite à l'entraînement, ce qui peut se traduire par un score plus élevé aux échelles mesurant le type d'erreur attentionnelle fait au quotidien (Gagnon & Belleville, 2012).

4.4. Effet de l'âge sur la capacité de transfert

Certaines études suggèrent que l'âge pourrait avoir un impact sur les capacités de transfert (Dahlin et al., 2008; Kühn & Lindenberger, 2016). En effet, certains auteurs soulèvent l'hypothèse qu'une diminution des capacités plastiques du cerveau avec l'âge aurait pour effet de limiter la capacité des âgés à généraliser leurs apprentissages. Cette hypothèse est appuyée par certaines études montrant moins d'effet de transfert chez les âgés, lorsque ces derniers sont comparés à de jeunes adultes (Dahlin et al., 2008; Derwinger, Neely, Persson, Hill & Bäckman, 2003; Neely & Backman, 1993). Par exemple, Dahlin et al., (2008) montrent un transfert de contenu sur une tâche de mémoire de travail similaire à celle entraînée (différent format de réponse et niveau de charge en mémoire plus élevé) uniquement pour le groupe de jeunes adultes. Les auteurs suggèrent que la complexité de la tâche aurait limité le transfert chez les âgés. Cependant, certaines études montrent des effets de transfert équivalent entre les deux groupes d'âge (Bherer et al., 2005; Li et al., 2008). Ainsi, Li et al., (2008) montrent des effets de transfert de contenu similaires pour les âgés et les jeunes adultes sur une tâche de mémoire de travail de complexité différente à celle entraînée. Bherer et al., (2005) montrent aussi un transfert de contenu similaire pour les âgées et les jeunes adultes suite à un entraînement en situation de double-tâche. Cela irait plutôt dans le sens d'une préservation des capacités plastiques du cerveau.

5. Substrats neuronaux du contrôle attentionnel et des interventions cognitives

5.1. L'imagerie par résonance magnétique fonctionnelle (IRMf)

L'imagerie par résonance magnétique fonctionnelle (Huettel, Song & McCarthy, 2014; Kim et al., 1993; Ogawa et al., 1992) est une mesure non invasive qui permet de mesurer indirectement l'activité neuronale du cerveau. Le signal *Blood-Oxygen-Level Dependent* (BOLD) est utilisé pour détecter les changements de propriété magnétique de l'hémoglobine qui amène l'oxygène nécessaire aux neurones pour leur bon fonctionnement. Un changement des propriétés magnétiques survient selon que l'hémoglobine est porteuse ou non d'oxygène. Les processus cognitifs sollicités par une tâche entraînent une modification du flux sanguin local (réponse hémodynamique) qui induit une augmentation (et parfois une diminution) du signal BOLD dans les régions cérébrales qui les soutiennent. Le changement est mesuré par rapport à une condition de contrôle. La résolution temporelle de l'IRMf est relativement lente puisque la réponse hémodynamique est caractérisée par un pic apparaissant après une dizaine de secondes seulement. À l'inverse sa résolution spatiale est excellente, de l'ordre du millimètre, ce qui représente un des avantages les plus importants de la technique. La technique a aussi l'avantage d'être facilement accessible et peu invasive. Utilisée dans le cadre des études d'intervention, la neuroimagerie fonctionnelle permet de mieux comprendre les effets des entraînements cognitifs sur le cerveau. Quand on s'intéresse au vieillissement, les changements d'activation observés suite aux interventions sont généralement interprétés à la lumière des activations reliées aux tâches qui sont entrainées et des effets de l'âge sur ces activations. La prochaine section présentera donc un bref survol des études ayant tenté de déterminer les régions qui sont associées au contrôle attentionnel chez le sujet jeune et âgé.

5.2. Substrats neuronaux du contrôle attentionnel

Les régions impliquées dans le contrôle attentionnel sont relativement bien connues. Les études en neuroimagerie ont montré l'implication d'un réseau fronto-pariétal (Cole et al., 2013; Corbetta & Shulman, 2002; Dosenbach, Fair, Cohen, Schlaggar & Petersen, 2008; Joyce & Hrin, 2015; Zanto & Gazzaley, 2013) dans le contrôle cognitif (contrôle attentionnel) et la mémoire de travail. Ce réseau a été mis en évidence à l'aide de tâches complexes nécessitant la régulation de différents processus cognitifs et la sélection des actions appropriées dans la réalisation d'un but, par exemple des tâches de mémoire de travail verbale ou visuelle, d'attention divisée et de flexibilité (Cole et al., 2013; Hwang, Hallquist & Luna, 2012; Joyce & Hrin, 2015; Spreng, Sepulcre, Turner, Stevens & Schacter, 2013). Le réseau comprend plusieurs régions cérébrales qui incluent le cortex préfrontal (CPF) dorsolatéral (CPFDL) (BA 6, 8 et 9), le cortex cingulaire antérieur (CCA), médian (BA 32), ventro-latéral (BA 47), le lobule pariétal inférieur, le cervelet et certaines régions sous-corticales dont le noyau caudé (Joyce & Hrin, 2015; Wager & Smith, 2003). Le cortex fronto-polaire (BA 10) a également été impliqué dans les processus cognitifs de haut niveau (contrôle attentionnel ; habiletés de coordination) et permettrait l'intégration et la coordination de certaines fonctions exécutives nécessaires à l'accomplissement de tâches nouvelles et complexes, la prise de décision et les capacités métacognitives.

Comme notre travail portera plus particulièrement sur le paradigme de double-tâche, la prochaine section s'attarde aux études de neuroimagerie ayant utilisé ce type de protocole. Afin de quantifier les régions cérébrales spécifiques aux tâches en attention divisée, la majorité des études utilisent une condition en attention focalisée comme condition contrôle (Adcock, Constable, Gore & Goldman-Rakic, 2000; Corbetta, Miezin, Dobmeyer, Shulman & Petersen, 1991; Erickson, Ringo Ho, Colcombe & Kramer, 2005; Loose, Kaufmann, Auer & Lange, 2003; Schubert & Szameitat, 2003; Szameitat, Schubert & Müller, 2011). Certaines études rapportent que l'attention divisée amène un recrutement de nouvelles régions telles que le CPFDL (Corbetta et al., 1991; Johnson & Zatorre, 2006; Loose et al., 2003; Schubert & Szameitat, 2003; Skinner, Fernandes & Grady, 2009), le CCA (Corbetta et al., 1991; Loose et al., 2003) et le gyrus frontal médian (Schubert & Szameitat, 2003) lorsque comparé aux activations en condition d'attention focalisée. Selon ces auteurs, ces régions seraient reliées aux capacités de coordination en situation de double-tâche. D'autres études indiquent que l'attention focalisée et divisée activent un même ensemble de régions, mais que ces régions sont plus activées en contexte de double-tâche, en raison de la complexité de la tâche (Erickson et al., 2005; Hahn et al., 2008; Nebel et al., 2005). Ce manque de consensus pourrait être attribuable entre autres à la nature des tâches utilisées (Szameitat et al., 2011).

Dans le vieillissement, certains auteurs ont rapporté une diminution avec l'âge des activations préfrontales typiquement observées en condition d'attention divisée (Anderson et al., 2000; Milham et al., 2002; Prakash et al., 2009). Par exemple, Anderson et al., (2000) ont évalué à l'aide de la tomographie par émission de positrons (TEP) les différences d'activation lors de la réalisation de deux tâches en attention divisée chez des participants jeunes et âgés. Dans la condition d'attention divisée, les participants devaient à la fois encoder des paires de mots et discriminer des sons. Les auteurs rapportent une diminution de l'activité du CPF gauche chez les personnes âgées en condition d'attention divisée comparativement aux jeunes adultes. Dans le même ordre d'idées, Milham et al., (2002) ont mis en évidence à l'aide de l'IRMf, une diminution reliée à l'âge dans les régions du CPFDL et pariétales lors d'une version modifiée de la tâche de stroop (couleur/nom). Les résultats de cette étude ont été confirmés par celle de Prakash et al., (2009), qui à l'aide du même paradigme, montrent une diminution liée à l'âge dans le CPF. Selon les auteurs, lors des conditions incongruentes, les âgés présentent plus de difficultés que les jeunes à mobiliser les ressources nécessaires de façon flexible, ce qui entraine une baisse d'activation et une baisse de performance.

Il est à noter cependant que plusieurs études rapportent de plus grandes activations chez les âgées que chez les jeunes en condition d'attention divisée (Fernandes, Pacurar, Moscovitch & Grady, 2006; Hartley et al., 2011). Ainsi, Fernandes et al., (2006) montrent une activation bilatérale plus importante au niveau du CPFDL chez les âgées que chez les jeunes lors d'une tâche mnésique en condition d'attention divisée. Par contre, au niveau comportemental, les âgés présentaient des performances équivalentes à celle des jeunes lors du rappel en attention divisée. Les auteurs concluent que cette hyperactivation aurait une action compensatoire, c'est-à-dire que les âgés doivent recruter davantage les régions du CPF pour performer au même niveau que les jeunes et ainsi pallier à la diminution d'efficacité avec l'âge des régions spécialisées dans la réalisation de la tâche.

Les études rapportent donc soit des diminutions, soit des augmentations des activations préfrontales avec l'âge en condition d'attention divisée. Ces résultats divergents pourraient être expliqués par le fait que les âgés peuvent dans certains cas recruter des régions compensatoires, mais qu'ils n'arrivent pas toujours à le faire, par exemple quand la tâche est trop difficile.

5.3. Substrats neuronaux des interventions cognitives

Quelques études ont évalué les substrats neuronaux induits par des interventions cognitives chez des participants jeunes et âgés. L'étude de Nyberg et al., (2003) est l'une des premières à avoir évalué chez des participants jeunes et âgés, l'impact neuroplastique d'un bref entraînement de la mémoire faisant appel à l'imagerie mentale (la méthode des lieux) et ce, à l'aide de la TEP. Les participants devaient effectuer un rappel sériel de quatre listes randomisées de 18 mots. Les auteurs ont mis en évidence des augmentations d'activation au niveau du cortex occipito-pariétal (BA 19) chez les jeunes et les âgés ayant amélioré leur performance au post-test. L'activation de ces régions est cohérente avec le moyen mnémotechnique appris, puisqu'elles jouent un rôle dans l'imagerie visuelle. De plus, suite à l'entraînement, des augmentations d'activations dans les régions frontales ont été observées, et ce, uniquement chez les jeunes. Selon les auteurs, les résultats de cette étude suggèrent que l'utilisation de stratégies nouvelles pourrait dépendre du recrutement de régions cérébrales alternatives et que les différences observées en fonction de l'âge pourraient s'expliquer par une baisse des ressources disponibles, c.-à-d., par une difficulté pour les aînés à recruter les régions frontales qui sont plus sensibles au vieillissement (Nyberg et al., 2003).

En lien avec l'utilisation de stratégies nouvelles, une étude plus récente menée par Belleville et al., (2011) est la première à utiliser l'IRMf afin d'évaluer les processus neuroplastiques associés à l'effet d'un programme d'intervention (MEMO, Gilbert, Fontaine, Belleville, Gagnon & Ménard, 2008) faisant appel à différentes stratégies de mémoire (p.ex. techniques d'association nom-visage ; méthode des lieux) chez des participants âgés sains et avec TCL. Les résultats de l'étude montrent que suite à l'entraînement mnésique, les participants avec TCL présentent une augmentation d'activation à la fois dans des régions préalablement activées (gyrus temporal gauche et insula) et dans des régions alternatives qui n'étaient pas recrutées lors de la tâche de mémoire en pré-entraînement, notamment au niveau du lobule pariétal inférieur droit lors de l'encodage et le gyrus temporal supérieur lors de la récupération. De plus, les auteurs montrent que l'augmentation d'activation dans le lobule pariétal inférieur droit à l'encodage est positivement corrélée aux performances lors de la tâche de mémoire au post-entrainement, ce qui suggère la mise en place de processus compensatoires efficaces en lien avec les stratégies mnésiques apprises. Les âgés sains montrent quant à eux une augmentation de l'activation lors de la récupération, mais une diminution d'activation lors de l'encodage, ce qui pourrait être expliqué par le fait que les âgés utilisaient déjà des processus actifs d'encodage avant l'entraînement. L'entrainement les aurait amenés à une relative automatisation de la stratégie, ce qui fait qu'ils auraient moins besoin de recruter ces régions reflétant ainsi un gain en efficacité (voir plus bas).

Des résultats similaires à ceux observés chez les participants avec TCL ont été trouvés à l'aide d'un entraînement visant la mémoire associative (utilisation de l'imagerie mentale pour mémoriser des associations objets-lieux ; Hampstead et al., 2012). Les auteurs montrent des augmentations d'activations dans des régions préalablement recrutées (hippocampe gauche) et des régions alternatives (hippocampe droit) chez les TCL. Les résultats de Belleville et Hamptead suggèrent que l'apprentissage de nouvelles stratégies amène une augmentation d'activation dans des régions spécialisées et le recrutement de régions alternatives. Les régions recrutées semblent aussi refléter les stratégies apprises, par exemple en lien avec l'imagerie visuelle, le traitement sémantique et la mémoire associative.

5.3.1. Substrats neuronaux des entraînements en contrôle attentionnel

Très peu d'études en IRMf se sont penchées sur les substrats neuronaux des interventions visant le contrôle attentionnel chez la personne âgée. Parmi celles-ci, certaines études rapportent des diminutions d'activations ou une combinaison d'augmentation et de diminution suite aux entraînements.

Brehmer et al., (2011) ont évalué les effets de deux types d'entraînement en mémoire de travail : un entraînement *adaptatif* dans lequel ils faisaient varier le niveau de difficultés des tâches en augmentant ou diminuant le nombre d'items à mémoriser et un groupe contrôle actif qui exécutait les tâches, mais au même niveau de difficulté. Les auteurs montrent principalement des patrons de diminution d'activation dans de nombreuses régions cérébrales, notamment les régions frontales et pariétales, et ce pour les deux groupes entraînés. Les auteurs soutiennent que ces diminutions d'activation seraient reliées à un recrutement plus efficace des régions impliquées dans la tâche. En effet, pour l'entraînement *adaptatif,* les diminutions d'activation seraient associées à de meilleures performances lors de l'entraînement (Brehmer et al., 2011). Cette interprétation est appuyée par de nombreuses études qui se sont intéressées aux substrats neuronaux induits par l'effet de la pratique simple chez des sujets jeunes (Chein & Schneider, 2005; Kelly, Foxe & Garavan, 2006). Dans ce type d'intervention, on demande généralement aux participants de pratiquer la tâche de façon répétée ou en augmentant le niveau de difficulté de la tâche. Ces études montrent majoritairement des diminutions d'activation dans les régions initialement recrutées par la tâche (Brehmer et al., 2011; Garavan, Kelley, Rosen, Rao & Stein, 2000; Hempel et al., 2004; Kelly et al., 2006; Kelly & Garavan, 2005; Landau, Schumacher, Garavan, Druzgal & D'Esposito, 2004). Comme elles sont associées à une amélioration de la performance, ces diminutions d'activation refléteraient un recrutement plus efficace et une meilleure utilisation des circuits neuronaux nécessaires à la réalisation de la tâche (Chein & Schneider, 2005; Lustig, Shah, Seidler & Reuter-Lorenz, 2009).

D'autres études montrent une combinaison de diminution et d'augmentation d'activation (Erickson et al., 2007; Erickson et al., 2010). Erickson et al., (2007) et Erickson et al., (2010) ont évalué l'effet d'un entraînement en attention divisée (5 x 1 heure) sur l'activité cérébrale des âgés sains et de jeunes adultes. Le groupe d'entraînement était comparé à un groupe contrôle qui ne recevait aucune intervention. Les participants devaient réaliser deux tâches de discrimination visuelle en attention focalisée et de façon concurrente. Les résultats montrent un patron mixte de diminution et d'augmentation d'activation dans le cortex préfrontal ventral (CPFV) en situation de double-tâche pour le groupe entrainé. D'abord, les auteurs rapportent un patron de diminution d'activation dans le CPFV droit suite à l'entraînement pour les deux groupes d'âge. Cette diminution est expliquée comme étant le reflet d'une utilisation plus efficace de cette région cérébrale, probablement en lien avec l'automatisation de certaines stratégies (p.ex. sélection de la réponse). Ensuite, une augmentation d'activation est rapportée dans le CPFV gauche (près de la région de Broca) uniquement chez les âgés ayant amélioré leur performance au post-test, reflétant une plus grande asymétrie au niveau du CPFV suite à l'entraînement. Le recrutement de cette région pourrait refléter l'utilisation de stratégies de verbalisations internes lors de la réalisation de la double-tâche (orientées vers un but précis) (Erickson et al., 2007; Erickson et al., 2010).

5.4. Questions relatives aux effets des interventions sur les activations cérébrales

Bien que quelques études montrent que des interventions cognitives peuvent générer des changements fonctionnels mesurables en IRMf chez les participants âgés, celles-ci restent peu nombreuses. De plus, il reste plusieurs questions à élucider. D'abord, les patrons d'activation observés suite aux entraînements cognitifs semblent contradictoires d'une étude à l'autre. Certaines études montrent des diminutions d'activation, alors que d'autres montrent une combinaison d'augmentations et de diminutions. Il importe donc de comprendre ce qui détermine le type de changements cérébraux évoqués par les interventions.

Le type d'intervention cognitive utilisé dans les études mentionnées pourrait avoir un impact sur les patrons d'activation cérébrale. En effet, les études chez les participants jeunes et l'analyse des résultats observés chez les âgés, semblent indiquer que les entraînements visant la pratique répétée entraineraient plutôt des diminutions d'activation dans les régions préalablement impliquées dans la réalisation de la tâche, alors que les entraînements se basant sur l'apprentissage de nouvelles stratégies ou visant des capacités métacognitives, entraineraient quant à eux des augmentations d'activation dans des régions alternatives. L'impact du type d'entraînement sur les changements d'activation cérébrale reste donc à être élucidé et fait partie des objectifs de l'Article 4 de cette thèse.

Nous nous intéresserons également au décours temporel des changements d'activation au cours des interventions cognitives (Article 5). La littérature s'étant penchée sur les changements d'activations à différentes phases de l'entraînement a porté entre autres sur l'apprentissage de tâches motrices simples (Doyon & Benali, 2005; Doyon et al., 2011). Ces études montrent que les changements d'activation sont modulés par la phase d'apprentissage au cours de l'entraînement. Sachant que le recrutement des réseaux cérébraux devient de plus en plus efficace plus la tâche devient automatisée et bien apprise (Doyon & Benali, 2005), il est possible de se demander si tel est le cas lors d'un entraînement à une tâche cognitive. Les études ont souvent évalué les changements d'activation à l'aide de deux temps de mesure en IRMf ne permettant pas d'aller évaluer ce qui se passe durant l'entraînement et si les changements d'activation observés sont linéaires ou non.

6. Objectifs et hypothèses de recherche

En résumé, divers éléments majeurs ressortent de la revue de littérature qui précède et soutiennent le présent travail. L'objectif principal de la thèse est d'évaluer l'effet des interventions cognitives sur le contrôle attentionnel en faisant appel à des mesures comportementales et à des mesures d'IRMf. Pour être en mesure de développer des interventions cognitives ciblées et efficaces, il importe de bien comprendre d'où proviennent les difficultés attentionnelles chez la personne âgée. Il n'est pas clair si ces difficultés sont expliquées par une baisse des ressources attentionnelles disponibles avec l'âge, ou par des difficultés à modifier l'emphase attentionnelle en fonction des demandes externes. C'est un point de départ important, puisque les interventions doivent être guidées par une connaissance fine des atteintes et capacités résiduelles.

Ensuite, les interventions cognitives ayant ciblé le contrôle attentionnel semblent montrer qu'un entraînement à *priorité variable* pourrait être plus efficace qu'un entraînement à *priorité fixe* pour améliorer les capacités de coordination en double-tâche. Cependant, plusieurs questions restent à être élucidées. Entre autres, l'apport de la pratique aux tâches simples sur les performances en attention divisée, ainsi qu'une mesure plus précise de l'impact d'un entraînement à *priorité variable* sur les capacités de contrôle attentionnel chez la personne âgée. De plus, la notion de transfert de ces entraînements au fonctionnement quotidien (*transfert de contexte*) est encore peu connue et pourtant essentielle d'un point de vue clinique. Les études ayant montré les bénéfices d'un entraînement à *priorité variable* sur des mesures plus représentatives du fonctionnement au quotidien ont porté pour la plupart sur des groupes de jeunes adultes, ce qui rend difficile l'interprétation chez la personne âgée. Aussi, les effets de certains facteurs tels que l'âge et le type d'entraînement sur les capacités de transfert sont encore peu explorés.

Enfin, les substrats neuronaux sous-tendant les effets des interventions attentionnelles sont encore très peu connus. Les études actuelles sont assez contradictoires et montrent des patrons d'activation très variables suite aux entraînements. La nature des interventions reçues pourrait jouer un rôle important dans les patrons observés et semble peu explorée dans la littérature. De plus, aucune étude ne s'est intéressée au décours temporel des changements d'activation, ce qui peut être informatif quant aux fonctionnements des entraînements et des processus d'apprentissage sous-jacents. Cette thèse se propose donc d'essayer de répondre à ces questions à l'aide des cinq articles décrits ci-dessous.

6.1. Article 1: Effect of age on attentional control and dual-tasking

Objectifs. L'article 1 présente deux études visant à mieux comprendre et évaluer la source des différences reliées à l'âge en attention divisée. Plus spécifiquement, celui-ci vise à examiner si ces différences surviennent en raison 1) de difficultés en ce qui a trait aux capacités de contrôle attentionnel ou 2) d'une réduction des ressources générales qui affecterait la capacité des âgés à performer des tâches plus exigeantes. Pour cela, des participants jeunes et âgés ont effectué deux tâches en attention divisée, soit une tâche d'empan de chiffres et une tâche visuo-spatiale de poursuite d'une cible. Dans une première étude, comprenant 21 participants âgés et 21 participants jeunes, les capacités de contrôle attentionnel étaient évaluées en demandant aux participants de varier la proportion d'attention à accorder à l'une ou l'autre des deux tâches réalisées conjointement selon la consigne d'emphase attentionnelle. Dans une deuxième étude, 24 nouveaux participants âgés et 24 participants jeunes devaient réaliser les deux tâches conjointement et le niveau de difficulté d'une des deux tâches était manipulé de façon paramétrique et individuelle pour chaque participant en augmentant la vitesse de la cible à suivre.

Hypothèses.

1) Nous nous attendons à ce que les participants âgés présentent plus de difficultés que les jeunes adultes à varier le niveau d'attention à allouer à chacune des tâches selon la consigne d'emphase attentionnelle, reflétant un problème de contrôle attentionnel.

2) Nous pensons également que l'effet de l'âge sur le coût attentionnel ne sera pas amplifié par le niveau de difficultés de la tâche, indiquant qu'il n'est pas expliqué par une diminution de ressource.

6.2. Article 2: Identifying training modalities to improve multi-tasking in older adults.

Objectifs. L'étude 2 a deux objectifs : comparer l'efficacité de trois types d'entraînements attentionnels chez la personne âgée et évaluer le transfert de *contenu*. Pour cela, 42 participants âgés ont été randomisés à l'un de trois types d'entraînements attentionnels suivants : 1) un entraînement en pratique simple (*SINGLE*) où les participants pratiquaient deux tâches en attention focalisée, soit une tâche de vérification alpha-numérique de type (A + 2 = C) et une tâche de détection visuelle, 2) un entraînement à priorité fixe (*FIXED)* ou les participants devaient réaliser les deux mêmes tâches de façon concurrente en portant autant d'attention aux deux et 3) un entraînement à priorité variable (*VARIABLE*) dans lequel les participants étaient appelés à varier le niveau d'attention à allouer à chacune des tâches à travers plusieurs blocs. Les participants étaient entraînés par groupe de deux ou trois à raison de 6 séances d'une heure sur une période de deux semaines. Les participants étaient évalués avant et après l'entraînement à l'aide d'une tâche proche de celle entraînée. Les participants réalisaient une tâche de vérification alphanumérique et de détection visuelle en attention simple, en attention divisée et en allouant soit 20 % soit 80 % de leur attention sur l'une ou l'autre des deux tâches. Le transfert de contenu a été évalué avec une tâche de mémoire de travail (*N-Back*).

Hypothèses.

1) Suite à l'intervention, les trois groupes devraient améliorer leur performance en attention focalisée c.-à-d. lorsque les tâches sont réalisées individuellement. Le groupe *FIXED* et le groupe *VARIABLE* s'amélioreront en condition de double-tâche c'est-à-dire qu'ils montreront une diminution globale du coût attentionnel. Le groupe *VARIABLE* sera le seul à présenter une amélioration des capacités de contrôle attentionnel, c'est-à-dire qu'il sera en mesure de varier le niveau d'attention selon la consigne d'emphase attentionnelle.

2) Nous faisons l'hypothèse que seul les groupes *FIXED* et *VARIABLE* présenteront des effets de transfert sur la tâche de *N-Back* plus particulièrement sur la condition 2-*Back* puisque celle-ci est plus exigeante au plan exécutif. Nous nous attendons à ce que l'effet de transfert soit supérieur pour le groupe *VARIABLE*.

6.3. Article 3: Computerized attentional training and transfer with virtual reality: effect of age and training type

Objectifs. L'article 3 a trois objectifs : 1) évaluer le transfert de contexte en mesurant si les effets des entraînements se transfèrent à des tâches similaires à la vie quotidienne, 2) évaluer si les effets de transfert mesurés diffèrent selon l'âge des participants, 3) comprendre si un entraînement *VARIABLE* amène des effets de transferts plus importants qu'un entraînement en pratique simple (*SINGLE*). Pour ce faire, 30 participants âgés et 30 jeunes adultes ont été assignés de façon aléatoire à l'un des deux groupes d'entraînement. Dans l'entraînement *VARIABLE*, les participants devaient réaliser deux tâches conjointement (détection visuelle et vérification alphanumérique) et varier le niveau d'attention à porter à chacune des deux tâches. Dans l'entraînement *SINGLE*, les participants devaient exécuter chacune des tâches individuellement en attention focalisée. Le transfert est évalué en utilisant la réalité virtuelle (RV) et un questionnaire auto-administré. Pour évaluer les effets de transfert avec la RV, les participants étaient immergés dans une *promenade en voiture virtuelle*. Passagers d'une voiture, ils devaient guider le conducteur en cherchant des indications sur la route tout en effectuant une tâche auditivo-verbale complexe. Les participants ont aussi rempli un questionnaire auto-rapporté, le *Cognitive Failure Questionnaire* (CFQ) qui mesure la fréquence à laquelle ils commettent des erreurs dans la réalisation de tâches attentionnelles au quotidien.

Hypothèses.

1) Les participants du groupe *VARIABLE* amélioreront leur capacité de contrôle attentionnel sur la tâche similaire à celle entraînée et montreront un transfert dans l'environnement virtuel. Ces effets ne seront pas observés chez le groupe *SINGLE*.
2) Les deux groupes d'âge bénéficieront de façon équivalente de l'entraînement *SINGLE* et *VARIABLE*, mais les âgés devraient montrer un transfert moins important que les jeunes.

6.4. Article 4: The pattern and loci of training-induced brain changes in healthy older adults are predicted by the nature of the intervention

Objectifs. L'article 4 évalue l'impact de trois types d'entrainement attentionnel sur les changements d'activation en IRMf. Pour ce faire, 48 participants âgés sains ont été assignés à l'un des trois groupes d'entraînement (*SINGLE, FIXED* ou *VARIABLE*; voir section 6.2). Les tâches expérimentales utilisées étaient les mêmes que celles utilisées pour l'article 2 (section 6.2), i.e. une tâche d'équation alphanumérique et une tâche de détection visuelle. Les changements d'activation ont été mesurés avant et après l'intervention à l'aide de l'IRMf. Lors des séances d'IRMf, les participants réalisaient les deux tâches en attention focalisée, en attention divisée (autant d'attention sur les deux tâches) et variable (varier le niveau d'attention à allouer à l'une ou l'autre des deux tâches).

Hypothèses.

1) Comme il fait appel à de la pratique répétée, l'entraînement *SINGLE* devrait mener à des diminutions d'activation. En revanche l'entraînement *VARIABLE* devrait produire de

nouvelles activations ou des augmentations d'activation puisqu'il s'agit d'un entrainement stratégique et métacognitif. Ces changements seront observés dans des régions impliquées dans le contrôle attentionnel et la coordination multi-tâche. Un patron mitoyen est prévu en ce qui concerne la condition *FIXED*. Cette condition pourrait en effet produire soit des diminutions d'activation suite à la pratique des tâches en attention divisée, soit des augmentations d'activation dans des régions impliquées en attention divisée.

6.5. Article 5: Timecourse of brain and cognitive changes following two types of comupterized attentional training programs: A three-time points fMRI intervention study in older adults

Objectifs. L'article 5 a pour objectif principal d'évaluer le décours temporel en IRMf des changements d'activation suite à deux entraînements attentionnels chez la personne âgée saine. Dans cette étude, 30 participants âgés ont été assignés soit à un entraînement *VARIABLE* où les participants devaient varier le niveau d'attention à allouer à chacune des deux tâches (équation alphanumérique ou détection visuelle) ou un entraînement *SINGLE* dans lequel les participants étaient entraînés à réaliser les deux tâches individuellement en attention focalisée. Trois séances d'IRMf étaient réalisées : 1) avant l'entraînement (*BASELINE*), 2) après la 4^{e} séance d'entraînement (séance 4) et 3) après la 8^{e} et dernière séance d'entraînement (séance 8). Lors de ces séances, les participants devaient effectuer les deux tâches en attention focalisée et de façon concurrente en variant le niveau d'attention porté à l'une ou l'autre tâche.

Hypothèses.

1) Au niveau comportemental, nous nous attendons à ce que le groupe *SINGLE* améliore ses performances sur les deux tâches lorsqu'elles sont réalisées en attention focalisée, mais ne montre pas d'amélioration de ses capacités de contrôle attentionnel. Le groupe *VARIABLE* devrait améliorer ses performances en condition d'attention focalisée en condition de contrôle attentionnel.
2) Au niveau des activations, nous nous attendons à des diminutions d'activation pour le groupe *SINGLE* sur les tâches réalisées en attention focalisée. Nous faisons l'hypothèse d'un changement linéaire c'est-à-dire qu'une baisse d'activation sera observée en comparant le *BASELINE* à la session 4 et en comparant la session 4 à la 8. Pour le groupe *VARIABLE*, nous nous attendons à des augmentations d'activation ou de nouvelles activations du *BASELINE* à la session 4 dans des régions impliquées dans le contrôle attentionnel et la coordination multi-tâches. Nous faisons l'hypothèse que la pratique permettra d'automatiser la stratégie apprise et que ces activations diminueront de la session 4 à la session 8.

Chapitre II

Article 1: *Effect of age on attentional control in dual-tasking*

Article 1: Effect of age on attentional control in dual-tasking

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ABSTRACT

Background/Study Context: The age-related differences in divided attention and attentional control have been associated with several negative outcomes later in life. However, numerous questions remain unanswered regarding the nature of these age differences and the role of attentional control abilities in dual-tasking. The aim of this study was to evaluate the sources for age differences in dual-tasking and more specifically: (1) whether they occur because of differences in attentional control skills, or 2) whether the age-related decrement in dual-tasking is due to a general resource reduction that would affect the ability to complete any demanding task.

Methods: In two experiments, young and older adults were required to combine an auditory digit span task and a visuo-spatial tracking task, for which performance was individually adjusted on each task. In Experiment 1, attentional control skills were measured by instructing participants to deliberately vary attentional priority between the two tasks. In Experiment 2, resource availability was measured by varying the level of difficulty of the visuo-spatial tracking task in a parametric manner by increasing the speed of the target to be tracked.

Results: Both experiments confirmed the presence of a larger dual-task cost in older adults than in young adults. In Experiment 1, older participants were unable to vary their performance according to task instructions compared to younger adults. Experiment 2 showed that the age-related difference in dual-task cost was not amplified by a variation in difficulty.

Conclusion: A marked age-related difference was found in the ability to control attentional focus in response to task instructions. However, increasing resource demand in a parametric manner does not increase the age-related differences in dual-tasking, suggesting that the difficulties experienced by older adults cannot be entirely accounted for by an increased competition for resources. A reduction in attentional control skills is proposed to account for the divided attention deficit reported in aging.

INTRODUCTION

Many studies have reported a higher dual-task cost in older adults compared to their younger counterparts (Craik, 1977; Crossley, & Hiscock, 1992; Hartley, & Little, 1999; Li, Lindenberger, Freund, & Baltes, 2001; Salthouse, Rogan, & Prill, 1984; Verhaeghen, Steitz, Sliwinski, & Cerella, 2003; Whiting, & Smith, 1997). This may be due to an impairment of attentional control, a skill that enables flexible coordination and switching between tasks, both of which are necessary for goal-oriented behaviors. In turn, it may reflect a general age-related resource reduction, as dual-tasking produces more competition for limited resource capacities than single-tasking. The goals of this study were to evaluate the presence of age-related differences in the ability to control attentional allocation in a divided attention task (Experiment 1) and whether divided attention is due to a reduction in general resources available for dual-tasking (Experiment 2).

Attentional control is considered as being central to many theories of cognitive aging and is part of numerous models of cognitive functioning (Braver et al., 2001; Braver, & West, 2008; Salthouse, Atkinson & Berish, 2003). It is defined as a top-down executive process that enables complex goal-oriented behaviors under attentionally demanding conditions (Milham et al., 2002). A few models have attempted to better define this concept. In the model proposed by Braver et al., (2001), goal maintenance is considered a key mechanism of cognitive or attentional control, and a critical component for successful performance in a wide variety of cognitive tasks. This is used to support and select the actions necessary for complex behavior. For example, when participants are given task instructions in dual-attention, goals must be actively represented and maintained in a form that can bias attention allocation and response selection toward appropriate behavior. In this model, attentional control is particularly important in situations with a strong competition for response selection, such as a complex dual-tasking paradigm (Braver et al., 2001; Braver & West, 2008). This is empirically supported, as studies using factor-analytic techniques (Engle, Tuholski, Laughlin, & Conway, 1999; Miyake et al., 2000) have shown that attentional control is largely involved in both coordinative ability and dual-tasking.

Age-related differences in attentional control have been well documented (Braver et al., 2001; Braver, & West, 2008; Reuter-Lorenz, Festini & Jantz, 2016; Salthouse, Rogan, & Prill, 1984; Verhaeghen, 2011). A meta-analysis review conducted by Verhaeghen (2011) showed that tasks involving coordinative ability such as dual-tasking show more age-related differences than other executive control tasks, e.g., those involving resistance to interference. Along these lines, Braver, & West, (2008) proposed that aging is associated with a decline in the ability to adequately control the top-down strategic processing needed in tasks that involve conflicting perceptual or response demands. Dual-tasking is an interesting instance of a task that requires attentional control, as it entails the coordination of the concurrent processing of different streams of information and the ability to switch between different tasks that need to be completed. It is thus possible that impaired control in top-down processing plays an important role in the difficulties in dual-tasking observed in older adults.

In the present study, we measured attentional control skills with a dual-task paradigm that required voluntarily changing the focus of attention in response to external demands. Various dual-task situations that occur in everyday life require one task to be prioritized over the other such as having a conversation with a passenger while driving a car in heavy traffic, planning and executing responses to avoid a collision, or crossing the street while talking on a hands-free cell phone. In experimental conditions, complying with priority instructions can be considered as requiring control over attentional priority (Anguera et al., 2013; Belleville, Mellah, de Boysson, Demonet, & Bier, 2014; Bier, de Boysson, & Belleville, 2014; Gopher, 1996; Kramer, Larish, & Strayer, 1995). In these conditions, participants are asked to complete two tasks in combination, but are instructed to place more of their attentional priority on one of the two tasks. Age-related differences were found in the ability to divide attention (Anderson, Bucks, Bayliss, & Della Sala, 2011; Craik, 1977; Craik, Govoni, Naveh-Benjamin, & Anderson, 1996; Craik & McDowd, 1987; Crossley & Hiscock, 1992; Hartley & Little, 1999; Li, Lindenberger, Freund, & Baltes, 2001; Mcdowd & Craik, 1988; Verhaeghen, & Cerella, 2002; Verhaeghen, Steitz, Sliwinski, & Cerella, 2003; Wright, 1981). There is also an indication of an impairment in the ability to vary attentional priority (Salthouse, Rogan, & Prill, 1984). In the study carried out by Salthouse, Rogan, & Prill, (1984), younger and older adults were given instructions and payoffs to vary their attentional emphasis among two visual memory tasks. In one of three experiments, the authors found that older adults had difficulties modulating their attention as a function of emphasis instructions. This difficulty in changing attentional focus as a function of external demands is indicative of a decline in attentional control capacities. However, in experiments 2 and 3, older adults seemed to allocate their attention across emphasis conditions in a similar fashion than their younger counterparts despite a less efficient performance in divided attention (Salthouse, Rogan, & Prill, 1984). Here, the authors modified the dual-task paradigms in order to reduce the response interference between both visual memory tasks, which could have reduced the coordination requirement of the task and boosted the performance of older adults. Also, the size of the groups was markedly reduced in both experiments 2 and 3, which could have diminished the statistical power. Yet, the authors concluded that the age-related differences could be due to an increased complexity of the situation rather than a problem in attentional allocation, and reflect a resource reduction (Salthouse, Rogan, & Prill, 1984).

The hypothesis that divided attention and attentional allocation deficits may reflect sensitivity to task demand is consistent with the hypothesis that cognitive aging is characterized by a reduction in resources, which has a larger impact on more demanding than on less demanding tasks (Shallice, 1994). As task demand increases, a resource ceiling is reached, leading to insufficient processing and age-related decrement (Reuter-Lorenz, & Cappell, 2008; Reuter-Lorenz, Festini & Jantz, 2016). If this is the case, age-related differences in dual-tasking should be sensitive to increasing the demand of the constituent tasks or to modifying certain aspects of the task design.

Some evidence suggests that the age-related differences in divided attention augment as task demand increases (Hartley & Little, 1999; Huxhold, Li, Schmiedek, & Lindenberger, 2006; McDowd & Craik, 1988). In these studies, difficulty or task demand has often been manipulated by using different types of tasks that are considered to be of varying levels of difficulty (Huxhold, Li, Schmiedek, & Lindenberger, 2006; McDowd & Craik, 1988; Vaportzis, Georgiou-Karistianis, & Stout, 2013; 2014). For instance, two studies showed that dual-task conditions that combine automatized tasks for which older adults have accumulated experience (e.g., word recognition) increases the performance of older adults and reduces the age-related differences, probably because highly-practiced tasks require less resources (Allen, Lien, Ruthruff, & Voss, 2014; Lien et al., 2006). McDowd & Craik, (1988) assessed whether task difficulty had an impact on the age-related difference on dual-tasking by varying the types of tasks to be combined in their dual-task paradigm (e.g., pressing a key when hearing a word spoken by a female voice or detecting target words corresponding to a certain category) or the number of choices involved in one of the tasks (e.g., two, four, or eight-choice decisions). More recently, Vaportzis, Georgiou-Karistianis, & Stout, (2013) used a dual-task paradigm with conditions of increasing difficulty by combining two digit recall tasks (forward (simple) and backward (complex) digit recall) and two reaction time (RT) tasks (simple choice RT and complex choice RT) that were meant to be of differing levels of difficulty. Both studies showed an age-related difference in dual-task costs, which was amplified with increased task difficulty. However, in both studies, interpretation of the difficulty effect is elusive, as tasks of different difficulty levels also vary in nature. Here, we propose to measure the effect of task difficulty on divided attention by manipulating the properties of the two tasks in a parametric manner and by adjusting the tasks so that differences in difficulty are equivalent in young and older adults.

This paper presents two experiments that were carried out to identify the source of the dual-tasking difficulties in healthy older individuals relative to young adults. First, we evaluated the effect of aging on attentional control by measuring the ability to vary attentional allocation as a function of task instructions. Because dual-tasking is complex and may be explained by differences in resource availability, we also measured whether increasing the level of difficulty of a dual-task would modulate the age-related differences in dividing attention. We varied task demand of one of the constituent tasks by manipulating the level of difficulty in a parametric manner. The demands of both tasks were individually adjusted. This has consequences when comparing groups that differ in their ability to perform on one or both constituent tasks. If healthy older adults have a reduced ability to perform one or both tasks separately, it could create greater difficulty when combining the two tasks or when attempting to control their attention. Thus, we controlled reduced performance ability by adjusting the tasks according to individual levels of ability. In both experiments, young and older adults were required to combine an auditory digit span task and a visuo-spatial tracking task, and performance was individually adjusted. Experiment 1 measured the ability of young and older adults to vary their attentional priority between the two tasks in response to specific instructions. Experiment 2 varied the level of difficulty of the visuo-spatial tracking task by increasing the speed of the target to track as a function of individual performance level. Healthy older adults were expected to have more difficulties than young adults in controlling their attentional priority between the two tasks. It was also anticipated that older adults would present a larger dual-task cost but that age-related differences would not be amplified by a variation in difficulty.

Experiment 1

METHODS

Participants

Forty-two subjects (21 young adults and 21 older adults) participated in Experiment 1. All participants were recruited in the community through postings, advertisements in retirement centres and magazines for seniors. Participants were included if they were French-speaking, community dwelling, living in the Montreal area, right-handed, and had normal or corrected-to-normal hearing and vision. Exclusion criteria included: alcoholism or substance abuse; presence or history of a neurological disorder or stroke; presence or history of a severe psychiatric disorder (e.g., depression, schizophrenia, bipolar disorder).

The two groups were matched on gender and educational level and all participants completed the Mill Hill Vocabulary Test (Gérard, 1983), a widely used francophone test in which subjects are asked to identify the synonym of a target word among six choices. The characteristics of the 42 participants are presented in Table I. The two groups were comparable on educational level, F (1,40) = .71, $p > .05$, performance on the Mill Hill, F (1, 40) = 1.45, p = .42, and gender composition, χ^2 (1) = .074, p = .63.

Table I. Mean scores for age, education and clinical measures

	Younger ($n = 21$)	Older ($n = 21$)	F	χ^2	p
Age	22.42 (2.9)	72.19 (3.4)			
Gender	16 F, 5 M	14 F, 7 M		0.07	.63
Education	14.79 (2.3)	14.21 (2.1)	0.71		.41
Mill Hill (/ 44)	28.24 (3.2)	30.42 (5.4)	1.45		.42

Note. Standard deviations are given in parentheses.

Apparatus, Stimuli and Procedure

The dual-task paradigm employed in this study was adapted from a dual-task paradigm originally used by Baddeley and collaborators (Baddeley, Logie, Bressi, Sala, & Spinnler, 1986) and is part of the Batterie d'Évaluation de la Mémoire Côte des Neiges (Chatelois et al., 1993). The paradigm involved a visuo-spatial tracking task combined with a digit recall task. For the visuo-spatial tracking task, the subject is instructed to follow a visual target moving on a computer screen with a rectangular cursor controlled by a computer mouse. In case of tracking failure, the square target turns black, providing feedback to the subject that the cursor was out of the target. In the digit recall task, participants are presented with a series of digits in an auditory form and are asked to report them in the same order as presented. The digits are presented at a rate of one item per second and recall is done verbally. The tasks were carried out in two conditions: a focused attention condition (where each task, tracking and span, was done on its own) and a divided attention condition (where the two tasks were done concurrently).

As a preliminary phase to assess the speed of the participants' tracking task, the procedure started with a familiarization process with mouse use and the tracking activity. During this phase, subjects simply tracked the target moving at a very slow pace (0.2 and 0.4 pixel per seconds) in the horizontal, vertical and oblique axes until they reached perfect tracking performance under these particular conditions. Two-practice trials were done on each different axes and speeds. Then, each participant's baseline levels were determined separately for the tracking and span task. Indeed, the speed of the visual target chosen to test the participants as well as the length of the lists used in the span series were determined individually for each person.

The baseline level on the tracking task was determined by using a modified version of the staircase psychophysical procedure. Participants were required to track targets moving at different speeds for 10 seconds on each speed. The procedure was used to obtain a speed at which participants obtained correct tracking about 70% of the time. Performance on tracking for a given speed corresponded to the percentage of time spent on the target in a period of pursuit and was computed by the program after each tracking trial. The staircase procedure began by assessing the participant at a slow pace (0.5 pixels per seconds) for which subjects usually reached a tracking performance above 90%. The speed was gradually increased by 0.2 pixels per second until the participant reached a performance of 65%. The procedure then reversed (decreasing the speed of the target) until the participant reached correct tracking 90% of the time. The presentation of ascending and descending series of speeds was repeated until a similar threshold (65% - 75%) was obtained on two consecutive series.

The baseline level of the digit recall task was determined by using the standard auditory digit span procedure of the Batterie d'Évaluation de la Mémoire Côte des Neiges (Chatelois et al., 1993). One practice trial preceded the task. This procedure consists of presenting four sequences of two items. If the subject recalled at least two of the four sequences correctly, four sequences of one item longer (i.e., three items) were presented. The procedure continued until the participant failed to meet the criteria. The longest sequence correctly recalled on at least half of the trials (i.e., two of the four trials) was used as the digit span threshold for the participant. In the experimental phase, participants were asked to recall 10 sequences of digits the length of which was one item less than their individually determined digit span threshold.

In the experimental phase, participants were first familiarized with the dual-task condition by practicing the two tasks together for two sequences of digits. Following the practice, participants performed the two tasks in focused attention and divided attention (concurrently) where participants were asked to vary their attentional priorities across three emphasis priority instructions (80% visual tracking; 50% visual tracking and 20% visual tracking). Accordingly, for the 80% visual tracking priority, participants were asked to attribute 80% of their attention on the visual tracking task and only 20% of their attention on the digit span task. In the 50% visual tracking priority, participants were asked to put an equal amount of attention of both tasks. In the 20% visual tracking priority, participants were asked to attribute 20% of their attention to the visual tracking task and 80% to the digit span task. Ten sequences of digits were administered for each emphasis priority instruction. According to an ABBA design, participants completed A) one block in focused attention (tracking, digit span), followed by B) two blocks in divided attention (2x [80/20, 50/50, 20/80]), and A) one final block of focused attention (tracking, digit span), for a total of 4 blocks. Inside each divided attention block, the order of presentation of each emphasis priority instructions were distributed within each subject using a Latin square design.

RESULTS

Preliminary analyses

Preliminary analyses with t-tests were performed to compare young and older participants on their span size and speed for which they obtained 70% correct tracking. For the span capacity, the analysis revealed a smaller span size in older adults ($M = 5.5$) compared to the younger participants ($M = 6.2$) ($p < .001$). Furthermore, older adults obtained a higher visual tracking threshold for the 70% speed criterion ($p < .001$). Thus, older adults required slower moving targets to obtain performance accuracy that was similar to that of young subjects.

Experimental phase

Dual-task scores (focused – divided / focused) were used as the dependent variable. This divided attention cost represents the proportional loss of performance in the divided attention condition as a function of performance in focused attention. Thus, this score controls for baseline performance and provides a measure of divided attention performance. For example, if the participant recalls an average of 6 digits in the focused attention condition and 5 digits in condition of divided attention, the dual-task cost would be low (6 - 5 / 6 = 0.16), but if the same participant recalls 2 digits in divided attention, the dual-task cost score would be higher (6 - 2 / 6 = 0.66). They were computed separately for the digit recall and visuo-spatial tracking task for each emphasis priority (80% visual tracking; 50% visual tracking; 20% visual tracking). Divided attention cost scores were analyzed with a mixed ANOVA using Emphasis (80% visual tracking, 50% visual tracking or 20% visual tracking) and Task (digit span; tracking) as within-subject factors, and Group (Young; Old) as a between-subject factor. Sensitivity analysis for the impact of potential non-sphericity was studied using the Greenhouse-Geisser correction.

Mauchly's test indicated that the assumption of sphericity was violated for Task x Emphasis interaction, χ^2 (2) = 8.1, *p* = .05, but not for the effect of Emphasis, χ^2 (2) = 1.2, *p* = .105. Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity. The correction was not necessary in our case, as no differences were found in our conclusions and on the significance of our results. We thus chose to report the results assuming sphericity.

The Emphasis x Task x Group interaction was significant, F (2, 39) = 3.64, $p < .05$ (η2 = 0.11). To identify the source of the interaction, ANOVAs were computed separately for each group with the variables emphasis and task. Considering the size of our sample and the homogeneity of the observed standard deviation, decomposition of the interactions were conducted inside the analysis of variance, which enables us to use all of the data available to estimate variance and the error of each comparisons.

For the younger adults, a main task effect was found, $F(1, 20) = 7.54$, $p < .05$ (η2 = 0.27), which was qualified by a Task x Emphasis interaction, $F(2, 19) = 5.19$, $p < .05$ (η2 = 0.20). Figure 1a shows the divided attention cost for younger adults on each task as a function of emphasis instructions. Mean comparisons revealed that the dual-task cost varies as a function of emphasis for both the digit span and the visuo-spatial tracking tasks, and goes in the opposite direction, as expected, as a function of the changes in priority required by task instructions. For the visuo-spatial tracking task, $F(2, 19) = 3.98$, $p < .05$ (η2 = 0.16), the dual-task cost in the 50% Tracking (M = .04) emphasis instruction condition was smaller than in the 20% Tracking (M = .08) emphasis instruction condition ($p < .05$). For digit recall, there was a smaller dual-task cost in the 20% Tracking (M = .04) than in the 50% Tracking (M = .15) and 80% Tracking (M = .13) ($p < .05$, in both cases), $F(2, 19) = 3.23$, $p < .05$ (η2 = 0.16). Figure 1a shows that younger adults tend to prioritize tracking when asked to equate their attention, as dual-task cost is smaller on tracking than on digit recall. When asked to shift their attention toward prioritizing digits, their dual-task cost on digits dramatically decreases and their cost on tracking increases. When asked to prioritize tracking, they can no longer improve their dual-task cost perhaps because it is already quite low. Thus, attentional priority to both tasks can be modulated by instructions, but this can be done to a larger degree for the digit recall task.

Figure 1b shows the divided attention cost for the older adults on each task as a function of emphasis instructions. For the older adults, no main effect of emphasis, task, or Emphasis x Task interaction was found (p = .45, .42, & .07 respectively; see Figure 1b). Note that because we had hypotheses regarding the effect of Emphasis, we decomposed the marginally significant Emphasis x Task interaction, but this revealed no further significant effect. These results indicate that the dual-task cost in older adults is comparable for the tracking and digit recall tasks and that it does not vary as a function of task priority instruction.

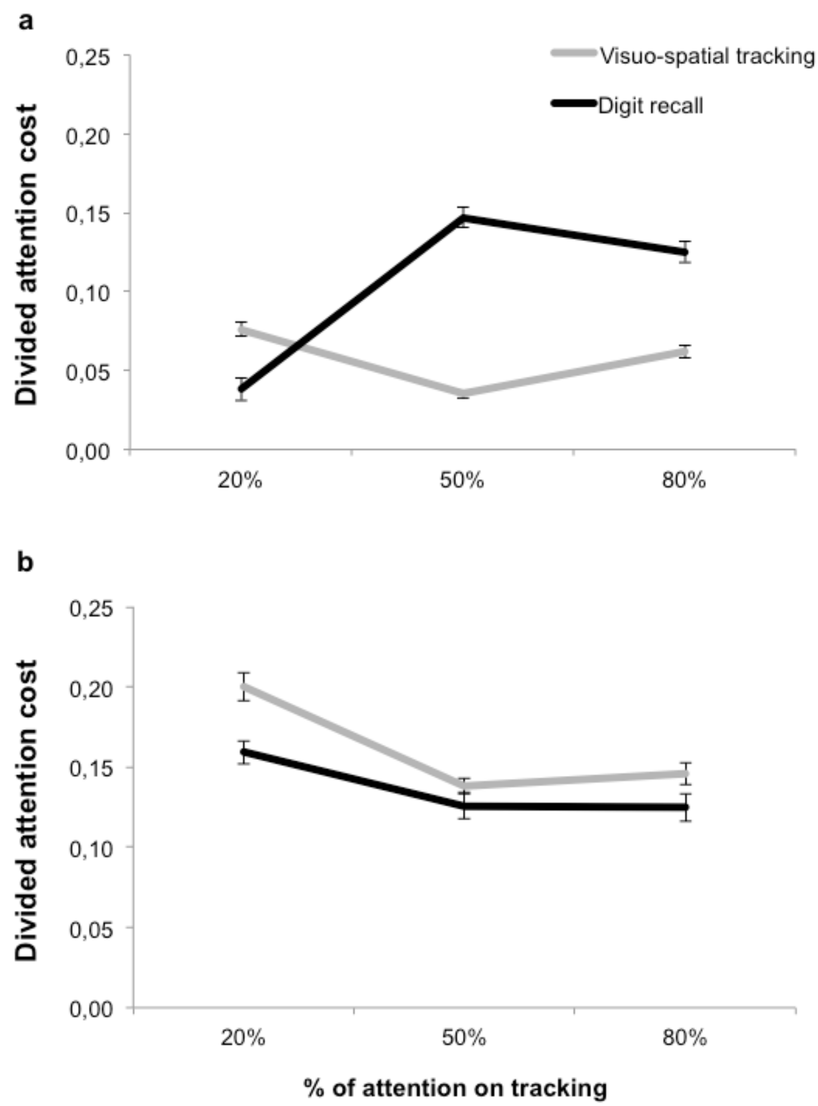

Figure 1. Divided attention cost [(focused – divided / focused)] for each task as a function of emphasis instruction (20% Visual Tracking, 50% Visual tracking, 80% Visual tracking) in divided attention for Young (a) and Older (b) adults. Error bars represent standard error.

Because we are interested in age differences, we also looked at whether the interaction results from age-related differences in the dual-task cost as a function of emphasis and task. We found that the age-related difference in dual-task cost is largest when participants are asked to prioritize digit recall ($p < .01$ on digit recall and $p < .05$ for tracking), the condition where younger adults decrease their dual-task cost. When participants are asked to place equivalent attention on both tasks (50% Tracking) or to prioritize tracking (80% Tracking), there is an age-difference on tracking only ($p < .05$ and $p < .05$ respectively; see Figure 1a and 1b).

DISCUSSION

In summary, results indicate that younger adults were better able to modify allocation priority as a function of task instructions, as younger participants dramatically lowered their dual-task cost on the digit recall task when the instructions required that this task be emphasized. On the contrary, older participants were unable to control their attention, as they showed similar dual-task costs irrespective of the emphasis instructions. Overall, these results indicate the presence of a marked age-related difference in the ability to control attentional focus as a function of external demands. The difficulty in responding to priority instruction may arise from the fact that this is a difficult task that places a high demand on attentional resources. This will be tested in the following experiment by increasing the demand of one of the two tasks and measuring if this increases the dual-tasking age-related difference.

Experiment 2

METHODS

Participants

Forty-eight different subjects (24 young adults and 24 healthy older adults) participated in Experiment 2. Participants were selected with the same criteria as mentioned in Experiment

1. Four participants (three young adults and one older adult) were excluded due to technical failure in the recording of their tracking performance. Therefore, a total of 21 young and 23 older adults were included in the analyses. The characteristics of the 44 participants are presented in Table II. The two groups were comparable on educational level, F (1, 42) = 2.98, p = .76 (η2 = 0.20), performance on the Mill Hill, F (1, 42) = 1.88, p = .65 (η2 = 0.20), and gender composition, χ^2 (1) = .052, p = .82 (η2 = 0.20).

Table II. Mean scores for age, education and clinical measures

	Younger ($n = 21$)	Older ($n = 23$)	F	χ^2	p
Age	23.33 (7.22)	65.95 (6.19)			
Gender	13 F, 8 M	15 F, 8 M		0.05	.82
Education	13.81 (2.20)	12.04 (4.18)	2.98		.76
Mill Hill (/44)	22.19 (2.46)	25.62 (3.13)	1.88		.65

Note. Standard Deviations are given in parentheses.

Apparatus, Stimuli and Procedure

The tasks used (tracking, digit span) were the same as in Experiment 1. The baseline level was assessed using the same staircase procedure but the goal of the procedure for the visual task was to obtain three different speeds of varying difficulty levels. The procedure identified speeds for which participants performed at 90% (easy speed), 70% (moderate speed), and 50% (difficult speed) correct tracking. Performance on tracking for a given speed corresponded to the percentage of time spent on the target in a 15 sec tracking period and was computed by the program after each tracking trial. The procedure started by assessing the participant at a slow pace (0.5 pixels per seconds) for which subjects usually reached a tracking performance above 90%. The speed was then gradually increased by 0.2 pixels per second until the participant reached a performance of 70% and 50%. The procedure then reversed (decreasing the speed of the target) until the participant would reach 90% percent correct tracking. The presentation of ascending and descending series of speeds was repeated until stable performance was obtained. Stable performance was defined as the time at which similar speed was obtained for each threshold target (50%, 70%, 90%) on three consecutive series. This determined three speeds for each participant, for which his/her performance was 90%, 70% or 50% correct.

The baseline level of the digit recall task was determined in the same manner as in Experiment 1, except that participants were asked to recall 15 sequences of digits, the length of which was one item less than their individually determined digit span threshold.

In the experimental phase, participants were first familiarized with the dual-task condition by practicing the two tasks together for two sequences of digits. Following the practice session, participants performed the two tasks in focused attention and divided attention, where participants were instructed to perform both tasks as best as they could, but to try to maintain performance on tracking. This was done to reduce the likelihood of inter-individual variability in the trade-off pattern. Tracking was performed using the three speeds determined previously. According to an ABBA design, participants completed A) one block of focused attention (digit span, tracking), followed by B) two blocks of divided attention (2x [90%, 70%, 50%]), and A) one final block of focused attention (tracking, digit span), for a total of 4 blocks. The order of presentation of the speed was varied across subjects using a Latin square design. Accuracy was recorded for both tasks.

RESULTS

Preliminary phase

Preliminary analyses with t-tests were performed to compare young and older participants on their span size and speed for which they obtained 90%, 70% and 50% correct tracking. The span capacity of the healthy older adults (M = 6.05) did not differ from that of their younger counterparts: (M = 6.38) (p = .38). However, older adults obtained higher visual tracking thresholds for each speed criterion (p = .001, .051 and .028, for the 90%, 70% and 50% respectively). Thus, older adults required slower moving targets to obtain a performance similar to that of the younger subjects.

Experimental phase

As in Experiment 1, dual-task scores (focused – divided / focused) were used as the dependent variable. They were computed separately for the digit recall task and the visuo-spatial tracking task. Divided attention cost scores were analyzed with a mixed ANOVA using tracking speed (90%; 70%; 50%) and task (digit recall; visuo-spatial tracking) as within-subject factors, and age (young; old) as a between-subject factor. As in Experiment 1, sensitivity analysis for the impact of potential non-sphericity was studied using the Greenhouse-Geisser correction. Mauchly's test indicated that the assumption was not violated for either tracking speed effect, χ^2 (2)= 5.4 p = .067 or Tracking speed x Task interaction, χ^2 (2)= .91 p =.634. We report the results assuming sphericity as the Mauchly's tests were not significant and no differences were found in our conclusions and on the significance of our results. As in Experiment 1, for the error terms, decomposition of the interactions was conducted inside the analysis of variance, which enables us to use all of the data available to estimate variance and the error of each comparisons.

Figure 2 shows the divided attention cost for both young and older participants on each task (digit span; visual tracking). There was a main effect of tracking speed, $F(2, 42) = 10.46$, $p < .001$ ($\eta2 = 0.20$), indicating higher divided attention cost as the level of difficulty increased. This effect was qualified by a Tracking speed x Task interaction, $F(2, 42) = 7.07$, $p < .001$ ($\eta2 = 0.14$). Decomposition of the interaction indicated that the difficulty effect was present in both tasks but was larger for digit recall ($p < .001$) than for the tracking task ($p = .04$). The Group effect was not significant. The Task x Group interaction was marginally significant, $F(1, 42) = 3.48$, $p = .06$ ($\eta2 = 0.07$). None of the other interactions reached significance.

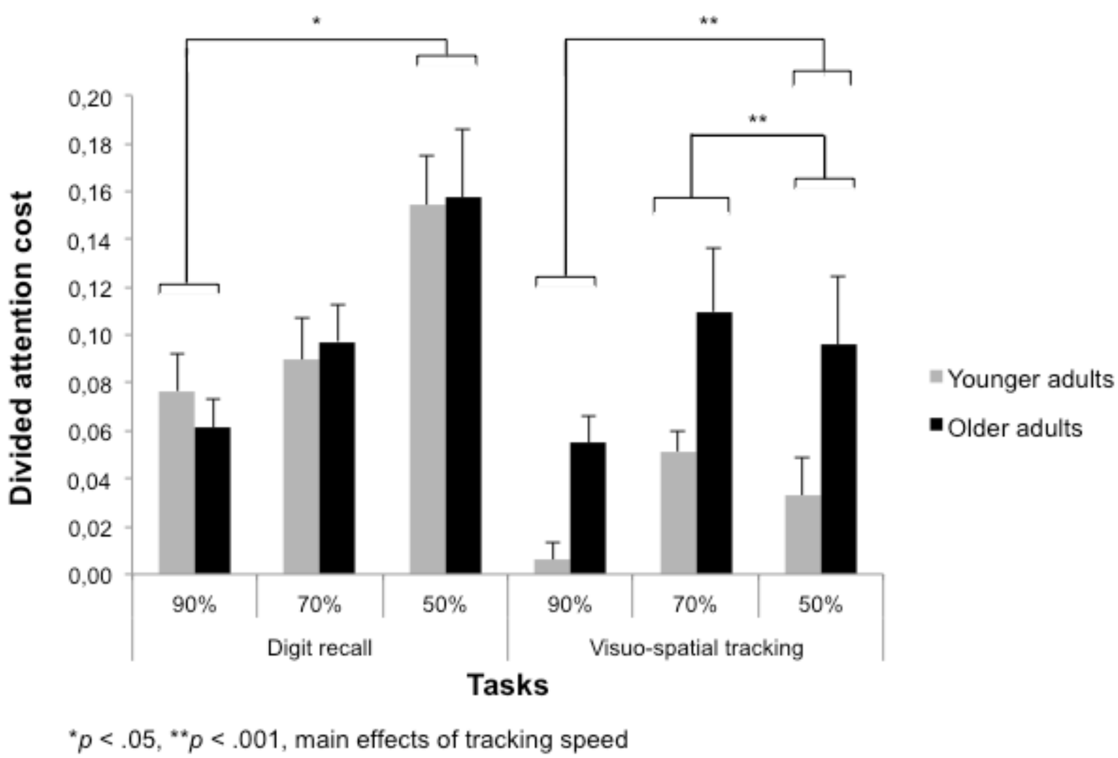

Figure 2. Divided attention cost [(focused – divided) / focused] for both Younger and Older participants on each task (digit recall; visuo-spatial tracking) as a function of tracking speed (90%, 70%, 50%). Error bars represent standard error.

Since we had a priori hypotheses regarding the impact of age on both tracking and digit recall performance, further analyses were carried out in order to identify the source of the interaction. Figure 3 shows the overall dual-task cost for each task for younger and older adults. Older adults were found to have a higher dual-task cost than younger adults on the visuo-spatial tracking task ($M = .09$ vs. $M = .03$, $p = .05$) but not on the digit recall task (*N.S*). Furthermore, younger adults had a higher dual-task cost on the digit span task ($M = .11$) than on the visuo-spatial task ($M = .03$) ($p < .01$), whereas dual-task cost was equivalent for the two tasks in older adults (*N.S*).

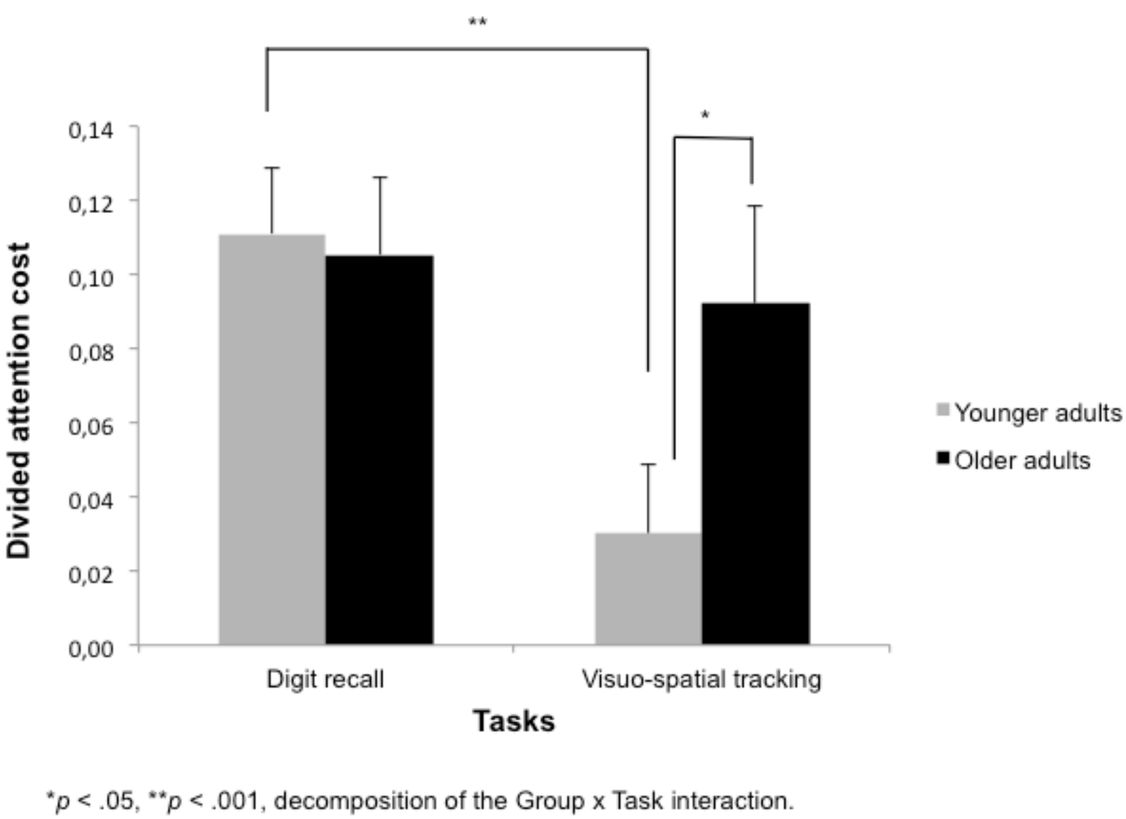

Figure 3. Divided attention cost [(focused – divided) / focused] for each task, averaged for all three tracking speeds (90%, 70%, 50%) for the Young and Older adults. Error bars represent standard error.

DISCUSSION

In summary, dual-task cost increases when increasing the tracking speed. This indicates that the dual-tasking cost is partly explained by a competition of resources. Importantly however, increasing difficulty does not modify the age-related differences, which implies that difficulties experienced by older adults cannot be entirely accounted for by an increased competition for resources. There were also some other interesting findings from this experiment. Particularly, there was a marginally significant Group x Task interaction. This comes from the fact that younger adults obtained a higher dual-task cost on the digit span task compared to the tracking task, whereas older adults showed a similar dual-task cost on both tasks. This is likely related to the fact that instructions required that participants maintain their performance on the tracking test and that only younger adults were able to comply.

GENERAL DISCUSSION

The present study assessed conditions that produce dual-task difficulties in healthy older individuals relative to young adults. The main objectives were to evaluate (1) whether they occur because of differences in the ability to control attentional allocation in a divided attention task, or 2) whether the age-related decrement in dual-tasking reflects reduced resources, a condition that should be particularly detrimental to demanding tasks. In two experiments, young and older adults were asked to combine auditory digit recall with a visuo-spatial tracking task, for which performance was individually adjusted on each task. Experiment 1 measured the ability of young and older adults to vary their attentional emphasis between the digit recall and visual tracking tasks in response to priority instructions. In Experiment 2, the level of difficulty of the visuo-spatial tracking task was varied in a parametric manner by increasing the speed of the target to track and by adjusting the tasks so that differences in difficulty were equivalent in young and older adults.

Our first objective was to assess whether age differences in dual-tasking occur because of differences in the ability to control attentional allocation. Attentional control is defined as the ability to exert conscious top-down monitoring and control over attention. It is highly involved when the individual is engaged in divided-attention tasks. We hypothesize that this is particularly the case when external demands require that participants actively manipulate, control, and switch their attentional allocation. We thus assessed the capacity of older adults to modulate their attentional allocation priority as a function of instructions as a direct link to attentional control skills. Engaging appropriate, controlled attention abilities should result in a differential dual-task cost as a function of emphasis instructions.

The results from Experiment 1 indicate marked age-related differences in the ability to vary attentional allocation. In this experiment, participants were asked to vary their attentional emphasis between the two tasks in response to instructions that required different prioritisation. Results indicate that the younger adults were better able to modify allocation priority as a function of task instructions, particularly for digit recall. Also, the younger participants dramatically lowered their dual-task cost on the digit recall task when the instructions required that the memory task be emphasized. The outcome is strikingly different for the older adults. Indeed, the older participants had similar dual-task costs on both the digit span and tracking tasks, regardless of the emphasis instructions. This suggests that they were unable to control their attention. The results are consistent with a previous study by Salthouse, Rogan, & Prill (1984) (Experiment 1 of 3) in which specific instructions and payoffs were given to the participants as a function of the level of attention required on each task. Overall, these results indicate that healthy older adults have marked difficulties in controlling their attentional focus as a function of external demands. Note that some of the results from Experiment 2 also support a deficit in attentional control. In this experiment, younger adults obtained a higher dual-task cost on the digit span task compared to the tracking task, which is consistent with our instructions that emphasized maintaining performance on the tracking test. By contrast, older adults showed a similar dual-task cost on both tracking and recall. This suggests that the younger adults complied with the instructions requiring them to focus on the visuo-spatial tracking task, whereas the older adults did not.

Age-related difficulties in dividing attention and controlling attentional focus could be due to the fact that these are demanding tasks. Thus, our second objective was to assess whether the age-related differences in dual-tasking reflect a reduction in resources available for demanding tasks. One innovation was to vary the level of difficulty of one of the two tasks in a parametric manner rather than manipulating task difficulty by varying the type of the tasks, as has been done in previous studies (Huxhold, Li, Schmiedek, & Lindenberger, 2006; McDowd & Craik, 1988; Vaportzis, Georgiou-Karistianis, & Stout, 2013). We found that dual-task cost increases when varying tracking speed, which indicates that our design was sound and that the manipulation of speed increased the difficulty in dual-tasking. This also indicates that dual-task cost is partly explained by a competition at the resource level. Nevertheless, we found no age-related differences as a function of demand, as both young and older adults exhibited similar patterns of dual-task cost changes with increased levels of difficulty. Interestingly, these results are coherent with a previous study that used a similar paradigm (Logie, Cocchini, Della Sala, & Baddeley, 2004). Young and older adults were asked to simultaneously complete a visual tracking task and a digit recall task. In one of the experiments, the demand for the tracking task changed within five levels of demand, ranging from well below to well above individually determined thresholds. Consistent with our results, no interaction was found between age and task demand. Interestingly, the effect of task difficulty was larger for digit recall than for tracking, which is in line with our instructions to maintain performance on the tracking test. The absence of a difficulty effect on the age-related divided attention cost suggests that difficulties experienced by older adults cannot be entirely accounted for by an increased competition for resources. It is not due to a general difficulty effect, due given that it is more difficult to complete two tasks than one.

It is important to mention that our design individually adjusted the difficulty level of each task. We believe that, when interested in manipulating conditions, it is particularly important to understand the mechanisms accounting for cognitive aging. For instance, age-related differences are found on a number of cognitive tasks, and finding a larger dual-task cost may result from the combination of tasks that are more difficult for older adults than younger adults (Allen, Lien, Ruthruff, & Voss, 2014: Lien et al., 2006). In the majority of the studies showing a larger dual-task cost in older relative to young adults, individual differences in single-task performance were not individually adjusted (see Verhaeghen, Steitz, Sliwinski, & Cerella, 2003). Because we used individually assessed levels of difficulty and compared performance against each individual's own baseline, differences in baseline performance were unlikely to affect the results. Moreover, setting the difficulty level at each individual's performance capacity ensured that results could not be described as participants having reached a ceiling performance on one of the tasks.

In spite of the fact that we adjusted performance, we found a larger dual-task cost in older relative to young adults. All conditions of Experiment 1 produced larger dual-task costs in older vs. young adults on tracking or on tracking and digit recall. The effect was present in Experiment 2, though it was marginally significant and only present on the tracking performance. These results are coherent with studies reporting an age-related dual-task cost, even after comparing single-task performance across groups (Hartley & Little, 1999; Logie, Sala, MacPherson, & Cooper, 2007; Salthouse, Fristoe, Lineweaver, & Coon, 1995). Our finding supports the conclusion that individual differences in the constituent tasks among young and older adults are insufficient to account for the age-related increase in dual-task cost and lends further support to our hypothesis of age-related differences in attentional control skills.

Overall, the combined results found in Experiment 1 and 2 suggest that dual-task difficulties in healthy older adults may arise from their reduced ability to control their attentional abilities. This suggests that task designs that limit the demand in attentional control skills or training programs that improve those skills could reduce the dual-tasking deficit found in older adults. For instance, Grabbe & Allen (2012) showed that the dual-task performance of older adults was improved when providing greater environmental support through response code compatibility. A number of studies have also shown that training attentional control improves the divided attention capacities of older adults (Bier, de Boysson, & Belleville, 2014; Kramer, Larish, & Strayer, 1995).

It is important to address the limitations of the present study. First, Experiment 2 might have been underpowered, as the Group x Task interaction was only marginally significant. Importantly, however, sample size proved sufficient to reveal other robust effects, and Experiments 1 and 2 showed consistent findings. An additional limitation found in our study is the fact that we did not vary the levels of difficulty and task instructions within the same experiment. Though this was done to reduce the complexity of the design and analyses, it reduced our ability to infer whether difficulty has an additive effect on the ability to control attention. Furthermore, our use of the term control is based on the hypothesis that modifying one's attention requires control capacities and that the change in performance as a function of task instruction reflects such capacities. Indeed, it is based on an interpretation that the performance we observed actually reflects control processes. Finally, attentional control relies on a set of different executive processes and as we did not include any additional executive measures, it is not possible to determine whether there is a relationship between performance on our tasks and performance on other executive capacities.

In conclusion, our findings provide some important information on dual-task performance in healthy older adults. First, older adults are less able to control their attention in response to external instructions. Because a dual-task paradigm requires attentional allocation, difficulties in attentional control may be a critical factor in age-related dual-task deficits. It may also contribute to the attentional difficulties that older adults experience in their daily lives and of their potential negative outcomes, such as falls (Faulkner et al., 2007; Gaspar, Neider, & Kramer, 2013) or automobile collisions (Daigneault, Joly, & Frigon, 2002). Second, the age-related differences in dual-task performance cannot be accounted for by a simple reduced-resource hypothesis, as varying the difficulty level of the tasks did not increase the age-related difficulties in dual-tasking. Finally, our results were found using a design that individually adjusted task demand, indicating that the effect goes beyond performance reduction in constituent tasks. The present study indicates that attentional control is a significant factor in explaining the age-related difference in dual-task cost.

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Chapitre III

Article 2: *Identifying training modalities to improve multi-tasking in older adults*

Article 2: Identifying training modalities to improve multi-tasking in older adults

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Abstract

Studies that have measured the effects of attentional training have relied on a range of training formats, which may vary in their efficacy. In particular, it is unclear whether programs that practice dual-tasking are more effective in improving divided attention than programs focusing on flexible allocation priority training. The aims of this study were as follows: (1) to compare the efficacy of different types of attentional training formats and (2) to assess transfer to distal measures. Forty-two healthy older adults were randomly assigned to one of three training groups. In the SINGLE training condition, participants practiced a visual detection and an alphanumeric equation task in isolation. In the FIXED training condition, participants practiced both tasks simultaneously with equal attention allocated to each. In the VARIABLE training condition, participants varied the attentional priority allocated to each task. After training, all participants improved their performance on the alphanumeric equation task when performed individually, including those in the SINGLE training condition. Participants in the FIXED training condition improved their divided attention, but only the participants in the VARIABLE training condition showed a greater capacity to vary their attentional priorities according to the instructions. Regarding transfer, all groups improved their performance on the 2-back condition, but only the VARIABLE and FIXED conditions resulted in better performance on the 1-back condition. Overall, the study supports the notion that attentional control capacities in older adults are plastic and can be improved with appropriate training and that the type of training determines its impact on divided attention.

Keywords: Attentional training, Divided attention, Multitasking, Aging

INTRODUCTION

Because we live in complex environments, divided attention is constantly required in our everyday lives. Having a conversation with the passenger while driving a car, planning and executing responses to avoid a collision, or crossing the street while talking on a hands-free cell phone are a few examples of daily activities that require divided attention between two or more concurrent tasks. There is abundant evidence indicating that older adults have more difficulty in performing two tasks concurrently (Anderson et al., 2000; Hartley & Little, 1999; McDowd & Shaw, 2000; Salthouse, Rogan, & Prill, 1984; Verhaeghen, 2011; Verhaeghen & Cerella, 2002; Verhaeghen, Steitz, Sliwinski, & Cerella, 2003). The age-related decline in divided attention and attentional control has been associated with several negative outcomes later in life. These outcomes include falling (Faulkner et al., 2007; Gaspar, Neider, & Kramer, 2013) and automobile collisions (Daigneault, Joly, & Frigon, 2002). Finding ways to improve divided attention abilities could therefore have a significant impact on the daily living activities of older adults. However, training programs may differ in their ability to improve attentional control in healthy older adults and to promote transfer to untrained tasks. The present paper pursues two broad objectives: 1) comparing three different attentional training formats to select the most efficient training modalities; 2) assessing transfer to distal and proximal measures to identify training strategies that lead to meaningful cognitive improvements.

Divided attention is part of the attentional control capacities. Attentional control (Baddeley & Hitch, 1975; Norman & Shallice, 1980) refers to the ability to coordinate and monitor information processing and relies on a set of distinct cognitive processes including inhibition, task switching, and dividing and modulating attention (Baddeley, 1996; Miyake et al., 2000). These processes allow one to select the most efficient strategy with which to complete a task based on environmental demands. Among the different attentional control capacities, divided attention represents a potentially critical target for cognitive training. First, and as mentioned above, its impairment can have an impact on different dimensions of everyday life. Second, this is an area of frequent complaints among healthy older adults (Langlois & Belleville, 2013; Weaver Cargin, Maruff, Collie, Shafiq-Antonacci, & Masters, 2007). Indeed, one of the most frequent complaints is a decreased capacity to memorize or learn new things while in an attention-demanding environment (Langlois & Belleville, 2013).

There is increasing evidence that carefully designed training strategies can lead to meaningful improvements in attention. It is however unclear which components optimize the therapeutic effects in older adults because of the large number of training programs that have been used. Studies have aimed to train divided attention in older adults and examine how training the ability to modulate attention according to task demands differs from training a static division of attention. These training protocols are known as variable-priority training (VP) and fixed-priority training (FP), respectively. Specifically, FP training consists of performing the two tasks simultaneously while allocating the same amount of attention to each task; VP training requires participants to modulate their attentional priority by emphasizing performance on one task over the other. The level of attention allocated to each task varies throughout the training.

It has been proposed that VP training may be more effective than FP training in improving dual-task coordination and enhanced attentional control, because participants are trained to manage competing task priorities through self-regulation of their attentional priorities. Indeed, studies have reported enhanced dual-task coordination and attentional control following VP training compared to FP training (Gagnon & Belleville, 2012; Kramer, Larish, & Strayer, 1995; Lee et al., 2012; Voss et al., 2012). For instance, Kramer et al., (1995) evaluated the effects of three one-hour sessions of FP and VP training using a visual monitoring task and an alphabet-arithmetic task. They found that both groups improved their ability to divide attention, but that the gain was greater for those that received VP training. Gagnon et Belleville (2012) compared the effects of six one-hour sessions of VP and FP training in people with mild cognitive impairment. Importantly, the authors added a self-regulatory strategy to the VP training condition in order to favor meta-cognition, which has been suggested to be critical for intervention success (Clare, Wilson, Carter, Roth, & Hodges, 2004). They found that after training, only the VP training group had a reduction in performance costs associated with dual-task performance, suggesting a unique benefit of VP training. Lee et al. (2012) and Voss et al. (2012) used a complex video game (Space Fortress, Donchin, 1995) to compare the efficacy of FP and VP training in young adults. Participants in the VP training group were asked to modulate their attention to different components while playing the game (e.g., control the movement of their ships, monitor the number of times they shot the enemy, or monitor their ability to gain a bonus). Participants in the FP training group were asked to maximize performance and focus on obtaining the highest total score by emphasizing each task component equally. In both studies, better game mastery and skill acquisition were found in the VP training group.

In contradistinction, Bherer et al. (2005, 2008) failed to obtain superiority for VP training over FP training. They assessed VP and FP training using simultaneous visual (letter) and auditory (tone) discrimination tasks. The training groups were compared to a no-contact control group, which performed only the pre- and post-training sessions. The authors found improvement in divided attention abilities for both training groups, but not for the no-contact control group. Importantly, there was no additional benefit for the VP group compared to the FP group. One possible reason why Bherer et al. (2005, 2008) failed to replicate the benefits of VP training over FP training could be that the two tasks were relatively simple. The use of these simple discrimination and computer-paced tasks may have reduced the coordination requirement of the task, hence downplaying the relevance for attentional control training. Studies showing superior effects of VP over FP training used relatively complex tasks that were self-paced. These tasks might be more amenable to variations in attentional control.

Another point of difference is that many of these studies have used a 50-50 dual-task emphasis condition (i.e., allocating the same amount of attention to each task) as their critical outcome variable (Bherer et al., 2005, 2008; Gagnon & Belleville, 2012; Kramer et al., 1995). This condition was used in these aforementioned studies, as their objective was to assess the effect of different training formats on dual-tasking. However, our goal in the present study was different, as our main aim was to measure the effect of different training modalities on controlled attention and modulation capacities, with an analysis of attentional priority instructions. Complying with priority instructions was considered as an instance of real-life conditions in which individuals are required to vary their attentional priority in response to environmental demands. Our paradigm differentiates the effect of training on divided attention abilities (or dual-tasking) from the effect of training controlled attention abilities. This was considered crucial, as aging has been associated with increased difficulty in the ability to flexibly allocate attentional resources. Be this as it may, our paradigm will include a condition that will require equivalent emphasis on both and this will allow measuring dual-tasking per se.

Another important and disregarded issue is whether improving efficiency on each of the single constituent tasks improves the ability to combine them. Theories of attentional control indeed postulate that combining tasks that are automatized is not as demanding as combining tasks that are new (Shallice, 1994). It is therefore possible that some of the improvement in dual-task performance was due to an increased ability to perform each task in isolation. Accordingly, developing expertise by practicing two separate tasks in isolation (full attention) should result in improvements when performing the tasks simultaneously. The specific impact of training two tasks in isolation, and the way this affects performance when the two tasks are combined, remains poorly understood. Indeed, very few studies (Bherer et al., 2005, 2008; Gagnon & Belleville, 2012 ; Kramer et al., 1995) have included a full attention training condition.

Another important issue is whether the effects of training transfer to performance on untrained tasks. According to the taxonomy proposed by Barnett and Ceci (2002), transfer can be qualified as *near* or *far*. *Near transfer* involves transfer to tasks that share a similar context, whereas *far transfer* involves transfer to tasks that are dissimilar. The extent to which dual-task training benefits the performance on untrained tasks is not clear. Although some studies have reported significant near transfer (Bherer et al., 2005, 2008; Boot, Kramer, Simons, Fabiani, & Gratton, 2008; Kramer et al., 1995; Lee et al., 2012; Lussier, Gagnon, & Bherer, 2012) and far transfer effects (Bherer et al., 2005, 2008; Gagnon & Belleville, 2012) following divided attention training, others have reported no convincing evidence of transfer effects following working memory or complex task training (Dahlin, Neely, Larsson, Bäckman, & Nyberg, 2008; Green & Bavelier, 2008; Owen et al., 2010).

As discussed by Lövden and colleagues (2010), the assessment of transfer effects is challenging, as the selection of both the transfer tasks as well as the appropriate control group comparisons necessitates a precise understanding of the mechanisms of action of training programs, most of which are still largely unknown. A detailed analysis of the cognitive components and strategies involved in both the training programs and the transfer tasks is indeed necessary in order to predict transfer effects and thus cognitive plasticity.

Here, one might expect that the training program involving larger metacognitive abilities (e.g., VP training) would result in a larger transfer effect than the training program that only relies on repeated practice. Indeed, some studies have reported larger near transfer effects (Kramer et al., 1995; MacKay-Brandt, 2011) for VP training compared to FP training. At the same time, both Bherer et al. (2005; 2008) and Gagnon and Belleville (2012) found similar transfer effects for both VP and FP training. In turn, some studies have failed to observe far transfer effects from either type of training (Lee et al., 2012; MacKay-Brandt, 2011). Thus, whether VP and FP training differ in terms of their ability to transfer from untrained tasks remains to be elucidated.

In summary, previous studies have shown that attentional training programs can improve attentional capacities in older adults; however, conditions that are most favorable remain to be better understood. First, it is unclear whether this improvement is more effective with FP or VP training. Second, it is not clear whether simultaneous dual-task training results in improvement over and above that reached by practicing each constituent task. Another important question is how different training modalities impact transfer effects to untrained tasks; specifically, whether VP, FP, or single-task training promotes near- or far-transfer effects.

To address these questions, we randomly assigned participants to one of three training groups in which they learned to perform a simple visual detection task and a complex alphanumeric equation task. The first group trained on the two tasks separately (SINGLE). The second group trained on both tasks simultaneously and were told to allocate equal amounts of attention to both tasks (FIXED). The third group trained on both tasks simultaneously but were instructed during training to modulate the amount of attention given to each task on a trial-by-trial basis (VARIABLE). In order to create an experimental design akin to real-life conditions in which individuals need to flexibly allocate their attention across tasks, we administered a combination of tasks that vary in their level of complexity and attentional demand. In daily life, it is indeed frequent that one has to divide their attention between tasks that differ in terms of how complex and “attractive” they are. For example, this is the case when a skilled driver engages in a complex conversation.

Efficacy was measured with a near-transfer task where the same task was used as in training, but with different stimuli. We expected that performance on both tasks in isolation would improve in all three groups after training. More importantly, we expected that the FIXED training group would improve their ability to divide attention by lowering their overall dual-task cost on both tasks after training, regardless of emphasis instructions. As for the VARIABLE training group, we anticipated that participants would improve their controlled attention abilities (i.e., changing attentional priorities in response to specific environmental demands). Thus, the performance of the VARIABLE training group should differ as a function of attentional allocation priority instructions after training. As a result, we expected a lower dual-task cost on the alphanumeric equation task when this task was asked to be emphasized (80% Equation), and lower dual-task cost on detection when this task was asked to be emphasized.

To measure far-transfer effects, we used a working memory task (N-back task with a 1-back and 2-back condition). The N-back task was selected to measure transfer, as it is thought to require attentional control, particularly the ability to flexibly update working memory content and to manage proactive interference, an instance of coordination and monitoring capacity (McCabe et al., 2008; Miyake et al., 2000). N-back requires interleaving different subtasks:

processing incoming information, maintaining activation of recently processed and potentially relevant information, and discarding recently processed but irrelevant information. Our hypothesis was that VARIABLE training and FIXED training, to a lesser extent, improved these abilities and would transfer to performance on the N-back task. We hypothesized a larger transfer to the 2-back than to the 1-back condition given that it is more demanding at the executive level.

METHOD

Participants

Forty-two healthy older adults participated in this study. All participants were recruited in the community through advertisements in retirement centers and magazines for seniors. They underwent a telephone interview to provide initial selection information. Participants were included if they were French-speaking and community-dwelling, living in the Montreal area, right-handed, and had normal or corrected-to-normal hearing and vision. Exclusion criteria included: alcoholism or substance abuse; presence or history of a neurological disorder or stroke; presence or history of a severe psychiatric disorder (e.g., depression, schizophrenia, bipolar disorder); general anesthesia in the past six months. Eligible persons were invited to come to the laboratory for a standardized clinical and neuropsychological battery in order to evaluate their clinical status and cognitive functioning. The battery included a general measure of cognitive functions (Montreal Cognitive Assessment, MoCA), the geriatric depression scale (GDS), one test of “fluid” intelligence (Digit symbol; Wechsler, 1997), and one test of “crystallized” intelligence (Similitude subtest; Wechsler, 1997).

Intervention

Two tasks were used for training: a visual detection task and an alphanumeric equation task. Both tasks were run on Compaq Pentium d530 computers, and responses were given on the keyboard. In the visual detection task, 3x30 square-inch (7.6×76 cm2) red or white rectangles appeared randomly at the bottom of the computer screen for 500 ms each, interspaced by 250 ms intervals (ISI). Participants were asked to press the spacebar key every time the rectangle was red and were to do so as quickly and accurately as possible. For the alphanumeric equation task, stimuli consisted of equations (addition or subtraction) containing letters (from N to Z) and numbers (1 or 2) in the format x + (or -) $n = z$. Participants were asked to indicate whether the equation was true or false. The letter x corresponded to the starting point in the alphabet, the + or – sign indicated the direction of the equation, and n was the number of letters that separated the starting point from z. The equation was visually presented in the middle of the screen for a maximum period of 3750 ms with 1500-ms interstimulus intervals. The participants were asked to judge the veracity of the equation by pressing one of two keys: the "F" key with the left index finger when the equation was false, and the "J" key with the right index finger when the equation was true. For example, the equation $N + 2 = P$ is true because P is 2 letters after N in the alphabet, whereas the equation $S - 1 = Q$ is false because one letter down from S in the alphabet is R and not Q. False equations were created by presenting a response that was one letter away (plus or minus) from the correct response. In the two divided attention training conditions (FIXED and VARIABLE), each block contained twenty equations, half of which were false and half of which were correct. Each equation appeared with five rectangles, including one to three red rectangles. Thus, 40% of the rectangles were red, with a total of 20 to 100 rectangles per block, depending on the participant's speed. The trial length was defined as the time required for participants to solve the equation. As soon as the participants responded to the equation, the next equation appeared and the trial was terminated. Thus, visual targets were only presented during the time participants took to solve the equation. This ensured that the participants were in a state of divided attention during the entire period. If a participant did not complete the alphanumeric equation within the required period of time, the next equation was presented immediately and the trial was considered as failed. Accuracy and reaction time (RT) were recorded for both tasks. Each training session comprised 13 blocks of 20 trials of the task. The more specific content of each block depended on the training condition as described below.

In the *Variable divided attention training condition (VARIABLE),* participants were asked to perform both tasks simultaneously and to vary their allocation priorities across the series of blocks. Prior to each block, instructions informed the participants as to how much attention should be given to each task. There were three different levels of attentional allocation priority: 80% Equation; 50% Equation; and 20% Equation. The 80% Equation instruction condition indicated that participants should allocate 80% of their attention to the alphanumeric equation task and 20% to the visual detection task. For the 50% Equation instruction condition, participants had to allocate an equal amount of attention to both tasks. Finally, for the 20% Equation instruction condition, 20% of the participants' attention was asked to be on the alphanumeric equation task and 80% on the visual detection task. The instructions were visually presented on the screen and read aloud to participants. To enable better understanding, instructions were supported by an illustration of a rectangle-shaped box divided into two colored parts of different proportions, representing the percentage of attention required by each task. After each block, a histogram was presented to the participants indicating their baseline level for the training session (as measured earlier by the focused attention condition) and the targeted accuracy threshold according to the emphasis instructions. For example, if a participant responded correctly on 75% of the alphanumeric equations in the focused attention condition, their accuracy threshold to attain in the 80% Equation emphasis instruction would be 60%. Before displaying their actual performance on the histogram on the computer screen, participants were asked to draw their own estimate on the paper histogram. In this manner, participants were informed as to whether they had attained the requested priority proportion to allow them to better adjust the emphasis at the next block. Each session comprised nine blocks in which the participants had to combine both tasks. To provide a baseline, participants completed two blocks of each task in the focused attention condition at the beginning and end of each session.

In the *Fixed divided attention training condition (FIXED),* participants were asked to complete the two tasks simultaneously and to give the same amount of attention to both tasks. Thus, they were asked to allocate 50% of their attentional resources to the visual detection task and 50% to the alphanumeric equation task. Each session comprised nine blocks where the participants had to combine both tasks. To provide a baseline, participants completed two blocks of each task in the focused attention condition at the beginning and end of each session.

Finally, in the *Single task training condition (SINGLE),* participants performed both tasks individually with focused attention. To equate the number of blocks with the other two training conditions, it was composed of six blocks of one task and seven blocks of the other task. The number of blocks for each task alternated between sessions, so that participants would receive the same amount of exposure to both tasks over the course of the whole training program. The starting task at session one was counterbalanced across participants.

Outcomes measure

Primary outcome measure. Participants were asked to perform the visual detection and alphanumeric equation tasks separately (focused attention) and in combination (divided attention). The material was similar to that used in training, except that the equations contained letters from a different part of the alphabet (A to M rather than N to Z) to reduce potential practice effects due to familiarization with the letter position in the alphabet. Each condition (focused and divided) was presented in four blocks of 24 trials (for a total of 96) following an ABA design. Participants first completed each task with focused attention, followed by three blocks of the dual-task condition (80% Equation, 50% Equation, 20% Equation). The two tasks were then completed again with focused attention. No feedback was given during the task.

Generalization measures. Generalization of training effects was measured with the N-Back task, with a 1-back and a 2-back condition. For the N-back task, a series of letters were presented visually in the center of the screen. Letters appeared sequentially for 500 ms, with an interstimulus interval of 2500 ms. In the 1-back condition, participants were asked to judge whether the letter was the same as that presented just one position before for the 1-back condition, or two positions before for the 2-back condition. Each condition was presented in four blocks of 45 trials, 15 of which were targets. The order of presentation of the blocks followed an ABBA design. For the 2-back condition, the number of isolated trials (i.e., ABH**B**D) and embedded trials (i.e., ABH**BH**) was equivalent in each block to equate the level of difficulty. Accuracy and reaction time for the correct answers were tested separately for each condition (1-back and 2-back).

Design

Participants were randomized to one of the three training conditions, stratified by education and age to equate the three groups on those variables. Randomization was performed by an independent research technician. Training was provided in six one-hour sessions over two weeks. The outcome measures were assessed one week prior to the first training session and one week following the last training session. Two versions were available for the N-back task and therefore, different versions were used in the pre- and post-sessions with order counterbalanced across participants.

RESULTS

Demographic and clinical data

Five participants were excluded for technical difficulties with the recording of their responses. The characteristics of the 37 remaining participants are presented in Table I. Participants allocated to the three training groups were first compared on their socio-demographic and clinical characteristics using ANOVAs, with group (SINGLE; FIXED; VARIABLE) as a between-subject factor. The three training groups were comparable for age, $F(2, 34) = 0.12$, $p = .88$; educational level, $F(2, 34) = 0.58$, $p = .56$ and performance on clinical measures.

Table I. Mean scores for age, education, and clinical measures

	SINGLE (*n = 12*)	FIXED (*n = 13*)	VARIABLE (*n = 12*)	*F*	*p* value
Age	68.67 (8.28)	69.85 (5.96)	68.83 (5.24)	0.12	0.89
Education	14.75 (3.39)	15.15 (2.58)	16.17 (3.90)	0.58	0.56
MoCA	27.83 (1.64)	27.31 (1.60)	27.33 (2.57)	0.27	0.76
GDS (/ 15)	1.58 (1.44)	1.31 (1.25)	2.58 (3.48)	1.08	0.35
Similarities (WAIS-III)	12.58 (1.44)	12.23 (1.88)	12.58 (1.73)	0.18	0.84
Digit symbol	12.83 (2.55)	11.77 (1.53)	11.58 (2.02)	1.29	0.29

Standard Deviations in Parentheses

Dependent variables

Accuracy (AC) and reaction time (RT) were used as dependent variables in the focused attention condition of the visual detection and alphanumeric equation task. RTs less than 150 ms and greater than 4000 ms were excluded, as well as RTs for commission errors. Because there were many dependent variables, a divided attention cost was computed by combining the RT and AC for each task in the divided attention condition relative to the focused attention condition, with the following equation: {[(RT divided – RT single) / RT single] + [(AC single – AC divided) / AC single]}. In the equation, RT single and AC single represent performance in the focused attention condition for reaction time and accuracy. RT divided and AC divided represent performance in the divided attention conditions (80% Equation, 50% Equation or 20% Equation) for reaction time and accuracy. This divided attention cost represents the proportional loss of performance in the divided attention condition as a function of performance in focused attention. Thus, the formula controls for baseline performance and provides a measure of divided attention performance. When participants had a longer reaction time or lower accuracy in focused versus divided attention, this was scored as zero to avoid a negative attentional cost score.

Pre-training

To assess whether there were group differences prior to training in spite of the randomization, divided attention cost during the pre-training session was first analyzed. The divided attention cost scores for each task as a function of emphasis instructions are displayed in Figure 1. We performed a mixed ANOVA using divided attention cost as a dependent variable, emphasis (80% Equation, 50% Equation or 20% Equation) and task (alphanumeric equation; visual detection) as within-subject factors, and group (SINGLE; FIXED; VARIABLE) as a between-subject factor.

The ANOVA showed no main effect of Group (p = .62) and no interaction involving Group, indicating that the three groups had similar baseline performance prior to training (p = .34, .86 & .58, respectively). A main effect of task was found $F(1, 34) = 16.39$, $p < .001$, as participants had an overall higher dual-task cost in the visual detection task (M = 0.75) compared to the alphanumeric equation task (M = 0.21). This effect was qualified by a Task x Emphasis interaction, $F(2, 34) = 11.92$, $p < .001$. Decomposition of the interaction indicated a significant emphasis effect for both the visual detection ($p < .001$) and the alphanumeric equation tasks ($p < .001$), but it can be seen that it goes in the opposite direction as would be expected. Follow-up tests revealed that participants had a higher dual-task cost on the alphanumeric equation task in both the 20% Equation (M = 0.23) and the 50% Equation emphasis instructions (M = 0.24) conditions than in the 80% Equation (M = 0.15) instructions condition (p = .04 & .009, respectively). For the visual detection task, participants had a lower dual-task cost in the 20%

Equation (M = 0.67) compared to both 50% Equation (M = 0.77) and 80% Equation (M = 0.79) instructions conditions (p = .04 & .009, respectively). Thus, as shown in Figure 1, prioritizing a task - whether it is the alphanumeric equation or the visual detection task - results in a decrease of dual-task cost on the task relative to a condition in which the two tasks are instructed to be equally emphasized.

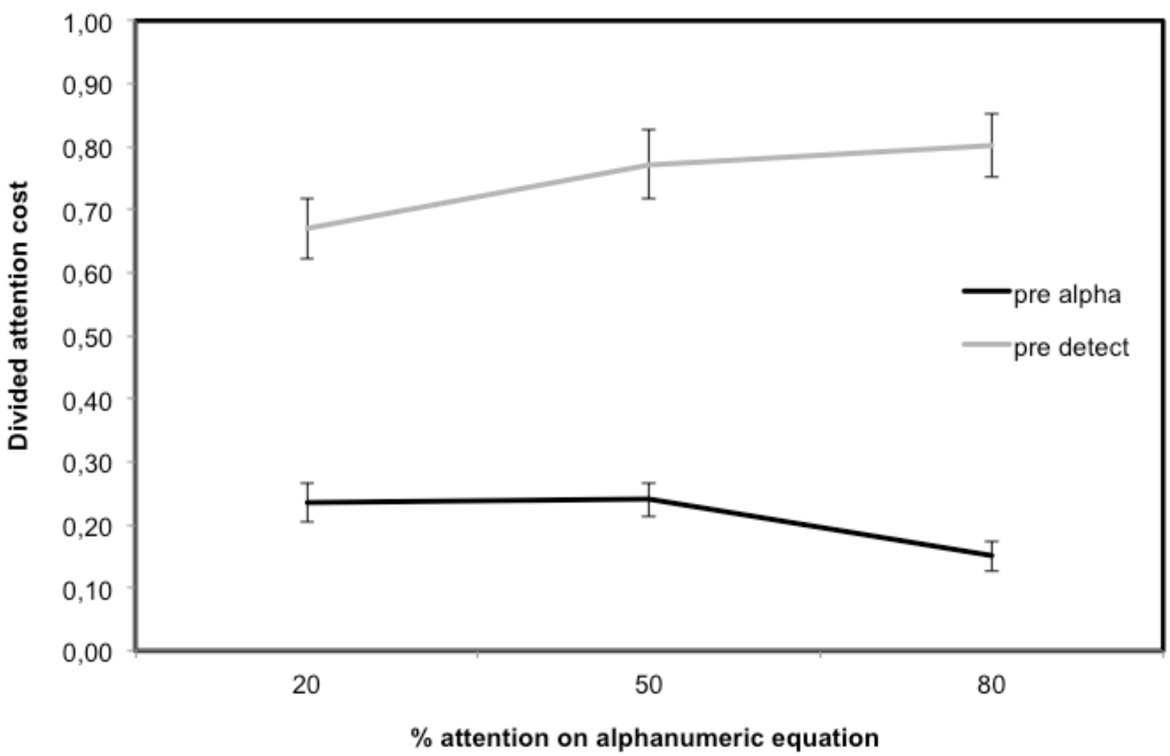

Figure 1. Divided attention cost for each task as a function of emphasis instruction (20% Equation, 50% Equation, 80% Equation) in pre-intervention (errors bars represent standard error).

To assess whether the three groups differed in focused attention prior to training, separate ANOVAs were computed for each task on the AC and RT recorded at pre-training, using group (SINGLE; FIXED; VARIABLE) as a between-subject factor. Table II shows the pre-training performance of each training group on the two tasks in the focused attention condition. The ANOVA for the alphanumeric equation task shows that the three training groups had similar performance prior to training for both AC and RT, (p = .85 & .39, respectively). Similar results were found for the analysis of the visual detection task, which revealed no main group effect for either AC or RT (p = .55 & .09, respectively).

Training effects

Focused attention. Table II shows the pre- and post-training performance of each training group on the two tasks in the focused attention condition. To assess the effects of training on task performance, separate mixed ANOVAs were computed for each task on AC and RT, using time (pre- and post-training) as a within-subject factor and group (SINGLE; FIXED; VARIABLE) as a between-subject factor. The ANOVA showed a main effect of time on RT for the alphanumeric equation task $F(1, 34) = 9.83$, $p < .001$, indicating that the task was completed more rapidly following training compared to before training. There was neither a main group effect nor a Time x Group interaction, indicating that after having received training, all three groups had faster RT on the alphanumeric equation task completed under focused attention (p = .29 & .39, respectively). Similarly, when analyzing AC for the alphanumeric equation task, we found a main effect of time $F(1, 34) = 14.8$, $p < .001$, and no main effect of group or Time x Group interaction (p = .96 & .56, respectively). The analysis of RT for the visual detection task revealed no main time or group effects and no Time x Group interaction (p

= .54, .55 & .21, respectively). Similarly, analysis of AC for the visual detection task revealed no main time or group effects and no Time x Group interaction (*p* = .10, .24 & .91, respectively). Thus, the three groups showed no gains from pre- to post-training in AC and RT on the visual detection task in the focused attention condition.

Table II. Accuracy (AC) (%) and reaction time (RT) (ms) for alphanumeric equation task and visual detection task in the focused attention condition in pre-training and post-training

	Pre		Post	
	AC	RT	AC	RT
Alphanumeric equation				
SINGLE	84.1 (3.1)	2383 (121.0)	86.8 (3.1)*	2307 (127.0)*
FIXED	75.2 (4.6)	2315 (105.0)	90.0 (3.6)*	2146 (84.0)*
VARIABLE	77.3 (5.5)	2466 (73.0)	89.8 (2.0)*	2154 (100.0)*
Visual detection				
SINGLE	82.3 (8.3)	493 (19.0)	86.8 (7.7)	539 (37.0)
FIXED	92.6 (6.0)	438 (13.0)	99.3 (0.4)	449 (21.0)
VARIABLE	93.8 (5.2)	494 (30.0)	98.8 (0.7)	468 (13.0)

Standard Deviations in Parentheses, * $p < .01$, main group effect

Divided attention and attentional control. The divided attention cost scores for each task as a function of emphasis instructions are displayed in Figure 2. Divided attention cost scores were analyzed with a mixed ANOVA using time (pre- and post-training), emphasis (80% Equation, 50% Equation or 20% Equation), and task (alphanumeric equation, visual detection) as within-subject factors, and group (SINGLE; FIXED; VARIABLE) as a between-subject factor. The Time x Emphasis x Task x Group interaction was significant, $F(1, 34) = 3.26$, *p* <

.001. To identify the source of the interaction, ANOVAs were computed separately for each group with the variables time, emphasis, and task.

For the VARIABLE training group, a significant Time x Emphasis x Task interaction, $F(2, 33) = 5.17$, $p < .001$, was found. This was due to the presence of an Emphasis x Task interaction in post-training, $F(2, 33) = 18.23$, $p < .001$, but not in pre-training ($p = .26$). Examination of Figure 2a and mean comparisons revealed that for both tasks, performance did not vary as a function of the priority emphasis instruction before training. However after training, the dual-task cost vary as a function of emphasis for both the alphanumeric equation and the visual detection tasks, but in opposite direction. After training, the main effect of emphasis found for the alphanumeric equation task, $F(2, 33) = 8.83$, $p < .001$, revealed that the dual-cost in the 80% Equation ($M = 0.10$) emphasis instruction condition was smaller than in the 50% Equation ($M = 0.20$) and 20% Equation emphasis instruction condition ($M = 0.24$) (p = .03 & .001, respectively). The main effect of emphasis on visual detection at post-training, $F(2, 33) = 14.13$, $p < .001$, revealed a smaller dual-cost in the 20% Equation ($M = 0.39$) than in the 50% Equation ($M = 0.53$) and 80% Equation ($M = 0.39$) (p = .03 & .002, respectively). Thus, participants were better able to prioritize the visual detection task (20% Equation emphasis) after training, when this was required. As a result, and as shown on Figure 2a, there is a significant 37 % dual-cost reduction from pre- (.62) to post-training (.39) for the visual detection task in the condition requiring emphasis on the detection task (20% Equation; $p = .02$). There was also a significant 28% dual-cost reduction in the 50% Equation emphasis instruction condition from pre- (.73) to post-training (.53) ($p = .001$). These results indicate that from pre- to post-training, participants improved their ability to vary the level of attention placed on each task in response to the instructions.

For the FIXED training group, a main time effect, $F(1, 34) = 6.97$, $p < .001$, was found, indicating that participants improved their divided attention cost from pre- to post-training. Indeed, as shown in Figure 2b, participants lowered their dual-task cost from pre- to post-training, regardless of both tasks and instructions. There was also a significant Emphasis x Task interaction $F(2, 33) = 5.17$, $p < .001$. Decomposition of the interaction indicated that the emphasis' main effect was significant only for the visual detection task ($p < .001$), due to a smaller dual-task cost in the 20% Equation ($M = 0.70$) compared to both the 50% Equation ($M = 0.80$) and 80% Equation ($M = 0.83$) instructions ($p = .02$ & $.05$, respectively). Importantly, there was no Time x Emphasis x Task interaction, indicating that participants did not improve their ability to either divide or vary their level of attention after training ($p = .35$).

For the SINGLE training group (Figure 2c), the Emphasis x Task interaction was significant, $F(2, 33) = 6.02$, $p < .001$. Decomposition of the interaction indicated that the emphasis effect was significant for both alphanumeric equation, $F(2, 33) = 7.30$, $p < .001$, and visual detection, $F(2, 33) = 4.55$, $p < .001$, but that the patterns differed. In the alphanumeric equation task, participants had a lower dual-task cost in the 80% Equation than the other two conditions ($p = .02$ & $.02$, respectively). In the visual detection task, participants had a lower dual-task cost in the 20% Equation than in the other two conditions ($p = .02$ & $.03$, respectively). Importantly, there was no main effect of time or Time x Emphasis x Task interaction, indicating that participants did not improve their ability to either divide or vary their level of attention after training ($p = .81$).

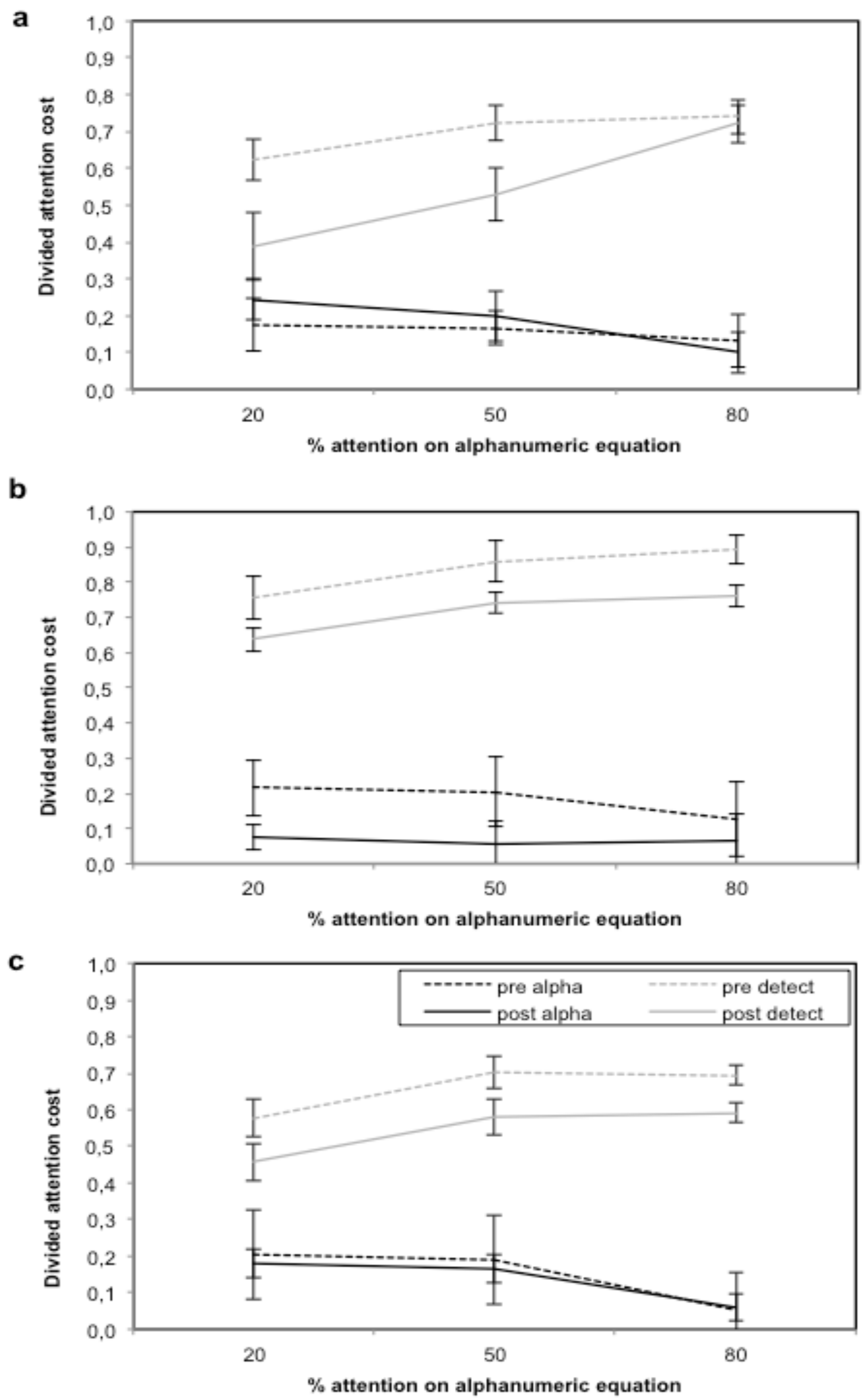

Figure 2. Divided attention cost for each task as a function of emphasis instruction (20% Equation, 50% Equation, 80% Equation) in divided attention for the VARIABLE (a), FIXED (b) and SINGLE (c) training group in pre- and post-intervention (error bars represent standard error).

Far-transfer measure

We performed separate mixed ANOVAs for AC and RT and the 1-back and 2-back conditions, using time (pre- and post-training), as a dependent variable and group (SINGLE, FIXED, VARIABLE) as a between-subject factor. Results are presented in Table III. There was no main effect of time or Time x Group interaction on the 1-back or 2-back conditions when using AC as a variable. Analysis on RT for the 1-back condition revealed a Time x Group interaction, $F(2, 32) = 3.99$, $p = .003$. Participants in the VARIABLE and FIXED training group significantly improved their completion time ($p = .005$ and $p = .002$, respectively), whereas no improvement was found for the SINGLE training group. Analysis on for the 2-back condition revealed a main effect of time, $F(1, 32) = 39.59$, $p < .001$, with all group performing more quickly after training. Group differences, however, were found in pre-training for AC and RT on the 1-back and 2-back conditions. Analysis on RT for the 1-back condition revealed a main group effect, $F(2,34) = 8.16$, $p < .001$. Post-hoc comparisons revealed that the VARIABLE training group was slower in pre-intervention compared to both FIXED and SINGLE groups prior to training ($p = .04$ & .03, respectively). For the 2-back condition, the analysis showed a main group effect, $F(2,34) = 8.16$, $p = .003$. Post-hoc comparisons revealed that the VARIABLE group was slower than the FIXED group in pre-intervention ($p = .02$). No group differences were found on AC for both 1-back and 2-back conditions ($p = .81$ & .44, respectively).

Table III. Accuracy (%) and reaction Time (ms) for the 1-back and 2-back conditions in pre-training and post-training

Reaction Time				
	1-back		2-back	
	Pre	Post	Pre	Post
SINGLE	734.85 (131.95)	716.29 (94.14)	907.04 (232.60)	801.73 (199.68)**
FIXED	739.69 (127.54)	658.58 (126.87)*	856.65 (115.54)	729.25 (153.97)**
VARIABLE	950.18 (156.33)	828.54 (184.09)*	1027.71 (176.90)	898.18 (110.05)**

Accuracy				
	1-back		2-back	
	Pre	Post	Pre	Post
SINGLE	88.19 (5.60)	93.11 (3.21)	80.51 (10.73)	85.31 (10.56)
FIXED	87.97 (4.18)	94.94 (2.21)	85.92 (6.84)	91.46 (5.34)
VARIABLE	91.47 (6.56)	86.51 (7.85)	89.11 (7.85)	83.01 (9.44)

Standard Deviations in parentheses
* $p < .05$, main time effect
** $p < .01$, main group effect

Considering the group differences in pre-intervention, an improvement ratio was computed on RT and AC for both conditions of the generalization measure (1-back; 2-back) with the following equation: [(Post-Pre) / Pre) * 100]. This decrement indicates the improvement from pre- to post-training, controlling for the individual's performance in pre-training. An improvement ratio on AC and RT for the 1-back and 2-back conditions is presented in Figure 3. Separate ANOVAs were computed on the AC and RT improvement ratio for both 1-back and 2-back conditions, using training group (SINGLE; FIXED; VARIABLE) as a between-subject factor. The analysis on AC showed no significant effects of group for the 1-

back or the 2-back conditions (p = .50 & .19, respectively). When analyzing RT, a main group effect was found for the improvement ratio of the 1-back condition, $F(2, 34) = 3.89$, $p = .031$. The improvement ratio was larger in the VARIABLE (M = 12.93) and FIXED (M = 10.53) training group relative to the SINGLE training group (M = 1.42) (p = .02 & .03, respectively). There was no effect of group for the 2-back condition (p = .47).

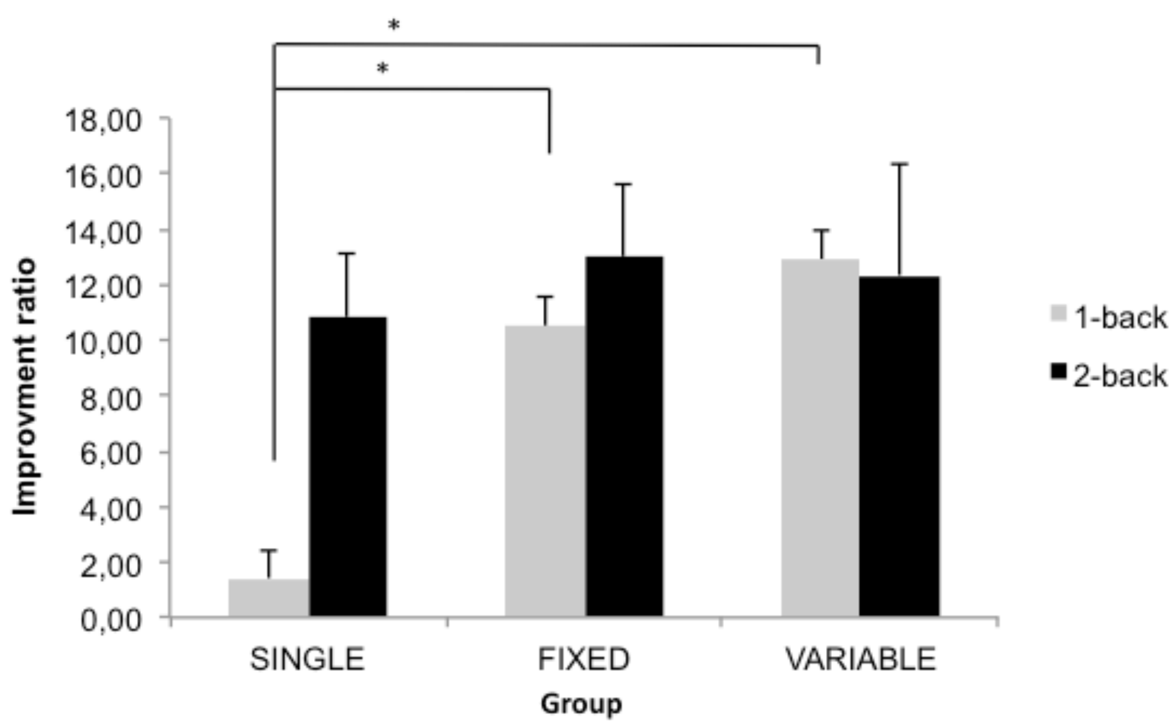

Figure 3. Reaction time improvement ratio [(Post-Pre) / Pre) * 100] for the 1-back and 2-back conditions for SINGLE, FIXED and VARIABLE training group expressed in absolute value (error bars represent standard error). *$p < .05$

To assess whether a ceiling effect in the SINGLE training group could account for the results on RT, we computed correlations between RT at pre-training and the magnitude of the training effect, and found a significant negative correlation ($r = -0.51$, $p < .05$). Thus, faster participants during training showed lower training effects, which supports the possibility that a ceiling effect is what may have prevented us from observing a training effect on the 1-back test in that group.

DISCUSSION

There were two goals in this study: to compare and identify the most efficient attentional training formats that produce the largest benefit for older adults, and to assess whether efficacy transfers to distal measures. Older adults were randomized to three types of attentional training conditions: (1) *variable training* (VARIABLE), where participants practiced two tasks concurrently and varied their allocation priorities across a series of blocks; (2) *fixed attention training* (FIXED), in which participants practiced the two tasks concurrently and allocated the same amount of attention to both task; (3) *single task training* (SINGLE), where participants practiced each task individually with full attention. Participants were assessed before and after training in focused and divided attention, using two tasks similar to the ones administered during training. Indeed, one of the goals and strengths of this study was to assess whether older adults were better able to modify their attentional priority in accordance to external demands (task instructions in the present case). Assessing the effect of training on modulation requires an analysis of all instruction conditions. We used dual-task cost as an outcome, as it takes into account the performance level in focused attention. Thus, the presence of a Time effect, without an interaction with Emphasis, was thought to reflect the training effect on divided attention abilities. In turn, improvement of controlled attention abilities (i.e., changing attentional priorities in response to specific environmental demands) was expected to result in a differential dual-task cost as a function of Condition and thus, as a Time x Emphasis x Task interaction. Participants also completed a working memory task (N-back task; 1-back and 2-back conditions) to measure whether improvements would transfer to a task implicating the cognitive mechanisms expected to be improved with training (i.e., attentional control).

Results indicate that the different attentional training formats improve different aspects of attention that are highly coherent with the cognitive processes presumed to be enhanced by each training. It was hypothesized that the VARIABLE training condition increases the ability to control attention. This is confirmed by the finding of an improved ability to modify allocation priority as a function of task instructions. Furthermore, the extent to which participants comply with task instructions in pre- and post-training is clearly documented. Indeed, even though participants were prioritizing the alphanumeric equation task over the visual detection task in all three emphasis instructions in pre-training, participants still tried to comply with the instructions by slightly lowering their dual-task cost on the task that needed to be prioritized. More interestingly, this effect was highlighted only in the VARIABLE training group after training. As a result, participants considerably lowered their dual-task cost on the visual detection task after training. They showed the opposite effect when the instructions required that the alphanumeric equation be emphasized. Thus, participants in the VARIABLE group enhanced their dual-task coordination and management skills after training. This improvement reflects an increased ability to switch attentional priorities and increased meta-cognition abilities.

The outcome is strikingly different in the FIXED condition, in which participants were only asked to practice dual-tasking. In that case, participants showed an overall attentional cost reduction after training, but were not better able to vary their attentional emphasis across the two tasks. Finally, practice on individual tasks (SINGLE) resulted in better performance in the focused attention condition on the alphabetical task; however, participants who received this training did not improve their divided attention and were not better able to control their attention.

Of note, however, is that most previous studies have used the 50-50 dual-task emphasis condition as their critical outcome variable. When using this condition as an outcome, we found that the FIXED and VARIABLE training improved performance but not the SINGLE training. This is consistent with the finding reported by previous investigators (Bherer et al., 2005, 2008) and further extent their finding by showing that it is not found in a control SINGLE training condition.

The results found with VARIABLE and FIXED training are coherent with what is reported in a number of previous studies (Gagnon & Belleville, 2012; Kramer et al., 1995; Lee et al., 2012; Voss et al., 2012), which indicate that VARIABLE training produces greater improvements on executive coordination skills than FIXED training programs. Two studies, however, have reported no difference between VARIABLE and FIXED training conditions (Bherer et al., 2005, 2008). One obvious explanation is that those studies have used the 50-50 priority condition as their main outcome and as we showed, both training conditions improve this variable. A number of other procedural variations could also explain the divergent findings across studies. One difference is the type of task participants were asked to combine. Indeed, Bherer et al. (2005; 2008) used simple auditory and visual discrimination tasks that were presented discretely and at fixed temporal intervals. In the present study, participants performed a combination of self-paced and force-paced tasks as well as a task involving complex processing (alphanumeric equation). It is possible that varying priorities is most beneficial in settings in which there is more freedom to coordinate the two tasks. Another difference is relative task complexity or salience. In the present study, participants reported that the alphanumeric equation task was more salient than the detection task prior to training. Indeed, dual-task cost was lower in the alphanumeric equation than in visual detection task, indicating that participants favored the former over the latter. As aforementioned, the dual-task condition used a combination of tasks that differed in their level of complexity and attentional demand - one being a more complex task drawing more resources than the other - in order to simulate real-life situations, as tasks executed in divided attention are rarely equivalent. This posed particular challenges to participants when they were asked to switch their attentional priority and emphasize detection (20% Equation emphasis instruction). Interestingly, however, this condition was particularly sensitive to VARIABLE training, as it showed larger changes. Thus, differences in salience might modulate differences in attentional control or modulation capacities. Also, training attentional control may be particularly well designed for dual-tasking in conditions of differential salience. For example, it might be more efficient to improve attentional control involved in driving while engaging in complex conversation, rather than that involved in driving while listening to the news on the radio.

One important component of this study was the inclusion of a control training condition in which participants practiced both tasks individually with the same intensity, and assessing whether this contributed to improved performance when combining them. This was motivated by models of executive control (Shallice, 1994), which suggest that combining automatized processes is easier than combining demanding ones (i.e., novel information). Thus, one reasonable prediction is that becoming more proficient in the task through practice would increase one's ability to combine them. It is critical to better understand the source of improvement in divided attention following dual-task training. Indeed, when practicing dual-tasking, participants gain practice in the individual tasks, which could make them easier to combine. It is thus important to make sure that the dual-tasking is bettered over and above the improved ability on the individual tasks. Results indicate that this is the case: participants in the SINGLE training condition improved their reaction time and accuracy in the alphanumeric equation task, but did not improve their ability to divide their attention between the alphanumeric and visual tasks. Thus, improvement in dual-tasking does not result merely from participants developing an expertise with individual tasks.

The results found for the FIXED and SINGLE training groups are in line with a recent study that used a driving video game (Anguera et al., 2013). Young and older adults were asked to drive a car while simultaneously detecting a visual signal. Participants were randomly assigned to one of three training groups: a multitasking training (MTT), in which they were asked to perform both tasks concurrently in divided attention; a single task training (STT), where participants performed both tasks individually; and a no-contact control group (NCC). After training, participants in the MTT training group showed a reduced multitasking cost from pre- to post-training, compared to the STT and NCC groups, with gains persisting up to 6 months. This reinforces the idea that a FIXED training format (or MTT) enables participants to perform better on both tasks concurrently. Our results under the SINGLE training condition is consistent with findings by Anguera et al., (2013) showing that enhanced multitasking ability was not solely the result of enhanced component skills, obtained by both the STT and MTT training groups, but rather a function of learning to resolve interference generated by the two tasks when performed concurrently. This suggests that it is possible to train specific dual-task coordination processes and that they are independent of those involved when practicing both tasks individually. The results are therefore consistent with the notion that the type of training, rather than solely the amount of practice, may be the best facilitator of skilled performance (Ericsson, 2007; Ericsson, Krampe, & Tesch-Römer, 1993). As was the case of Anguera's study, the present findings offer behavioral evidence that targeted cognitive training programs could potentially benefit healthy older adults and enhance specific cognitive abilities.

Another important issue is whether the benefits of training generalize to other stimuli and tasks. Indeed, we questioned whether transfer would be greater for VARIABLE training over FIXED and SINGLE training. We hypothesized that VARIABLE training would transfer more to the 2-back than to the 1-back condition because it was more demanding at the executive level. In fact, attentional control or the ability to coordinate and monitor information processing is viewed as highly implicated in the executive component of working memory (McCabe et al., 2008; Miyake et al., 2000).

We measured training transfer on the N-back task (1-back and 2-back condition), which involves on-line monitoring, updating and the manipulation of information within working memory (Owen, McMillan, Laird, & Bullmore, 2005). We found a complex set of intervention effects. On the 1-back condition, the VARIABLE and FIXED training formats resulted in larger improvements than the SINGLE format, which did not result in significant improvement from pre- to post-training. On the 2-back condition, all training groups improved their performance after training, including the SINGLE condition (see Figure 3). This goes against our hypothesis of larger gains in the 2-back condition. One possibility that could account for this result is the ceiling effect observed in the SINGLE training group, as participants were extremely fast prior to training. The three training groups might have improved in both the 1-back and 2-back conditions had there not been a ceiling effect. If so, the improvement in all groups may be due to the fact that they all practiced on alphanumeric equation, a task involving working memory abilities. It is also possible that these observed gains are solely due to test-retest, as participants completed the tasks twice (prior to and after training) and there was no no-contact group to assess this possibility.

In summary, our results indicate post-training changes on working memory following attentional training. These results are in line with other studies reporting transfer from similar training programs to distal generalization measures (Bherer et al., 2005, 2008; Gagnon & Belleville, 2012). Although a large number of studies report that transfer effects in dual-task training appear limited to near modality transfer or dual-task contexts, the present study demonstrates the possibility of relatively far transfer effects of training on broader working memory abilities. However, it is important to highlight that the result pattern differed from our predictions, and future studies will be required to determine whether the effects reflect the actual transfer or whether they are due to test-retest improvement. Furthermore, additional research is needed to further assess the breadth of those transfer effects, in particular whether the strategies participants learned during training or their improved capacities generalize to their everyday life activities. There are tools, such as self-administered questionnaires (Zanardo, De Beni, & Moè, 2006) and real-world safety tasks like driving simulators (Gaspar, Neider, & Kramer, 2013), that allow us to measure the impact of interventions on the complex activities of daily living. Virtual reality is also gaining in popularity, as it enables researchers and clinicians to create situations that simulate the complexities of daily life, while also allowing relatively solid experimental control. We are presently including this in our training procedure, as it may be one of the best strategies for enabling participants to transfer their attentional control abilities to a dual-task environment that is more representative of real-life settings.

In the current study, we found that it is possible to obtain selective effects, depending on the type of training used, and that these effects may generalize differently to untrained cognitive abilities. Our results can have far-reaching implications considering the increasing amount of effort put toward developing training programs that target older adults. A number of commercialized products [Brain Fitness Program (Posit Science); Brain train, Cogmed (Pearson); Cognifit (Cognifit personal coach)] aim to prevent or reverse the effects of aging on cognition (for a review see Jak, Seelye and Jurick, 2013) by training a variety of cognitive abilities such as attention, memory, processing speed, inhibition, and multitasking. Our findings indicate that selection of the training approach is not neutral and can determine the magnitude of effects obtained. Current commercialized programs could benefit from a more fine-tuned approach to multitasking training.

It is important to address some limitations in this study. First, the number of participants per training group was small. Although our sample size proved to be sufficient to find a robust training effect, it might have been possible to detect more subtle differences with larger groups, particularly regarding our transfer task. Second, our study did not include booster sessions or long-term follow-ups to assess durability of the training effect. It will be critical to examine whether these improvements are maintained or fade over time. An additional limit concerns the validity of the generalization measures in terms of ecological value; the tasks selected did not represent actual activities of daily living.

In summary, our findings confirm that attentional control capacities of older adults are highly plastic and can be improved when appropriate training is provided. However, not all training programs have the same effect. Our results are in line with other studies, showing benefits of the VARIABLE training over the FIXED training in enhancing executive coordination skills. Furthermore, our findings demonstrate the importance of individual practice when the tasks used involve complex processes. Finally, this study underlines the fact that the type of training is critical in determining the impact on the target cognitive ability and the degree of generalization to untrained tasks.

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Chapitre IV

Article 3: *Computerized attentional training and transfer with virtual reality: Effect of age and training type*

Article 3: Computerized attentional training and transfer with virtual reality: Effect of age and training type

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Abstract

Objective: The aims of this study were to assess whether computerized attentional training improves dual-tasking abilities in older adults and whether its effect and transfer are modulated by age and the type of training provided. This study also used virtual reality (VR) as a proxy to measure transfer in a real life related context.

Methods: Sixty participants (30 older and 30 younger adults) were randomized to either: 1) SINGLE-task training (two tasks practiced in focused attention; visual detection and alphanumeric equation task) or 2) divided attention VARIABLE-priority training (varying the amount of attention to put on each task when performed concurrently). Training effects were assessed at PRE- and POST- training with tasks similar to the one used in training. Transfer was measured with the *Virtual car ride,* an immersive dual-task scenario and a self-reported questionnaire.

Results: In older adults, VARIABLE-priority improved attentional control abilities and led to better transfer in the VR dual-task scenario compared to SINGLE-task. Younger adults benefited equally from the two types of training and transfer was found on the Alpha span task when performed concurrently in VR. SINGLE-task improved the ability of all participants to carry out the tasks in the focused attention condition. No transfer effects were found on the self-reported measure for either training type or age.

Conclusion: Attention remains plastic in old age and programs designed to improve attentional control might be beneficial to older adults. Importantly, training can produce transfer to more real life related tasks and transfer remains possible throughout the lifespan.

Keywords: Dual-task, Cognitive training, Transfer, Virtual-reality, Aging

INTRODUCTION

A range of different cognitive training programs can lead to training-specific improvements in older adults (Anguera et al., 2013; Ball et al., 2002; Karbach & Schubert, 2013; Lövdén, Bäckman, Lindenberger, Schaefer, & Schmiedek, 2010; Lustig, Shah, Seidler, & Reuter-Lorenz, 2009). However, it is critical to identify whether the benefit resulting from cognitive training transfers beyond the trained tasks to the daily lives of older adults, and whether different training types result in different effects and transfer (Melby-Lervåg & Hulme, 2013; Noack, Lövdén, Schmiedek, & Lindenberger, 2009; Owen et al., 2010). In this study, our aims are to: a) assess whether computerized attentional training improves dual-tasking abilities in older adults and whether the effect transfers to tasks similar to those encountered in daily life, b) examine whether effect and transfer are of the same magnitude in older and younger adults, c) unveil training aspects that modulate transfer effects and, in particular, whether divided attention training yields a larger transfer than repeated practice and, d) use transfer tasks that reflect real life situations, as most studies measure transfer with self-reported questionnaires or tasks that lack in ecological validity. The background relevant to these objectives is briefly presented below.

Impact of attentional training on proximal outcomes

Attentional control is defined as a top-down executive process that enables the execution of complex goal-oriented behaviors under attentionally demanding conditions, such as a complex dual-tasking paradigm (Milham et al., 2002). It is particularly important in situations with a strong competition for response selection and is considered a critical component for successful performance in a wide variety of complex cognitive tasks. Models of attentional control have emphasized the role of goal maintenance in attentional control abilities. In dual task conditions, goal maintenance is involved when there is a strong competition for response selection between the two tasks or when one of the two tasks has to be prioritized (Braver et al., 2001; Braver & West, 2008). There is now increasing evidence that training attentional control can improve dual-task performance and the control of attention when assessed with proximal measures, that is, with tasks that are close to those used during training.

Different types of attentional training show differences in their level of efficacy, which may be indicative of the active ingredient responsible for the improvement. In particular, many studies have reported the benefits of variable priority training in reducing dual-task cost (Bier, de Boysson, & Belleville, 2014; Kramer, Larish, & Strayer, 1995; Lussier, Bugaiska, & Bherer, 2016) and improving younger (Gopher, 2007; Gopher, Weil, & Bareket, 1994; Gopher, Weil, & Siegel, 1989) and older adults' ability to control attention in response to external demands (Bier et al., 2014; Lee et al., 2012; Lussier et al., 2016; Voss et al., 2012; Zendel, de Boysson, Mellah, Démonet, & Belleville, 2016). In variable priority training, participants complete two tasks in combination, but are instructed to vary the attentional priority that they place on the two tasks. It is hypothesized that variable priority training improves one's ability to purposely control attentional locus and increases metacognition (Gagnon & Belleville, 2012). Including variable priority in attentional training programs appears critical in improving dual tasking. Recent studies from our laboratory found larger dual-task coordination gain in older adults following variable priority training compared to 1) a fixed priority training (where participants are asked to allocate the same amount of attention on each task performed concurrently) and b) a single task training (where participants were trained to practice each task individually in focused attention) (Bier et al., 2014; Gagnon & Belleville, 2012; Zendel et al., 2016). A few studies have compared the effect of variable training in older and younger adults, to determine whether older adults show similar benefits from variable-priority training as younger ones when measured with proximal measures. Some studies show equivalent improvement in the two age groups (Bherer et al., 2005, 2008), and at least one study reported that older adults benefit more from variable priority training than younger adults (Kramer et al., 1995). There is thus evidence that this type of training might be particularly well suited to older adults when the effect is assessed with proximal measures.

Impact of attentional training on transfer

Because variable priority training involves metacognitive abilities and relies on flexible decisions based on environmental demands, one might expect it to result in transfer effects (Belleville, Mellah, de Boysson, Demonet, & Bier, 2014; Gopher, 2007; Lussier et al., 2016). Gopher (2007) has indeed suggested that variable priority training increases the participant's sensitivity and ability to cope with dynamic changes in demand and is likely to facilitate the coping and transfer of the acquired skill components to new tasks or conditions. Training transfer is defined as the aptitude for training to engage improvement on cognitive abilities or tasks that are not those that were trained (*content transfer*) (Butterfield & Nelson, 1991; Mayer & Wittrock, 1996; Noack et al., 2009) or to allow a succesfully learned skill, behavior or strategy to be applied in a context that is different from the one where it was learned (*context transfer*) (Barnett & Ceci, 2002; Bransford, Brown, & Cocking, 2000; Lobato, 2006; Perkins & Salomon, 1988, 1992).

A few studies have reported *content transfer* from variable priority training in older adults. In a study conducted by Kramer et al. (1995), variable priority training improved the performance of older adults on the trained task (monitoring and changing display while responding to alphabet arithmetic items) and on a novel dual-task paradigm involving simultaneous scheduling tasks and a paired associate running memory tasks. Transfer on the new task was greater for the variable priority compared to the fixed priority training group. Similarly, Lussier et al. (2016) found a larger dual-task cost reduction for the variable priority compared to the fixed priority training group on transfer tasks, which changed the nature of the stimuli (e.g., letters vs. numbers) while keeping the same input of presentation (e.g., visual vs. auditory), and on tasks changing both the nature of the stimuli and the input of presentation. A few studies however, did not observe the advantage of variable priority training over fixed priority training on *content transfer* measures (Bherer et al., 2005) or found no transfer effects for either training type (Bherer et al., 2008).

Whether age impedes training transfer is unclear. Some have hypothesized that the reduced neural plasticity associated with aging would limit the ability for older adults to benefit from transfer effects (Dahlin, Neely, Larsson, Bäckman, & Nyberg, 2008; Kühn & Lindenberger, 2016). In line with this hypothesis, some studies have found smaller *content transfer* in older adults compared to their younger counterparts (Dahlin et al., 2008; Derwinger, Neely, Persson, Hill, & Bäckman, 2003; Neely & Backman, 1993). However, age-equivalent transfer supporting preserved cognitive plasticity in advanced age was also reported (Bherer et al., 2005; Karbach & Schubert, 2013; Lussier, Gagnon, & Bherer, 2012). Interestingly, studies reporting unimpaired transfer relied on variable prioity training. It is thus possible that this training condition is most appropriate to induce transfer in older adults as suggested by Gopher (2007).

Measuring transfer in everyday situations

Overall, many studies have shown that divided attention variable priority training can yield transfer (Bherer et al., 2005; Kramer et al., 1995; Lussier, Gagnon & Bherer, 2012; Lussier et al., 2016). However, these studies most often measure *content transfer* that is, transfer measured with cognitive tasks that are close to the training modalities. Such transfer measures are very far from representing the complexities of the tasks encountered in everyday situations, which makes it difficult to interpret the potential positive impact of divided attention variable priority training on a participant's everyday life. Furthermore, a few studies reported little transfer when transfer tasks differed from training on more than a few dimensions. This suggests that training may not transfer easily to real life situations, as they are typically very different from the training content and format. This stresses the importance of measuring *context transfer*, and whether training transfers to situations from everyday life.

Positive effects of cognitive interventions on self-reported questionnaires targeting activities of daily living (ADL) have been found in healthy older adults (Rebok et al., 2014; Willis et al., 2006) and in individuals with mild cognitive impairment (for a review see Chandler, Parks, Marsiske, Rotblatt, & Smith, 2016). For example, in the ACTIVE study, where participants were trained on one of three cognitive interventions (memory, reasoning or visual attention), transfer was measured using functional outcomes such as a self-reported questionnaire measuring the participants' difficulty in performing ADL taks. The attentional training, which focused on visual search and the ability to identify and locate visual information quickly in a divided attention format, was found to improve proximal cognitive outcomes and resulted in a reduced decline in self-reported IADL function at a ten-year follow-up compared to memory training (Rebok et al., 2014). Gagnon and Belleville (2012) compared transfer resulting from variable priority and fixed priority training in persons with mild cognitive impairment (MCI) with a self-reported questionaire (Divided Attention Questionnaire; DAQ) designed to provide a subjective account of the participant's difficulties in everyday activities that require divided attention (e.g., talking to someone while cooking or driving; listening to music on the radio while doing paperwork). Unexpectedly, the two training conditions were associated with a higher level of complaint on the DAQ after training. This could be due to the fact that participants were more aware of the difficulties they could have experienced in their daily lives after training. This illustrates the challenges related to the subjective nature and use of self-reported measures and raises concerns about participants lacking insight into beneficial changes produced by the training (Stuss et al., 2007; Zanardo, De Beni, & Moè, 2006).

Only a few studies have attempted to use performance-based tasks that bridge between the lab and home environments. For instance, Gopher, Weil, & Bareket (1994) found transfer from a 10-hour training variable priority training program to actual flight tasks in a group of young cadets. The authors found that the participants' flight performance increased by 30% after training on a complex computer game (Space Fortress). In the training, participants were asked to control the movement of a spaceship while firing missiles to destroy a space fortress. The variable priority component required participants to vary their focus of attention on different aspects of the game. A similar training involving attention management was also found to improve pilots' abilities to cope with very high workloads and competing attentional demands that are typical in flight training (Hart & Battiste, 1992). Boot et al. (2010) also showed a transfer effect following variable priority training on a complex simulated real world task (radar monitoring and flight simulator) in younger adults. Thus, variable priority training results in enhanced dual-task performance on complex real world tasks. However, more research is needed to confirm that a variable priority training program produces more transfer than single-task training. We also need to know whether older and younger adults show similar transfer to complex tasks, as most studies focused on younger populations.

Virtual-reality: a tool to measure transfer effect

VR may be a promising addition to a toolkit designed to assess the impact of cognitive training in real life settings. It is a computer-based technology that allows users to interact in real time with a multisensory simulated environment via behavioral interfaces (Fuchs, Moreau, & Berthoz, 2006; Saposnik et al., 2016). Its potential lies in its capacity to reproduce situations close to daily life while providing a controlled, standardized and safe environment (Rizzo, Schultheis, Kerns, & Mateer, 2004). VR appears to provide valid measures of real world capacities. A few studies reported that participants' performances in virtual environments are closely related to those in real word environments, and that this is the case in both younger (Waller, Hunt, & Knapp, 1998) and older adults (Allain et al., 2014; Cushman, Stein, & Duffy, 2008; Plancher, Gyselinck, Nicolas, & Piolino, 2010). For example, Cushman et al. (2008) found correlations between navigational deficits measured in the lobby of the Strong Memorial Hospital and those measured in a virtual reproduction of this environment. Plancher et al. (2010) found that older adults' memory recall performance of elements seen during the exploration of a virtual city correlated with their memory complaints in daily life. VR environments also provide a *sense of presence* for the user, which is the subjective experience to be in a place when one is physically in another (Witmer & Singer, 1998). This *sense of presence* was shown to help evoke emotional responses like the ones experienced in real life situations (Schuemie, Van Der Straaten, Krijn, & Van Der Mast, 2001). Thus, the sense of presence evoked by VR and its emotional correlates contributes to making it a representative tool of everyday life activities. As VR provides well-controlled yet ecological situations, we propose to use this technique as a way to appraise impact in real word situations in addition to self-reported questionnaires. To the best of our knowledge, VR has never been used to measure transfer effects following cognitive training.

Summary and objectives

In summary, many studies suggest that divided attention variable priority training improves attentional control capacities and dual-task performance and that the benefit is larger than the one found from pure dual-task training or repeated practice of an individual task. In the majority of studies, this advantage was shown to transfer to untrained tasks that are close to the ones used in training (e.g., the same task using a different input or output modality). However, little is known about the effect of training on tasks more akin to real life or that reflect the complexity of the processes involved in attentional tasks of everyday living. It is also unclear whether age reduces the capacity to benefit from cognitive training and to transfer that benefit to untrained tasks, as results from the litterature are inconsistent. Furthermore, most studies have assessed training to real-life tasks with younger populations, which limits the conclusion with regards to the transfer in older adults. These questions will be adressed here.

We will assess the effect of two types of attentional training, VARIABLE priority training vs. SINGLE-task training. In VARIABLE priority training, participants are asked to vary the amount of attention placed on each task performed concurrently (alphanumeric equation and visual detection). In SINGLE-task training, participants perform both tasks individually in focused attention. Because our focus was on transfer, we will compare VARIABLE priority training to a condition that is active, but for which we do not expect major dual task improvements based on previous findings (Bier et al., 2014; Zendel et al. 2016). Training effect will be measured with tasks that are close to the ones used in training. Transfer will be measured using a novel complex VR scenario that mimics a dual task situation that could occur while being a passenger in a car: The *Virtual car ride.* The dual-task VR scenario combines two tasks: the detection of a visual road sign (detecting a target city name passing on one of the road signs) and a complex working memory task presented orally (recalling a list of words in alphabetical order). We chose this task because it allows control over presentation and response conditions. Because working memory is known to be involved in complex real-life cognitive processes such as oral comprehension and logical reasoning, it was considered to be an appropriate compromise. Participants also complete the Cognitive failure questionnaire (Broadbent, Cooper, FitzGerald, & Parkes, 1982), a self-reported questionnaire where they indicate how often they judge committing errors in the completion of attention-demanding tasks from everyday life (for instance, *Do you fail to hear people speaking to you when you are doing something else? Never* to *Very Often*). Based on previous studies (Bier et al., 2014; Zendel et al., 2016), we expect that only the VARIABLE training group will improve attentional control measured on a proximal measure. We also expect that the VARIABLE condition will yield transfer, hence reducing divided attention cost in the VR environement. Older adults should benefit as much as younger ones from VARIABLE training but whether they show equivalent transfer is unclear based on previous findings.

METHODS

Participants

The study included 60 participants, 30 older adults and 30 younger adults. All participants were recruited in the community through advertisements in retirement centers and magazines for seniors. Participants were included if they were French-speaking and community dwelling, living in the Montreal area, right-handed, and had normal or corrected-to-normal hearing and vision. Exclusion criteria included: alcoholism or substance abuse, presence or history of a neurological disorder or stroke, presence or history of a severe psychiatric disorder (e.g., depression, schizophrenia, bipolar disorder), general anesthesia in the past six months, and impaired performance on the Montreal Cognitive Assessment (Nasreddine et al., 2005).

Participants underwent a telephone interview to provide initial selection information. Eligible individuals were invited to come to the laboratory for a standardized clinical and neuropsychological battery in order to evaluate their clinical status and cognitive functioning. The first session included one test of “fluid” intelligence (Wechsler, 1997) and one of “crystallized” intelligence (Vocabulary subtest; WAIS-III-R; Wechsler, 1997). Older participants also completed the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005). The study was approved by the Institut universitaire de gériatrie de Montréal Human Ethics Committee. Informed written consent was obtained from all subjects according to the Declaration of Helsinki.

Design

Subject flow is shown in Figure 1 according to the CONSORT reporting instructions (Schulz, Altman, & Moher 2010). Participants were randomly assigned by an independent research assistant to one of two training conditions, stratified by education and age to equate the groups on those variables. Proximal and transfer measures were completed in a single session one week prior to the first training session and one week following the last training session. Two task versions were used for the pre- and post-session (for the proximal and VR tasks), and the order of administration was counterbalanced across participants.

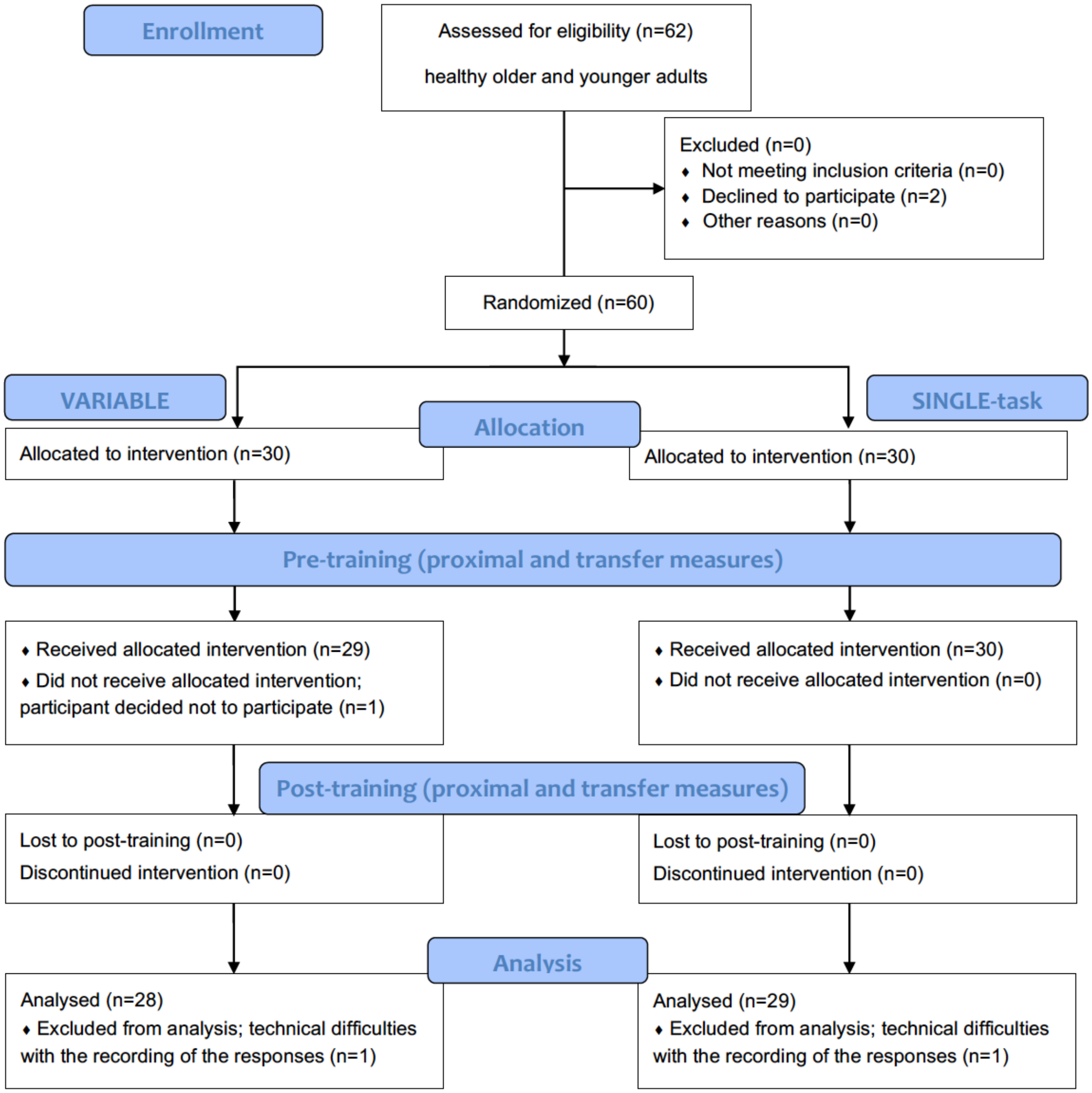

Figure 1. Flow chart according to the Consort reporting instructions.

Training method

The training program was similar to one used in previous studies (Belleville et al., 2014; Bier et al., 2014; Zendel et al., 2016). The divided attention paradigm included two tasks: a visual detection task and an alphanumeric equation task. The tasks vary in attentional demand, which should increase reliance on goal maintenance when required to vary attentional priority. Both tasks were run on Compaq Pentium d530 computers, and responses were provided on the keyboard. In the alphanumeric equation task, participants were asked to judge the accuracy of a set of visually presented alphanumeric equations. The stimuli consisted of addition or subtraction equations containing letters (from N to Z) and numbers (1 or 2) in the format x (+ or -) $n = z$. The letter x corresponded to the starting point in the alphabet, the + or – sign indicated the direction of the equation, and n was the number of letters that separated the starting point from z. For example, the equation N + 2 = P is correct because P is 2 letters after *N* in the alphabet, whereas the equation S - 1 = Q is incorrect because one letter down from S in the alphabet is R and not Q. Each equation was visually presented in the middle of the screen for a maximum period of 3750-ms with 1500-ms interstimulus intervals. The participant was asked to judge the accuracy of the equation by pressing one of two keys: the "F" key with the left index finger when the equation was incorrect, and the "J" key with the right index finger when the equation was correct. Half of the equations were correct. Incorrect ones were formed by selecting a letter that was 1 or 2 positions away from the correct result. Each training session comprised 12 blocks of 20 trials. The number of addition versus subtraction, one versus two steps, as well as correct versus incorrect equations, was equivalent across blocks of trials. In the visual detection task, red or white rectangles (3x30 square-inch (7.6×76 cm2) appeared randomly at the bottom of the computer screen for 500-ms each, interspaced by 250-ms intervals (ISI). Participants were asked to press the spacebar key every time the rectangle was red and were to do so as quickly and as accurately as possible. Accuracy (AC) and reaction time (RT) were recorded for both tasks. If a participant did not provide an answer within the required period of time, the next trial was presented and the previous was considered as failed. To provide a baseline, all participants completed two blocks of each task under focused attention at the beginning and end of each session.

In the variable priority training condition (VARIABLE), participants were asked to perform both tasks (alphanumeric equation and visual detection) simultaneously and to vary their allocation priority across a series of blocks. Each session comprised 12 blocks (four blocks in focused attention and eight in divided attention). Prior to each block, instructions informed the participants as to how much attention should be given to each task. There were two different levels of attentional allocation priority: 80% Equation and 20% Equation. The 80% Equation instruction condition indicated that participants should allocate 80% of their attention to the alphanumeric equation task and 20% to the visual detection task. For the 20% Equation instruction condition, 20% of the participants' attention was asked to be on the alphanumeric equation task and 80% on the visual detection task. The instructions were visually presented on the screen and read aloud to participants. To enable better understanding, instructions were supported by an illustration of a rectangular box divided into two colored parts of different proportions, each representing the percentage of attention required by each task. After each block, a histogram was presented to the participants indicating their baseline level for the training session (as measured earlier in the focused attention condition) and the expected accuracy given the emphasis instruction condition. For example, if a participant responded correctly on 75% of the alphanumeric equations in the focused attention condition, they would be expected to have 60% accuracy in the 80% Equation emphasis instruction condition. Before displaying their actual performance on the histogram, participants were asked to draw their own estimate on a paper histogram. Participants were thus evaluating their own performance and informed as to whether they had attained the requested priority proportion to allow them to better adjust the emphasis at the next block.

Each equation comprised five rectangles, including one to three red rectangles. Thus, 40% of the rectangles were red, with a total of 20 to 100 rectangles per block, depending on the participant's speed. The, visual detection targets were only presented during the time participants took to solve the equation. This ensured that the participants were in a state of divided attention during the entire period.

In the single task training condition (SINGLE-task), participants were asked to practice the alphanumeric equation task and the visual detection task under focused attention, that is, without combining them. To equate the number of blocks with the VARIABLE priority training condition, participants completed six blocks for one task and seven blocks for the other task in each session. The number of blocks for each task alternated between sessions so that participants would receive the same amount of exposure to both tasks over the course of the whole training program. The starting task at session one was counterbalanced across participants.

Both training were provided in eight one-hour sessions on weekdays over a period of two weeks. Each training session was performed in groups of two or three participants.

Outcomes measure

Proximal outcome measure

The proximal outcome measures were focused and divided attention tasks. Participants were asked to perform a visual detection task and an alphanumeric equation task separately (focused attention) and in combination (divided attention). The task was similar to that used in training, except that the equations contained letters from a different part of the alphabet (A to M rather than N to Z) and no feedback was provided. Each condition (focused and divided) was presented in six blocks of eight trials (for a total of 48) following an ABA design. Participants first completed each task with focused attention, followed by two blocks of the dual-task condition (80% Equation, 20% Equation). The two tasks were then completed again with focused attention. No feedback was given during the task.

Transfer measures in VR

Generalization of training effects was measured with the *Virtual car ride*. The virtual environment of the *Virtual car ride* was developed and rendered using the 3DVIA Virtools 5 3D engine and was run on a Dell Precision T3600 PC with an Inter® Xeon® CPU ES-1620 0 (3.60 Ghz, 10 Gbytes in RAM) processor and a NVIDIA GeForce GTX 600 Ti graphic card. The task was designed in collaboration with *Cliniques et développement in virtuo* (www.invirtuo.com). The virtual environment was three dimensional and the immersion was produced by an Nvisor ST50 audio-visual headgear and by a Worldviz PPT-X studio tracking system that allowed the participant to rotate their head in a 360-degree view, as well as look up and down. Participants were asked to sit on a chair while the assistant installed the headgear and the hand device (computer mouse). They were then immersed in the virtual environment and told that they were free to move their head and explore the environment. Car sounds were audible in the environment and other vehicles appeared on the road as distractors and to mimic real life situations (ambulance, cars).

In the *Virtual car ride,* participants sat in the passenger's seat of a car moving on a highway. They were not asked to drive, but were asked to guide the driver to their destination in the divided (road signs detection; *Alpha-Span*) or focused attention condition. In the road signs detection task, the participants were instructed to help the driver with directions to go to a specific city. A fictive city name was given to them prior to the beginning of the task and varied depending on the version of the task used (Chauminont; Montformeil). Participants were asked to press the left mouse button with their left index finger each time they would see the target city name passing on one of the road signs. The *Virtual car ride* lasted 4 minutes and included 40 road signs, 20 of which corresponded to the target, and the other half were distractors. In the Alpha span task (Belleville, Rouleau, & Caza, 1998), participants were asked to recall a list of words in alphabetical order. As a first step (outside the VR), a classic word span procedure was used to assess their short-term memory capacity. Then, 10 individually span level adjusted sequences of words were presented to the participants who were asked to rearrange and recall the words in alphabetical order. For example, the words *orme, pain, corde* should be recalled *corde, orme, pain*.

Participants were instructed to perform both tasks (the road signs detection and the Alpha span task) concurrently in a divided attention condition and to put an equal amount of attention on each task. As soon as the car started moving, the first sequence of words to be recalled was read at a rate of 1 item per second and the participants had to recall the words in their alphabetical order. If a participant did not provide an answer within the required period of time, the next list was provided and the sequence was considered as failed. A total of 10 to 12 lists were provided for each participant depending on the time taken to complete the car ride. Accurary (AC) was recorded for each of the tasks. The same procedure was used for the condition of focused attention, except that all participants received a fixed number of 10 sequences for the Alpha span task. Participants completed the Alpha span task first in focused attention, followed by the road sign detection tasks in focused attention. Both tasks were then combined in the divided attention condition.

RESULTS

Demographic and clinical data

The participants randomized to the two training conditions were first compared for demographics and clinical characteristics. ANOVAs with age, education level, and performance on clinical measures as dependent variables, and training group (VARIABLE vs. SINGLE-task) as between-group factors, showed no significant differences between the two training groups for both younger and older adults (see Table I).

Table I. Demographic and clinical characteristics for all participants included in the final sample (S.D. in parentheses)

	OLD		YOUNG	
	SINGLE Training n= 14	VARIABLE training n= 13	SINGLE Training n= 15	VARIABLE training n= 15
Age	73.05 (6.36)	69.70 (5.13)	25.71 (4.21)	26.19 (4.62)
Gender	12 F, 2 H	10 F, 3H	11 F, 3 H	12 F, 3H
Education	14.85 (4.63)	14.77 (2.68)	15.43 (2.06)	15.94 (2.12)
Moca (/30)	28,14 (1.20)	28,92 (1.38)	-	-
GDS (/15)	0.92 (1.27)	1.69 (2.01)	-	-
BDI-II	-	-	2.79 (3.56)	4.13 (2.86)
Vocabulary - WAIS-IV subtest	11.50 (2.10)	12.46 (1.12)	11.86 (1.46)	11.38 (1.97)
Digit Symbol-Coding WAIS-IV subtest	14.85 (1.47)	14.15 (2.51)	13.29 (2.73)	13.88 (3.03)

Standard deviations in parentheses

Proximal measures

Dependent variables

For the proximal outcome measures, we calculated a dual-task cost by combining the AC and RT for each task in the divided attention condition relative to the focused attention condition, with the following equation: {[(RT divided – RT focused) / RT focused] + [(AC focused – AC divided) / AC focused]}. In the equation, RT focused and AC focused represent performance in the focused attention condition for reaction time and accuracy. RT divided and AC divided represent performance in the divided attention condition (80% Equation or 20% Equation) for reaction time and accuracy. Thus, the formula controls for baseline performance. This divided attention cost represents the proportional loss of performance in the divided attention condition as a function of performance in focused attention and was used as the dependent variable.

Pre-training effects

To assess whether there were age differences in the ability to control attention prior to training and to assess whether the training groups were equivalent, performance in the pre-training session was first analyzed using a mixed ANOVA with dual-task cost as a dependent variable, Emphasis (20% Equation; 80% Equation;) and Task (alphanumeric equation; visual detection) as within-subject factors, and Training group (SINGLE-task; VARIABLE) and Age (Young; Old) as between-subject factors.

The ANOVA showed no main effect of Training group ($F<1$) and no interaction involving that factor, ($F<1$), indicating that the two training groups had similar performance at baseline. A main effect of Task was found $F(1, 53) = 465.95$, $p < .001$ ($\eta 2 = 0.90$), as participants had an overall higher dual-task cost on visual detection ($M = 0.84$) than on alphanumeric equation ($M = 0.23$). There was also a main effect of Age, $F(1, 53) = 57.51$, $p < .001$ ($\eta 2 = 0.52$), as older adults had a higher dual-task cost ($M = 0.63$) compared to younger adults ($M = 0.42$). This effect was qualified by a significant Emphasis x Task x Age interaction, $F(1, 53) = 17.33$, $p < .001$ ($\eta 2 = 0.25$). Inspection of Figure 2a and b suggests that the interaction arises from the fact that younger adults were better able to modulate their attention between the visual detection and alphanumeric tasks according to the instructions compared to their older counterparts. To confirm this interpretation, ANOVAs were computed separately for each age group with the variables Emphasis and Task as repeated factors.

In younger adults, a main Task effect was found, F (1, 29) = 119.46, $p < .05$ ($\eta 2 = .81$), indicating that the dual-task cost was higher on the visual detection task ($M = .64$) compared to the alphanumeric equation task ($M = .21$). This effect was qualified by Task x Emphasis interaction, $F(1, 29) = 101.18$, $p < .05$ ($\eta 2 = .78$). Decomposition of the interaction revealed that for both tasks, the dual-task cost varies as a function of the emphasis instruction, but that the emphasis effect goes in the opposite direction for the two tasks. Thus, the main effect of Emphasis, $F(1, 29) = 101.18$, $p < .001$ $\eta 2 = 0.67$) for the alphanumeric equation task was due to the fact that the dual-task cost was lower in the condition that requires prioritizing the alphanumeric equation task, the 80% Equation, ($M = 0.04$), relative to the one that requires prioritizing detection, the 20% Equation ($M = 0.37$) ($p < .05$). Inversely, the main effect of Emphasis, F (1, 29) = 101.18, $p < .001$ $\eta 2 = 0.78$, for the visual detection task was significant, as the dual-task cost was lower in the 20% Equation ($M = 0.43$) than in the 80% Equation ($M = 0.84$) ($p < .001$). Interestingly, and as shown in Figure 2a, there is a larger cost for the visual detection task than the alphanumeric equation when participants are asked to prioritize the latter, but this effect is no longer present when participants are asked to prioritize visual detection (20% Equation). These results suggest that younger adults can modulate their attentional priority between both tasks as a function of the emphasis instruction.

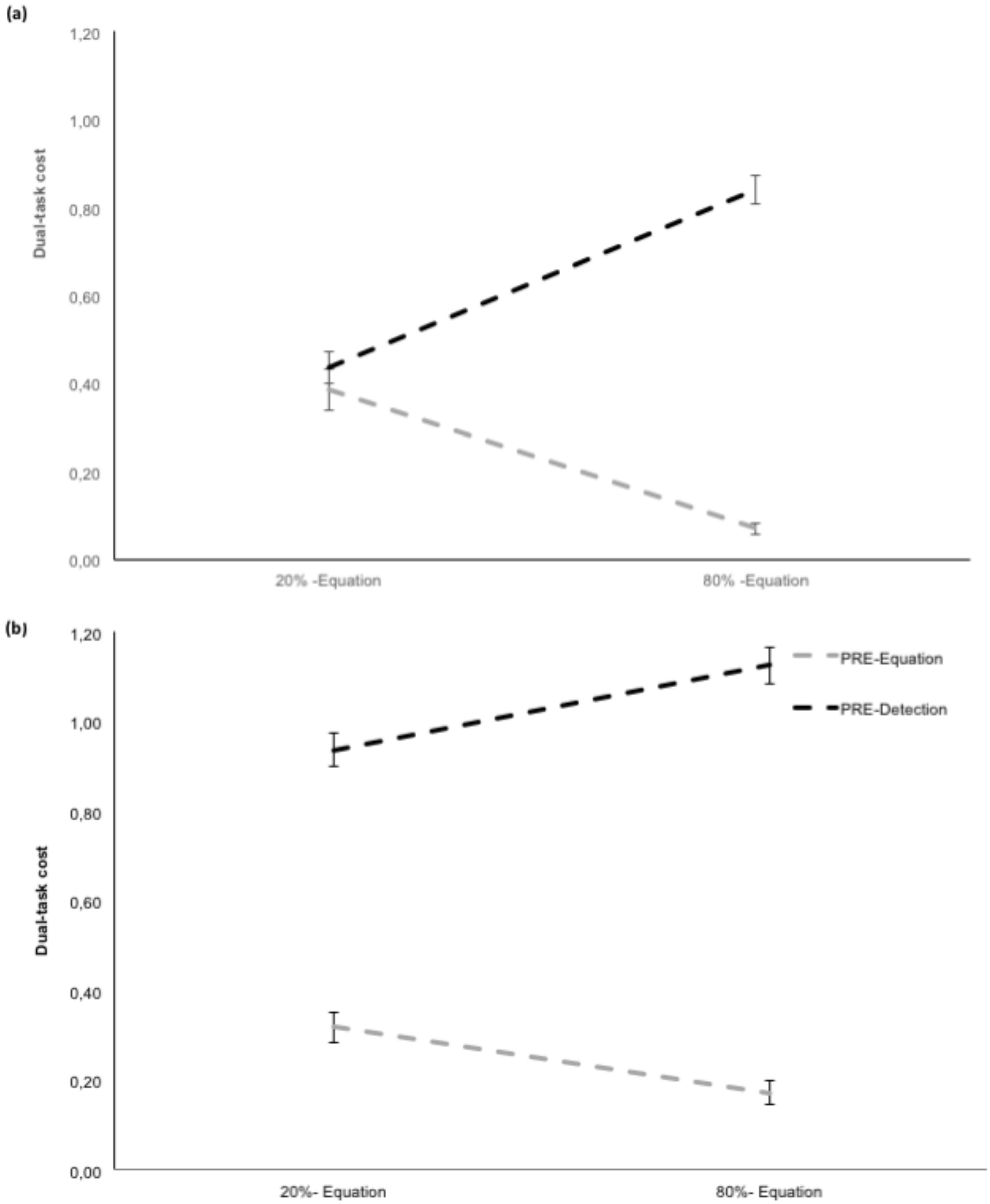

Figure 2. Divided attention cost for young (a) and older adults (b) on each task (alphanumeric equation; visual detection) as a function of emphasis intructions (20%-Equation; 80%- Equation) at baseline (error bars represent standard error).

The pattern is different in older adults. Similar to younger adults, a main effect of Task was found, *F* (1, 26) = 417.83, $p < .001$ (η2 = 0.94), indicating a higher dual-task cost for the visual detection task (*M* = 1.03) compared to the alphanumeric equation task (*M* = 0.24), and this effect was qualified by an Emphasis x Task interaction, *F*(1, 26) = 34.69, $p < .001$ (η2 = 0.58). Decomposition of the interaction revealed a significant Emphasis effect for both the visual detection *F*(1, 26) = 34.69, $p < .001$ η2 = 0.43 and the alphanumeric equation tasks *F*(1, 26) = 34.69, $p < .001$ η2 = 0.50. The Emphasis effect goes in the opposite direction. For the alphanumeric equation task, the main effect of Emphasis is explained by a lower cost in the 80% Equation emphasis condition (*M* = 0.17) than in the 20% Equation emphasis condition (*M* = 0.31), whereas for the visual detection task, it is explained by a larger cost in the 80% Equation emphasis condition (*M* = 1.12) than in the 20% Equation emphasis condition (*M* = 93). The source of the three-way interaction appears to arise from the fact that the disadvantage for dual-task cost on visual detection is more marked in older adults than in younger adults and their change in cost with emphasis is smaller. As a result, the cost disadvantage for the visual detection task is still present in older adults in the condition that requires prioritizing that task, contrary to what is found in younger adults. Thus, older adults prioritize the alphanumeric equation task, irrespectively of the emphasis conditions.

When comparing age groups on divided attention costs, older adults showed a higher visual detection dual-task cost than younger adults for both emphasis conditions (both $p < .001$, see Figure 2a and 2b), whereas they showed a larger alphanumeric equation task dual-task cost only for the 80% Equation emphasis.

Training effects on the proximal measures

<u>Divided attention condition</u>

To assess training effects, dual-task cost scores were analyzed with a mixed ANOVA using Time (pre- and post-training), Emphasis (80% Equation; 20% Equation), and Task (alphanumeric equation, visual detection) as within-subject factors, and Training type (SINGLE-task; VARIABLE) and Age (Young; Old) as between-subject factors. The Time x Emphasis x Task x Training type x Age interaction was significant, F (1, 53) = 3.26, $p < .001$ (η2 = 0.16). Inspection of Figures 3a, b and c indicate that this is due to training conditions having different effects in younger and older adults. To allow interpretation of the interaction, ANOVAs were computed separately for older and younger adults with the variables Time, Emphasis, Task, and Training type.

<u>For younger adults</u>, the analysis revealed no main effect of Training type ($F<1$) and no interactions involving that factor. As the two training types led to similar outcomes, Figure 3a shows pooled dual-task cost. Importantly, younger adults showed a significant Time x Task interaction, F(1, 28) = 53.49, $p < .001$ (η2 = 0.66). This was a cross-over interaction as shown in Figure 3a as the dual-task cost was modified on both tasks following training, but in the opposite direction. The visual detection dual-task cost was reduced from pre- (M= 0.64) to post-training (M= 0.46), whereas the alphanumeric equation dual-task cost increased from pre- (M= 0.21) to post-training (M= 0.39) ($p < .001$ & $p < .001$, respectively). As a result, the dual-task cost, which was larger for visual detection than for alphanumeric equation prior to training, was no longer different after training. Consistent with the results presented in the section on pre-training, this analysis also revealed a Task x Emphasis interaction, F(1, 28) = 96.69, $p < .001$ (η2 = 0.78) indicating that the dual-task cost for the two tasks varies as a function of the emphasis instruction

condition ($p < .001$). None of the other interactions reached significance. These results show that both training modified younger adults' initial bias in favor of the alphanumeric equation task, resulting in a reduction of the dual-task cost on visual detection and an increase of dual-task cost on the alphanumeric equation task.

For older adults, a significant Time x Emphasis x Task x Training type interaction, $F(1, 25) = 4.28$, $p < .05$, ($\eta 2 = 0.15$), was found. Inspection of Figures 3b and 3c suggests that this is due to the fact that only the participants trained in VARIABLE priority training improved their ability to modulate their attention according to the instruction after training. To support this intepretation, we computed Time x Emphasis x Task ANOVAs separately for the VARIABLE and SINGLE-task training types condition, which revealed that the two conditions led to different training effects.

In the VARIABLE condition, we found a significant Emphasis x Time x Task interaction, $F(1, 12) = 6.41$, $p < .05$, ($\eta 2 = 0.35$). No Time effect was found on the alphanumeric equation task on either emphasis condition (*$F<1$, in both cases)*. There was a Time effect in both emphasis conditions for the visual detection task. The interaction seems to arise from a larger emphasis effect following training than prior to training, and a larger training-related dual-task cost reduction on the visual detection task when the condition required prioritizing that task (20% Equation) than when it required prioritizing the Equation task ($M = 0.90$ vs. 0.54). Considering older adults had more difficulty prioritizing the visual detection task prior to training when asked to do so (20%-Equation condition), this indicates that after training, participants in the VARIABLE training group were able to modify their attentional priority in dual-tasking as a function of task instructions.

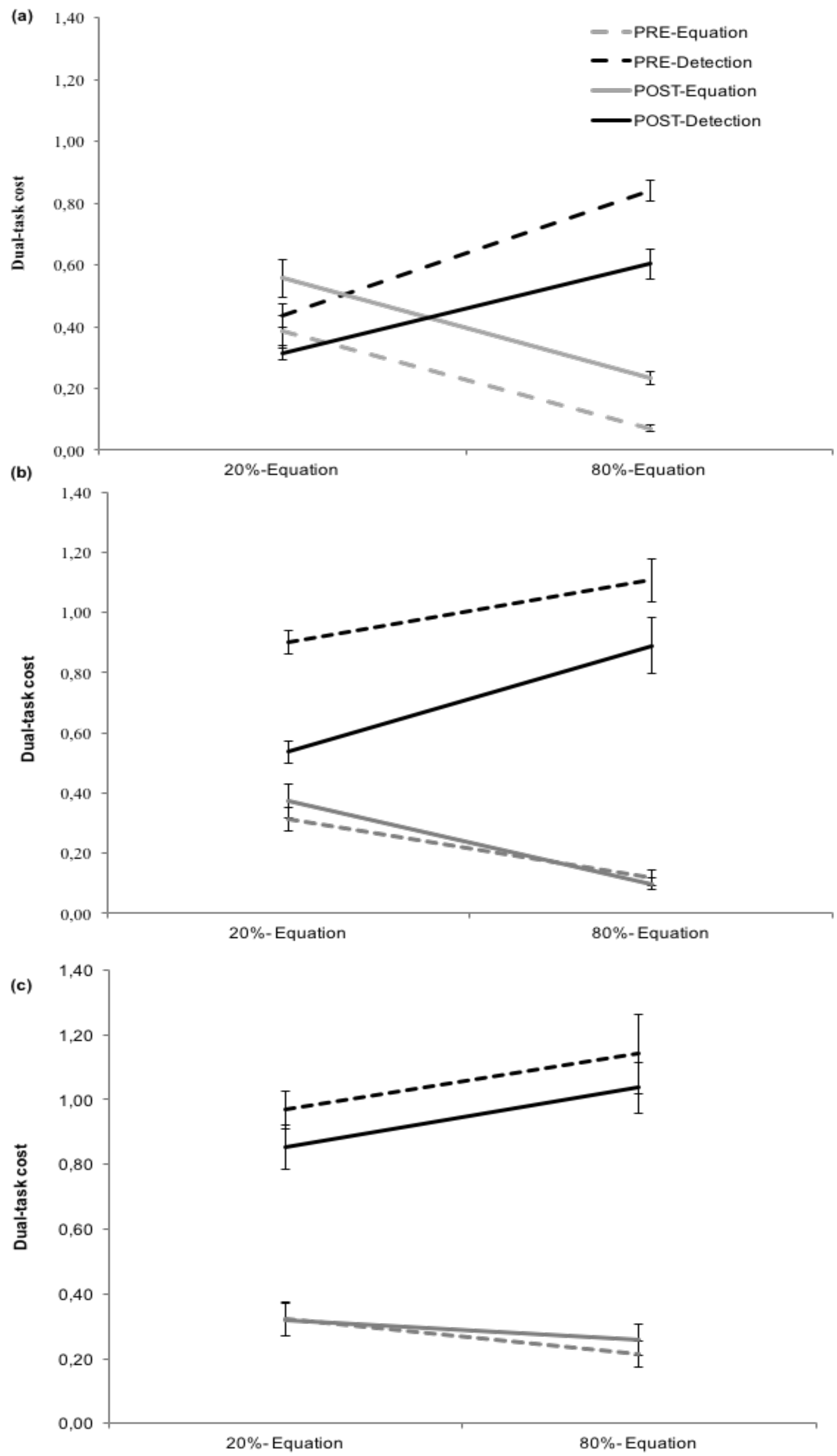

Figure 3. Divided attention cost for (a) young adults (pooled for the two training type and older adults (b) VARIABLE training and (c) SINGLE-task training, on each task (alphanumeric equation; visual detection) and emphasis instruction condition (error bars represent standard error).

In SINGLE-task training, there was no effect of Time and none of the interactions involving Time were significant (Figure 3c). Thus, older adults in the SINGLE-task training condition did not improve their dual-task cost or improve their ability to vary their level of attention based on instructions. Of note is the fact that the group showed an Emphasis x Task interaction, $F(1, 13) = 15.56$, $p < .05$ ($\eta2 = 0.54$) due to the fact that in the visual detection task, participants had a lower dual-task cost in the 20% Equation ($M = 0.91$) than in the 80% Equation emphasis instruction condition ($M = 1.09$) ($p = .001$).

Focused attention

We also examined the effect of training on performance for each task, as some of our participants were trained in a single-task condition. Table 2 shows the pre- and post training performance in focused attention for each training type and age group. To assess the effects of training, mixed ANOVAs were computed separately for each task on AC and RT, using Time (pre- and post-training) as a within-subject factor, and Age (Old, Young) and Training type (SINGLE-task, VARIABLE) as between-subject factors.

For the alphanumeric equation task, the ANOVA on AC indicated a Time x Training type interaction, $F (1,53) = 6.61$, $p < .05$ ($\eta2 = 0.11$), as only participants in SINGLE-task condition improved their accuracy following training ($p < 0.001$, $p = 0.19$, for SINGLE-task and VARIABLE, respectively). A main effect of Age was also found, $F(1, 53)= 9.23$, $p < .05$, due to higher accuracy in younger adults than in older adults. The ANOVA on RT showed a main effect of Time, $F(1, 53)=141.56$, $p < .001$ ($\eta2 = 0.73$), due to faster RT following training. A main effect of Age was also found, $F(1, 53)= 27.70$, $p < .001$ ($\eta2 = 0.34$), as younger adults were faster than older ones. The main Training type effect and the interactions involving that factor did not reach significance for RT ($F < 1$, in all cases).

Table II. Performances in single-task alphabetic equation and visual detection (reaction time and accuracy) in pre- and post- sessions for each training type

		Alphanumeric equation				**Visual detection task**			
		AC		**RT**		**AC**		**RT**	
		Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**
OLD	SINGLE	72.76 (13.33)	84.1* (3.1)	2739.98 (448.67)	2282.99** (388.51)	92.84 (3.24)	94.47 (2.57)	457.85 (32.45)	442.53** (40.15)
	DIVIDED	81.24 (9.35)	81.72 (18.94)	2548.72 (298.33)	2110.52** (413.27)	94.68 (2.36)	95.07 (2.24)	445.07 (27.29)	440.83** (37.88)
YOUNG	SINGLE	79.97 (11.22)	93.70* (3.17)	2152.33 (352.78	1613.46** (239.41)	95.23 (2.11)	94.30 (1.81)	412.09 (26.83)	402.97** (30.98)
	DIVIDED	84.29 (8.18)	90.31 (6.23)	2244.33 (401.82)	1789.97** (409.58)	95.65 (2.29)	94.59 (1.87)	412.39 (40.44)	409.58** (33.21)

Standard deviations in parentheses
* Time x Training type interaction, $p < 0.05$
** main effect of Time, $p < 0.001$ & $p < 0.05$, respectively

<u>On visual detection AC,</u> there was an Age x Time interaction, $F(1, 53)=28.24$, $p < .05$ ($\eta 2 = 0.11$), as younger adults were more accurate than older adults prior to training ($p < .05$), but not following training ($F < 1$). The RT analysis revealed a main Time effect, $F(1, 53)= 4.29$, $p < .05$ ($\eta 2 = 0.10$), indicating that the task was completed more rapidly following training and a main effect of Age, $F(1, 53)= 20.49$, $p < .001$ ($\eta 2 = 0.30$), indicating that younger adults responded faster than older ones. There was neither a main Training type, nor an interaction involving that factor ($F < 1$, in all cases).

Transfer measures

Virtual car ride – Divided attention

The dependent variable of interest for the *Virtual car ride* was the dual-task cost calculated with the following equation: (AC divided – AC focused) / AC focused). Costs were analysed with a mixed ANOVA using Time (pre- and post-training) and Task (road sign detection, Alpha span) as within-subject factors, and Training type (SINGLE-task; VARIABLE) and Age (Young; Old) as between-subject factors. The Time x Task x Training type x Age interaction just reached significance (p = .05). Since we had specific predictions regarding the effect of the training type on transfer, separate Task x Time x Training ANOVAs were computed for each age group.

In younger adults, none of the effects or interactions reached significance including the Task x Time x Training interaction (F < 1) (see Figure 4). Inspection of Figure 4 suggests that younger adults reduced their dual-task cost from pre- to post-training on the Alpha span task with both training types. However, the Time x Task interaction just missed significance (p = .07), as did the time effect for Alpha span (p = .07). No time effect was found on the road sign detection task (F <1). Thus, younger adults did not reduce their dual-task cost in the *Virtual car ride* following training, irrespective of training condition.

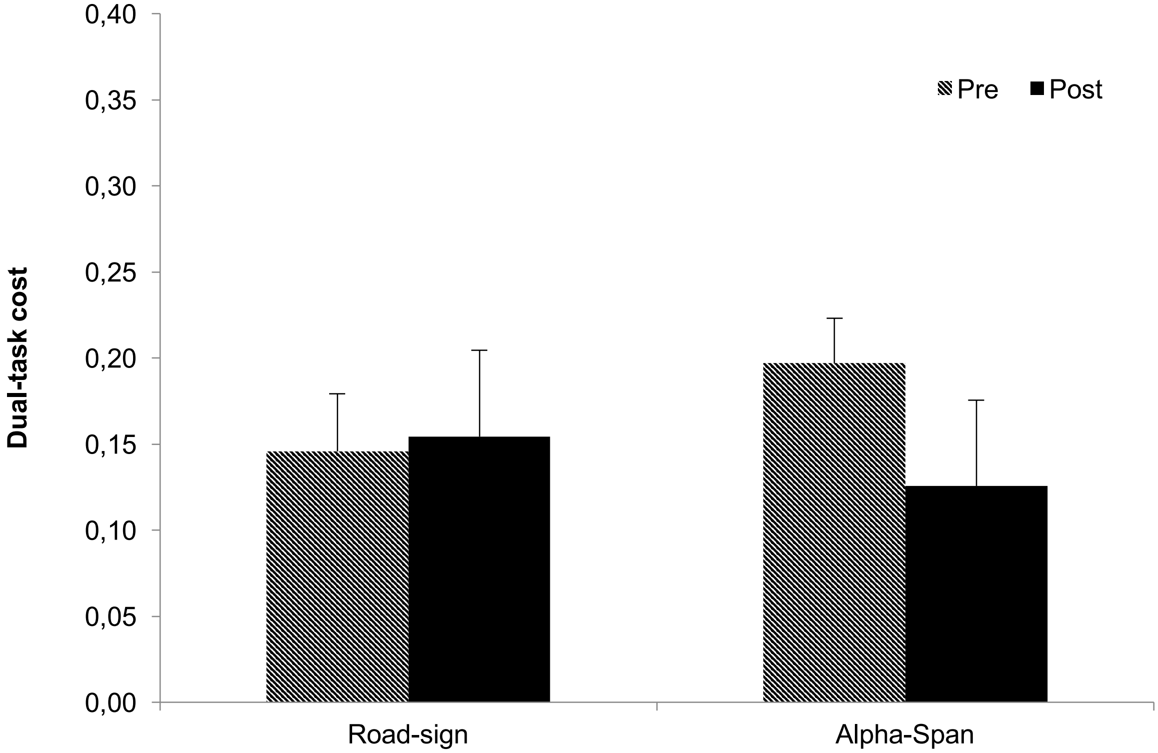

Figure 4. Divided attention cost for young adults (pooled for the two training types) on each task performed in VR (Road sign; Alpha-span) at PRE- and POST-training (error bars represent standard error).

For older adults, a significant Task x Time x Training type interaction was found, $F(1, 26) = 3.94$, $p < .05$, ($\eta 2 = 0.15$). Inspection of Figures 5a and 5b indicates that this is due to the fact that VARIABLE priority training improved dual-task cost on both transfer tasks, whereas SINGLE-task training improved only dual-task cost for the Alpha span task. This was confirmed by the decomposition of the interaction. In the VARIABLE training group, we found a main Time effect, $F(1, 26) = 6.50$, $p = .05$, ($\eta 2 = 0.20$), indicating a dual-task cost reduction from pre- ($M = 0.24$) to post-training ($M = 0.13$) irrespective of the task. A main Task effect was also found, which was due to the fact that the dual-task cost was generally larger for the road sign detection than for the Alpha span task, $F(1, 12) = 5.79$, $p < .05$ ($\eta 2 = 0.33$). None of the other effects or interactions reached significance. In the SINGLE-task training group, no Time effect was found ($F < 1$), but the Time x Task interaction was significant, $F(1, 13) = 11.59$, $p < .05$ ($\eta 2 = 0.47$) as participants reduced their dual-task cost following training but only on the Alpha span task ($M = 0.25$ and $M = 0.13$ in pre- and post-training respectively; $p < .05$).

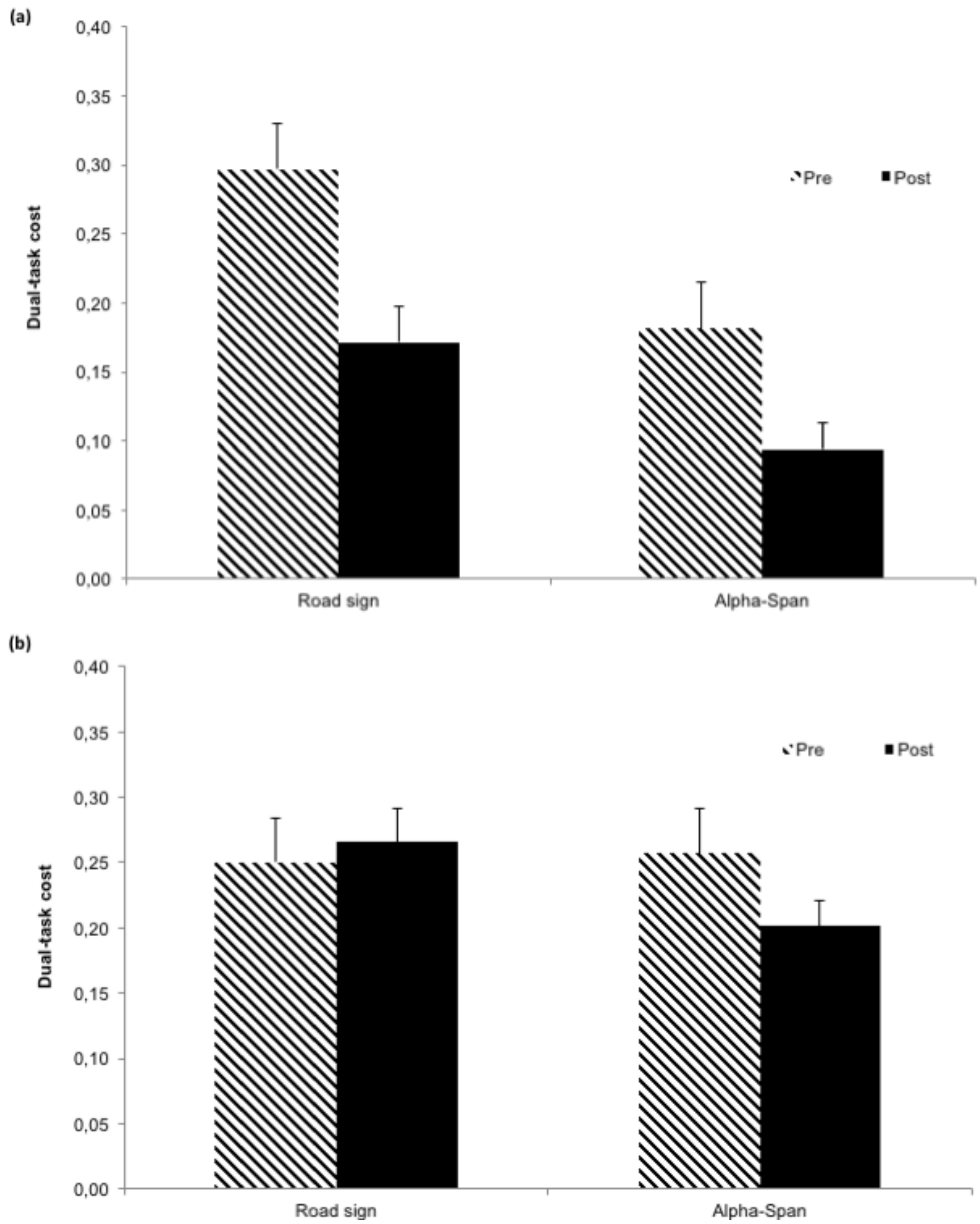

Figure 5. Dual-task cost for older adults in (a) VARIABLE training and (b) SINGLE-task training on each task performed in VR (Road-sign; Alpha-span) at PRE- and POST-training (error bars represent standard error).

Virtual car ride – Focused attention

To assess transfer in the focused attention condition, mixed ANOVAs were computed separately for each task on AC, using Time (pre- and post-training) as a within-subject factor and Age (Old, Young) and Training type (SINGLE-task, VARIABLE) as between-subject factors. For the Alpha span task, the ANOVA on AC indicated a Time x Age interaction, F (1,53) = 5.05, $p <$ .05 ($\eta 2$ = 0.09), as only younger adults improved their accuracy following training ($p < .05$, p = 0.69, for young and older adults, respectively). On the road sign detection task there was a main Time effect, F(1, 53)= 7.14, $p < .05$ ($\eta 2$ = 0.12), as all participants improved their performance, and a main effect of Age, F(1, 53)= 52.46, $p < .001$ ($\eta 2$ = 0.50), as younger adults were more accurate than their older counterparts. None of the other effects reached significance.

Cognitive failure questionaire (CFQ)

The Time (pre- and post-training) x Training type (SINGLE-task; VARIABLE) x Age (Young; Old) ANOVA on the total score of the CFQ revealed that none of the main effects or interactions reached significance ($F < 1$ in all cases).

Correlations

To further assess whether improvement in transfer tasks was due to the favourable effects from the training, we computed correlations between change scores on the *Virtual car ride* dual-task scores and CFQ questionnaire (pre- minus post-training scores) and change scores on three proximal measures: dual-task cost change score (pre- minus post-dual-task cost for the visual detection task in the 20% Equation condition), alphanumeric equation change score (pre- minus post-AC for the alphanumeric equation task performed in focused attention) and visual detection change score (pre- minus post-RT for visual detection performed in focused attention) (see Table III a and b). We chose those variables, as they were the ones for which improvement was found in both age groups. Correlations were computed separately for the two training types and age groups. We also computed correlations between change scores on the CFQ questionnaire and *Virtual car ride* dual-task cost.

Table III. Correlation between change scores on proximal measures and post-training improvement on the VR tasks in a) dual-task cost and b) focused attention for each training type and age

a) Correlations between change scores on proximal measure (pre- minus post- dual-task cost for the visual detection task in the 20% -Equation and change scores on the *Virtual car ride* (pre- minus post- dual-task cost for the road sign detection task and the Alpha-Span task) and CFQ questionnaire total score **b)** Correlations between change scores on proximal measure (pre- minus post- AC for alphanumeric equation task in focused attention and RT for visual detection task) and change scores on the *Virtual car ride* (pre- minus post- dual-task cost for the road sign detection task and the Alpha-Span task) and CFQ questionnaire total score.

a)

	Correlation value					
	OLD			YOUNG		
Training type	Road sign	Alpha-Span	CFQ	Road sign	Alpha-Span	CFQ
SINGLE training	0.29	0.94	0.11	0.03	-0.20	0.09
DIVIDED training	0.58**	0.10	0.25	-0.30	-0.15	0.18

** significant at p <.001

b)

		Correlation value					
		OLD			YOUNG		
Training type	Proximal measure	Road sign	Alpha-Span	CFQ	Road sign	Alpha-Span	CFQ
SINGLE training	Alphanumeric equation- AC	-0.12	0.16	0.26	-0.07	-0.32*	0.05
	Visual detection - RT	-0.31	0.02	0.42	0.11	0.43*	-0.32
DIVIDED training	Alphanumeric equation - AC	0.26	0.11	0.15	0.23	0.12	-0.12
	Visual detection -RT	-0.19	-0.23	0.46	-0.44	-0.42	-0.03

* significant at $p < .05$, ** significant at $p < .001$

For older adults, a strong significant correlation was found for the participants in VARIABLE training between change scores on VR road sign dual-task cost and proximal measure dual-task cost, $r = 0.58$, $p < .001$. This positive correlation indicates that larger dual-task cost improvement on the proximal measures was related to larger dual-task cost improvement on the VR road signs task. There were no other significant correlations (see Table III a). In particular, no correlation was found in the older adults randomized to SINGLE training between the change scores on the alphanumeric equation task or the visual detection task in focused attention and pre-post improvement on the VR Alpha span task (r = 0.16, $p = .24$) or the CFQ score (see Table III b).

For younger adults in the SINGLE-task training, there was a negative correlation between change scores on the alphanumeric equation task in focused attention and the VR dual-task change cost for Alpha span task (r = -0.32, $p = .04$). This negative correlation indicates that a larger improvement on the alphanumeric task after training is related to a larger improvement on the dual-task VR Alpha span task. We also found a positive correlation between change scores in the visual detection task and change scores on the VR dual-task Alpha span task (r = 0.43, $p = .02$), indicating that a larger improvement on RT on the visual detection task was related to a larger improvement on the VR dual-task Alpha span task. No correlations were found for the VARIABLE priority training.

DISCUSSION

Younger and older adults received one of two versions of a computerized attentional training program (VARIABLE priority; SINGLE-task) to examine the effect of age and training type on proximal training effects. We also used an immersive dual-task scenario in VR to measure transfer of training in a real life related context. When measuring the effect on proximal measures, we found that the attentional control abilities of older adults benefited more from training which involved divided attention with allocation variation (VARIABLE) than from a training which involved repeated practice of the individual tasks (SINGLE-task). We also found evidence of a better transfer on the VR dual-task for older adults trained in the VARIABLE priority than for those trained in SINGLE-task. Younger adults benefited equally from the two training types when measured with proximal measures of divided attention, but it did not improve their overall dual-task cost and did not improve their attentional control ability. A parallel effect was found in the transfer task, as the two training types only improved Alpha span dual-task cost in younger adults. All participants in the SINGLE-task training condition improved their ability to carry out the tasks in the condition of focused attention. Finally, no transfer effects were found on the self-reported measure for either training type or age.

Pattern of attentional control abilities in younger and older adults at baseline

Using attentional control training in older adults makes sense, as they experience increasing difficulties on these tasks as they age. Our results, which compare older to younger adults at baseline, confirm that older adults are impaired in their ability to flexibly vary attentional allocation when compared to younger adults. At baseline, younger adults were better able to modify allocation priority as a function of task instructions, reducing their dual-task cost properly on the task to be prioritized. In contrast, older adults prioritized the alphanumeric equation over the detection task regardless of emphasis instructions and their dual-task cost did not vary as a function of the task that was to be prioritized. This finding is consistent with substantial data suggesting that older adults are at a disadvantage when required to redeploy attention rapidly and strategically among several tasks performed concurrently (Aase, Fink, Lee, Kelley, & Pliskin, 2014; Bier et al., 2014; Hawkins, Kramer, & Capaldi, 1992; Kramer et al., 1995; Joan M McDowd & Oseas-Kreger, 1991; Joan M. McDowd & Shaw, 2000; Salthouse, Rogan, & Prill, 1984). One interesting feature of the paradigm used here is that the alphanumeric equation task is particularly salient and attracts more attention than the detection task prior to training. As a result, participants generally show a lower dual-task cost on the alphanumeric equation task than on visual detection, regardless of the emphasis instruction. This feature poses a particular challenge when participants are asked to emphasize the visual detection task (20% Equation). It also makes the paradigm particularly sensitive to attentional control deficit (Bier et al., 2014). Interestingly, while the same pattern (higher global dual-task cost on the visual detection task) was also found in younger adults as in older ones, it did not compromise the younger adults' ability to vary their attentional allocation according to task instructions.

Different computerized attentional training types resulted in specific training effects

Given the attentional control impairment found in older adults, attentional training has the potential to provide significant benefits. Here, VARIABLE-priority training improved older adults' ability to modify allocation priority as a function of task instructions. Following training, they considerably lowered their dual-task cost on the visual detection task when the instructions required that this task be emphasized, and they showed the opposite effect when the alphanumeric equation needed to be emphasized. In contrast, SINGLE-task training did not improve older adults' dual-task cost and their ability to modify attentional allocation. Notably, SINGLE-task training was not entirely ineffective. Older adults who received this training improved their accuracy and speed to complete the alphanumeric equation task when performed in focused attention. This confirms that cognitive training programs are specific: they improve the cognitive abilities that they target and yield *content transfer*, that is, transfer to untrained abilities. Furthermore, it indicates that being better on individual tasks doesn't necessarily mean that you will be better able to combine those tasks and to control your attention among them. Rather, this requires specific dual-task coordination training, as was provided by the variable-priority training condition (Anguera et al., 2013; Bier et al., 2014). Note that the training results found here in older adults are in line with what is reported in a few prior studies (Bier et al., 2014; Gagnon & Belleville, 2012; Kramer et al., 1995; Lee et al., 2012; Voss et al., 2012), showing benefits of a variable-priority training in reducing dual-task cost in healthy older adults (Bier et al., 2014; Kramer et al., 1995; Lussier et al., 2016) and improving the ability to control attention in response to external demands (Bier et al., 2014; Gopher, 2007; Gopher, Weil, & Siegel, 1989; Zendel et al., 2016).

Contrary to what was found in older adults, the two training types produced similar effects in younger adults. They both reduced the dual-task cost advantage of the more salient task (alphanumeric equation), which resulted in a dual-task cost increase on alphanumeric equation and a dual-task cost decrease on visual detection. Overall, there was no gain on divided attention or on attentional control. Comparing the data from older and younger adults suggests that the former might benefit more from variable priority training than the latter, to improve their dual-tasking and attentional control capacities. Interestingly, Kramer et al., (1995) also observed a larger benefit from variable priority training in older than in younger adults. A possible explanation is that older adults have more difficulties controlling their attention to begin with, which leaves more room for improvement. One could also argue that younger adults did exert better control of their attention following training, as they reduced their initial bias toward the alphanumeric equation. However, they clearly did not do it in a way that adressed the instructions, which might therefore indicate less compliance. Be this as it may, the fact that the magnitude of the training effect is similar if not larger in older adults compared to younger adults supports the notion that cognitive plasticity for attentional control is preserved in late adulthood and that older adults were provided with the appropriate training. These findings are of major importance since they show that training effects can differ depending on the population to which they are provided.

Impact of interindividual differences on training effects

The findings reported here are based on group effects. It is possible that interindividual differences determine differences in training efficacy. For instance, a few studies showed that individuals that start with a lower level of performance experience greater training gains than those with a higher level (Jaeggi et al., 2011; Zinke et al., 2012; 2014). It is therefore possible that persons with lower baseline abilities, older age or lower education, would respond better to the type of training used here. This interpretation is supported by the INTERACTIVE model, which suggests that training-induced changes might depend on an interaction between training modalites (i.e, format, target, training sequence) and the participant's individual characteristics (Belleville et al., 2014). Thus, one important question is to identify who will benefit most from a cognitive intervention and whether factors such as baseline cognitive strengths and weaknesses, cerebral characteristics or personality differences, modulate a participant's response to cognitive training (Erickson et al., 2010; Jaeggi et al., 2013; Strobach & Karbach, 2016).

It is also important to adress whether these interventions could be used with clinical populations. Importantly, Gagnon & Belleville (2012) found improvements from variable priority training on attentional control capacities and transfer to other executive tasks in amnestic MCI individuals who showed executive deficits at baseline. This result suggests that mildly impaired populations can benefit from this type of training and that the presence of executive deficits does not preclude a positive effect to occur. This could have tremendous implications, as the presence of executive impairment was associated with increased difficulties in daily life and was suggested to exacerbate functional impairment. Thus, providing training that targets these difficulties might have a positive impact on functional autonomy. Targeting attentional control abilities could also benefit other clinical populations characterized by attentional or executive deficits, such as younger or older adults with a traumatic brain injury (TBI) or post-stroke populations. Cognitive interventions have been widely used in these populations, but results suggest poor generalization of training effect to broader outcomes (Barker-Collo et al., 2009; Fetta, Starkweather & Gill, 2017; Palmese & Raskin, 2000; Park, Proulx & Towers, 1999; Sohlberg, McLaughlin, Pavese, Heidrich & Posner, 2000). Future research could assess whether the benefits of VARIABLE priority training can be found in these clinical populations and whether it favors transfer effects.

Transfer of training is modulated by training format and age

One major goal was to contribute to our knowledge on training transfer and particularly, to determine whether the benefits of training could generalize to a novel complex VR scenario, the *Virtual car ride* in contrast to a self-reported questionnaire and whether training type (SINGLE-task vs. VARIABLE-priority) and age had an impact on the magnitude of the transfer.

As expected, we found larger generalization of training gains on the dual-task cost experienced in the *Virtual car ride* for the older adults trained in VARIABLE-priority compared to the ones trained in SINGLE-task training. Indeed, participants trained in the VARIABLE-priority training showed a significant dual-task cost reduction from pre- to post-training on the two tasks performed in VR (road sign detection; Alpha span task), whereas this was not found in older adults enrolled in the SINGLE-task training. Furthermore, training gain on the VR dual-task cost was correlated with training gain on the proximal dual-task outcome, which confirms that it reflects actual transfer, whereas this was not the case for SINGLE-task training. Note that performance on the Alpha span task was improved in the SINGLE-task training. However, there is reason to believe that this is due to practice effects and to the fact that this task involves alphabet search, which was highly practiced in the alphanumeric equation. First, participants trained in the SINGLE-task condition improved their performance on alphanumeric equation in focused attention, which indicates that practice improved their ability for alphabetical search. Second, correlations were found in younger adults between the improvement on alphanumeric equation in focused attention and the VR Alpha-span dual-task cost reduction. Third, we did not find any correlation between improvements on proximal dual-task cost training reduction and VR Alpha-span dual-task cost reduction in the SINGLE-task training group. Fourth, younger adults, who did not improve their attentional control abilities, also showed a small non-significant improvement on the VR Alpha span task. These suggest that the improvement on Alpha span may be due to changes in a process different from the one that underlies attentional control, possibly better alphabetic search ability and better knowledge of the alphabetical order.

Overall, we found more evidence of *context transfer* than *content transfer*. *Content transfer* refers to transfer on cognitive abilities or tasks that are not trained (experimental or cognitive tasks) whereas *context transfer* refers to transfer of a learned skill or strategy in a new context (at home or in a more complex environment). VARIABLE-priority training led to transfer effects on dual-tasking abilities measured in VR. Thus, it transferred to an attentional control scenario performed in a virtually different context, a virtual car ride, but which involves the same cognitive processes as those trained. These results are in line with Gopher, Weil & Baraket (1994) and Hart & Battiste (1992) who found that benefits from variable priority training in younger adults generalized to a new complex and high demanding real-life related situations (flight performance). It is of note that contrary to these studies, transfer on the VR dual-task was not found in younger adults but only in healthy older adults. However, this is consistent with the data on proximal measures, as this is the group of older adults that showed improvement on proximal measures of attentional control. One could argue that SINGLE-task training also produced some *context transfer* since performance improved in the focused attention condition of the VR road sign detection task. SINGLE-task training shows little evidence for *content transfer*, in that it does not lead to better attentional control abilities, as proximal measures are concerned.

These findings are highly relevant to the field of cognitive aging, as evidence that attentional training could lead to *context transfer* in healthy older adults was lacking. Some studies reported *content transfer* in healthy older adults following VARIABLE-priority training (Kramer et al., 1995; Kramer et al., 1999; Lussier et al., 2016), where improvement was transfered to a task that was modified with respect to modality, response or material. However, the innovative feature of the present study was to use a transfer task that is more related to a real life setting and might therefore be used as a proxy for *context transfer*. Furthermore, this study examined the effect of age on transfer effects. Results of the present study suggest non-equivalent age generalizable gains as the magnitude of transfer was larger for older adults compared to their younger counterparts. This is quite an interesting finding, especially in light of the often reported observation of reduced training benefits for older adults (Zinke et al., 2014; Brehmer et al., 2012; Schmiedek et al., 2010). These results bring further support to the notion that cognitive plasticity is preserved in advanced age and that transfer to more complex tasks is possible in later adulthood.

Measuring transfer of training with virtual reality

One of the major contributions of the present study was to use transfer tasks that reflect real life situation, as most studies carried out with older adults measured transfer with self-reported questionnaires or tasks that lack in ecological validity. To our knowledge, this is the first study to use VR as a tool to evaluate transfer of training in an older population. We were able to measure transfer effects in the *Virtual car ride,* an immersive dual-task scenario designed to mimic the complexity of a real life situation. We also showed that these effects were not captured by the self-reported questionnaire, as no difference was found on the total score from pre- to post-training.

The present results are encouraging, as evidence of transfer to novel dual-task situations in more complex environments is scarce, particularly in older adults. Furthermore, VR may be an alternative tool to appraise cognitive performance, as traditional tasks are shown to have a limited predictive value for everyday performance (Chaytor & Schmitter-Edgecombe, 2003). In addition, transfer effects obtained on experimental tasks that only differ in terms of stimuli or response modality may be more difficult to generalize to a context from daily life. VR tasks were also shown to be more motivating for participants compared to traditional laboratory tasks, because of their engaging aspects (Corriveau-Lecavalier et al., submitted). Motivation is thus a crucial factor that could not only impact cognitive performance (Leeb et al., 2007), but also limit withdrawals from training research programs.

Limitations

It is important to recognize some of the limitations of this study. First, the number of participants per training group was small. Although our sample size proved to be sufficient to find a robust training effect, it might have been possible to detect more subtle differences with larger groups. Second, the level of difficulty of the tasks on proximal outcome and transfer measures was not adjusted, which might have reduced our ability to observe training gains and transfer effects in younger adults. Third, we did not include a fixed prority divided attention training condition. Thus, it is unclear whether such a training condition would have improved dual-task performance in the *Virtual car ride*. Even if the *Virtual car ride* was constructed to be more reprensentative of a real-life context and hence more ecologically valid than typical transfer measures, it is still an experimental task, as it is performed in a laboratory and in a controlled and standardized environment. Finally, cybersickness is a concern when using VR and it could limit its broad application, particularly with older adults, as they might be vulnerable to theses symptoms. Of note, our participants did not experience many of these symptoms. This might have been due to the short duration of the task and to the fact that they were seated during the tasks and few head movements were required, which could have helped reduce symptoms.

Conclusion and future research

In conclusion, we showed that divided attention VARIABLE-priority training improves older adults' attentional control capacities and dual-task performance and that the benefits are specific, in that the repeated practice of an individual task (SINGLE-task) improves neither dual-tasking nor attentional control. Older adults were impaired relative to younger ones prior to training and hence, the positive effect of VARIABLE-priority training was present only in the former. This indicates that attention remains plastic in old age and that programs meant to improve attentional control might be more beneficial to older and/or more challenged individuals. Importantly, the training effect found in this study transferred to a virtual reality task that reflects the complexity of the processes involved in attentional tasks of everyday living, which suggests that training can produce *context transfer* and that transfer may remain possible throughout the lifespan. Little is known about the extent and limits of transfer effects following cognitive training and measuring transfer is challenging, as we have very few tools that can provide objective measures of performance in complex activities of daily life. The present study innovates by measuring transfer effects using an immersive dual-task paradigm in VR and demonstrates its potential as a sensitive measure of *context transfer* for training in older adults. With the growing accessibility of VR devices in terms of cost and portability (wireless and smaller headset), the technique may represent an interesting avenue as a transfer measure, but also as a tool for training (Shuchat, Ouellet, Moffat & Belleville, 2012). Finally, more attention should be given to training components that enhance transfer.

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Chapitre V

Article 4: *The pattern and loci of training-induced brain changes in healthy older adults are predicted by the nature of the intervention*

Article 4: The pattern and loci of training-induced brain changes in healthy older adults are predicted by the nature of the intervention

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Abstract

There is enormous interest in designing training methods for reducing cognitive decline in healthy older adults. Because it is impaired with aging, multitasking has often been targeted and has been shown to be malleable with appropriate training. Investigating the effects of cognitive training on functional brain activation might provide critical indication regarding the mechanisms that underlie those positive effects, as well as provide models for selecting appropriate training methods. The few studies that have looked at brain correlates of cognitive training indicate a variable pattern and location of brain changes - a result that might relate to differences in training formats. The goal of this study was to measure the neural substrates as a function of whether divided attentional training programs induced the use of alternative processes or whether it relied on repeated practice. Forty-eight older adults were randomly allocated to one of three training conditions. In the SINGLE REPEATED training, participants practiced an alphanumeric equation and a visual detection task, each under focused attention. In the DIVIDED FIXED training, participants practiced combining verification and detection by divided attention, with equal attention allocated to both tasks. In the DIVIDED VARIABLE training, participants completed the task by divided attention, but were taught to vary the attentional priority allocated to each task. Brain activation was measured with fMRI pre- and post-training while completing each task individually and the two tasks combined. The three training conditions resulted in markedly different brain changes. Practice on individual tasks in the SINGLE REPEATED training resulted in reduced brain activation whereas DIVIDED VARIABLE training resulted in a larger recruitment of the right superior and middle frontal gyrus, a region that has been involved in multitasking. The type of training is a critical factor in determining the pattern of brain activation.

Introduction

Brain plasticity refers to the remarkable ability that cognitive systems have to modify their structure and functions in response to external or internal stimulation. There is ample evidence indicating that active processes of brain plasticity take place during early development, and following learning and sensory deprivation [1,2]. Recently, there has been accumulating indications suggesting that brain plasticity is a lifelong phenomenon and that it also occurs in older age and throughout the course of age-related neurodegenerative disorders [3,4,5,6,7]. Recent studies have revealed that cognitive training can be a powerful means of directing behaviorally relevant reorganization in the adult brain, and brain imaging has been key in revealing processes of brain plasticity and compensation in older adults [8,9]. Results of fMRI can reveal the patterns of brain changes that occur following training and can be used to indicate whether those programs increase the efficiency of specialized regions or whether they promote compensation through increased use of alternative processes. Furthermore, training-induced plasticity in older adults can be used as a model of brain reorganization and compensation in aging and provides information regarding the role of environmental stimulation on brain function over the lifespan.

However, important questions remain to be elucidated regarding the way cognitive training exerts its effect on brain changes, as different studies have revealed very different patterns of brain activation following cognitive training. One important question in our view is whether different training formats yield different patterns of activation. This is a critical component to better understand the effect of environmental stimulation and cognitive training on the brain. Training formats differ widely in terms of the cognitive component that they target (e.g., memory or attention) and in terms of the types of mechanisms that they engage or intend to impact upon (e.g., repeated practice to increase efficiency or learning new strategies to compensate via alternative pathways). Better understanding the type of brain changes induced by different training programs could help clinicians in selecting appropriate programs. For instance, clinicians may strategically select a program that improves a dysfunctional region (restoration), or one that allows the brain to support the impaired function by relying on unimpaired regions (compensation). Use of these strategies requires knowing which intervention has restorative effects and which has compensatory effects on the brain.

Understanding training-related brain changes is also relevant to theories of age-related compensation and plasticity. Older adults do not live in a vacuum, and they are constantly stimulated in their natural environment. Thus, a better understanding of the ways by which training shapes brain function might contribute to models of neural changes associated with environmental stimulation. In turn, theories of age-related compensation can guide predictions regarding the patterns of brain activation in older adults that should occur following training. Three of these models are particularly relevant here. The HAROLD model [3] suggests that the brains of healthy older adults compensate for the effect of aging by recruiting regions contralateral and homologous to the one typically involved in the task. The compensation-related utilization of neural circuits hypothesis (CRUNCH; [10]) also proposes that compensation is supported by increased activation in specialized brain regions, but that it can also occur by activating new, alternative regions. This would reflect strategic differences or a shift in the processes by which the task is completed. Both models predict that training should yield greater activation in regions not engaged by the task prior to training, and according to the HAROLD model, most likely, the contralateral homologue of the regions normally involved in the task. In contrast, the dedifferentiation model proposes that aging reduces the capacity to recruit specialized regions [11]. In this case, training should reduce rather than increase task-related brain activation (see Erickson et al. [12] for results in line with this prediction). Importantly, as none of these are training models, they do not address the effect that training formats can have on the patterns of compensation-related brain changes.

A few models have more specifically addressed the effects of cognitive training on the older adult brain and have included training format as an important factor to consider. Lovden and colleagues [13] proposed a theoretical framework to explain both age-related activation changes and training-induced brain changes in older adults. The model distinguishes different dimensions of the training format, one that modifies processing efficiency, and one that modifies the knowledge base or strategy registry. According to this framework, different types of training should have different effects on patterns of brain changes and on the extent and type of transfer expected to occur. Our own model, INTERACTIVE, suggests that training-induced activation changes depend on a number of interacting factors, including the format and characteristics of the training. It proposes that patterns of activation change are coherent with the underlying cognitive processes that could be modified by different types of training. For instance, the simple practice of a task should result in decreased activation within the brain regions involved in that task, due to more efficient processing in specialized regions. However, interventions involving teaching new strategies should result in increased activation of the alternative brain networks involved in learning those new strategies.

An analysis of the literature on training-induced brain changes in younger and older adults suggests that the training format is indeed a critical factor to explain differences in the patterns of brain changes. ***Decreased activation*** has been found in studies where younger adults repeated the task with no particular instruction or manipulation by the therapists or strong input-to-output mapping concordance (for a review see Chein & Schneider [14]). Similar findings were found in older adults when attention and working memory were trained with repeated practice and adaptive training [15]. The decreased activation was interpreted as resulting from a more efficient processing of the practiced task or a reduced reliance on controlled processing to accomplish the task. ***Increased activation or activation in new regions*** has also been reported in younger and older adults, and this has been suggested to reflect a change in the process used to complete the task - consistent with some of the predictions made by the CRUNCH model (Kelly, Foxe, & Garavan [16]). In older adults, the teaching of strategies or metacognitive training produced increased or new activation in brain regions that are expected to be engaged by the training; for example, the hippocampus for associative memory or the right parietal regions in the case of image-based mnemonics [17,18,19]. Intervention can also lead to a ***mixed pattern of increased and decreased*** recruitment. Braver, Paxton, Locke and Barch [20] found that following strategy training on task maintenance and updating, older adults showed a combination of increased activation in response to the cue and reduced activation in response to the probe, which was coherent with better selective attention. Erikson and collaborators [12] showed that practicing dual-task in healthy older adults reduced activation in the right ventrolateral prefrontal and dorsolateral prefrontal cortex, and increased left ventrolateral prefrontal activation. Belleville et al. [17] reported that mnemonic training in healthy older adults resulted in reduced activation during encoding; however, greater activation was found during retrieval.

Thus, studies of functional brain imaging following training in older adults found decreased activation, increased activation or a combination of increased and decreased activation. At first sight, this inconsistent pattern is troublesome, as it might suggest that functional brain imaging is not a reliable marker of brain training effects. However, these divergent results arise from a variety of different intervention modalities. The INTERACTIVE model suggests that training-induced activation changes depend on the characteristics of the training. Thus, predicting training effects requires an understanding of the mechanisms that are engaged or modified by the training program. Repeated practice appears to most often result in reduced activation, perhaps because it supports a more effective processing of the regions involved in the practiced task. In turn, training that involves teaching new strategies or that relies on metacognitive processes appears more likely to induce recruitment of new or alternative regions as proposed by the INTERACTIVE model.

Few studies have addressed the impact of training format in the interpretation of their findings, and no studies have compared activation changes as a function of the type of training. In this paper, we assess this interpretation directly and determine whether different patterns of brain activation in older adults can result from *repeated practice* or *strategic training*. The study measures the brain changes associated with three types of training, which are likely to differ in terms of mechanisms of action: (1) *repeated practice* of individual tasks in focused attention (SINGLE REPEATED), (2) *practice of divided attention* (DIVIDED FIXED), and (3) *training of strategic control of attention* (DIVIDED VARIABLE). Healthy older adults were randomized to one of the three training programs. Brain activation associated with performing individual tasks alone and both tasks combined was measured with fMRI prior to and following training. Our hypothesis is that decreased activation will be associated with repeated practice, whereas training that instantiates strategic control of attention strategies will be associated with new or increased activation in regions that are involved in controlled attention and multitasking. To our knowledge, this question has never been addressed empirically, and the training modalities have not been examined for the purpose of assessing compensation or training-induced activation changes.

Materials and Methods

1. Ethics statement

This study was approved by the Institut Universitaire de Gériatrie de Montréal Human Ethics Committee and by The Regroupement Neuroimagerie / Québec (RNQ) committee. Informed written consent was obtained from all subjects according to the Declaration of Helsinki.

2. Participants

Forty-eight healthy, community-dwelling older adults were initially recruited to participate in this study through advertisements in seniors centres and magazines for seniors. Exclusion criteria included: alcoholism or substance abuse, head trauma, cerebral infection, epilepsy, cerebrovascular diseases, neurodegenerative disorders, mild cognitive impairment, major psychiatric illness, visual or motor limitations that would prevent their use of the computer, medication that could impact cognitive and cerebral functioning, and MRI incompatibility. Participants completed the Montreal Cognitive Assessment (MoCA; [21]), the Geriatric Depression Scale (GDS; [22]) to exclude persons with mild cognitive impairment or dementia, and the Coding and Similitude subtests of the WAIS-R [23] for characterization. They received a small financial compensation for their transportation expenses.

3. Design

Subject flow is shown in Figure 1 according to the CONSORT reporting instructions [24]. Participants were randomly assigned by an independent research assistant to one of the three training conditions described below. There were two different versions of the pre- and post-session tasks, and their order was counterbalanced across participants.

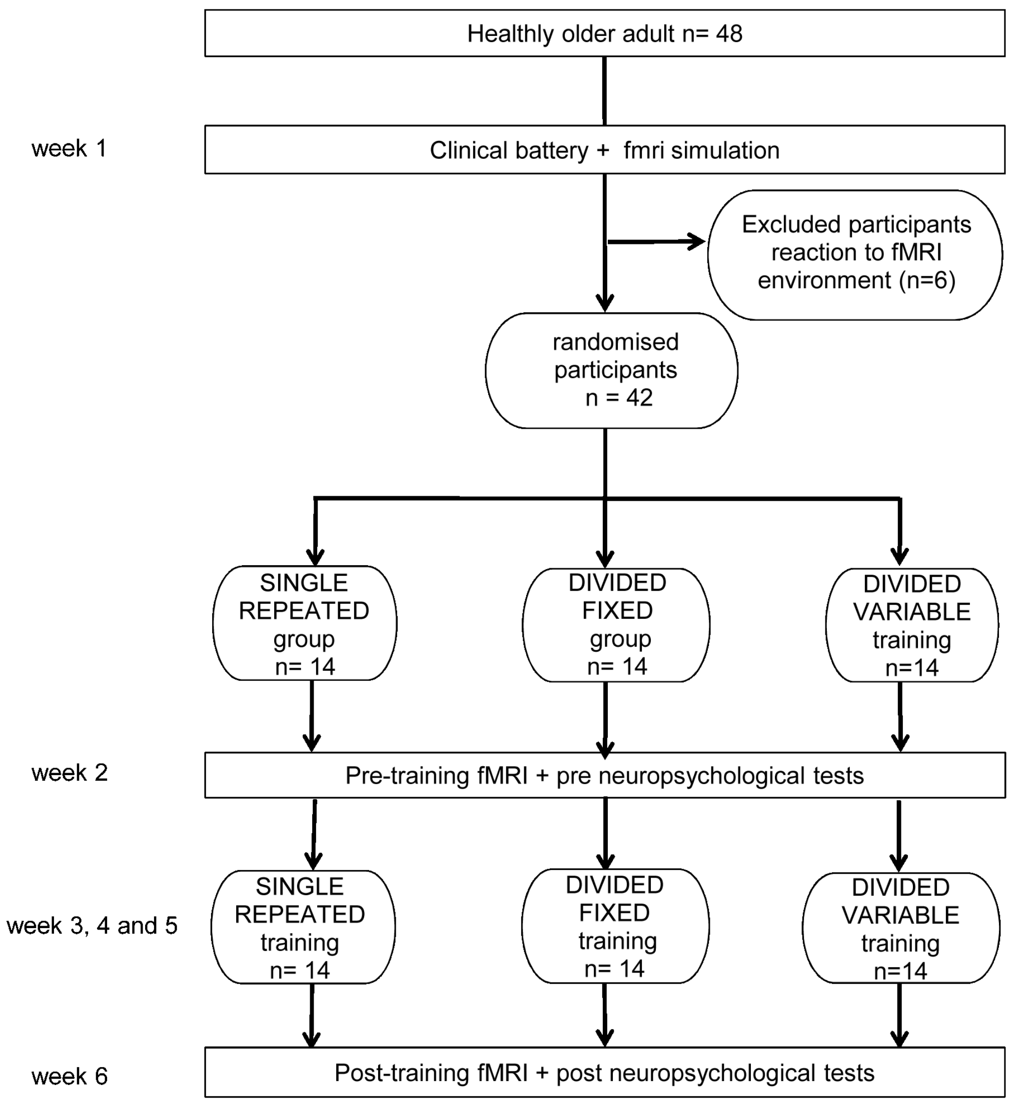

Figure 1. Flow chart according to the Consort reporting instructions.

4. Training method

Two tasks were used for the training: an alphanumeric equation task and a visual detection task. The tasks were either completed individually, in the condition of focused attention (single-tasking), or combined in the condition of divided attention (dual-tasking) (See Figure 2). Both tasks were run on Compaq Pentium d530 computers, and responses were given on the keyboard.

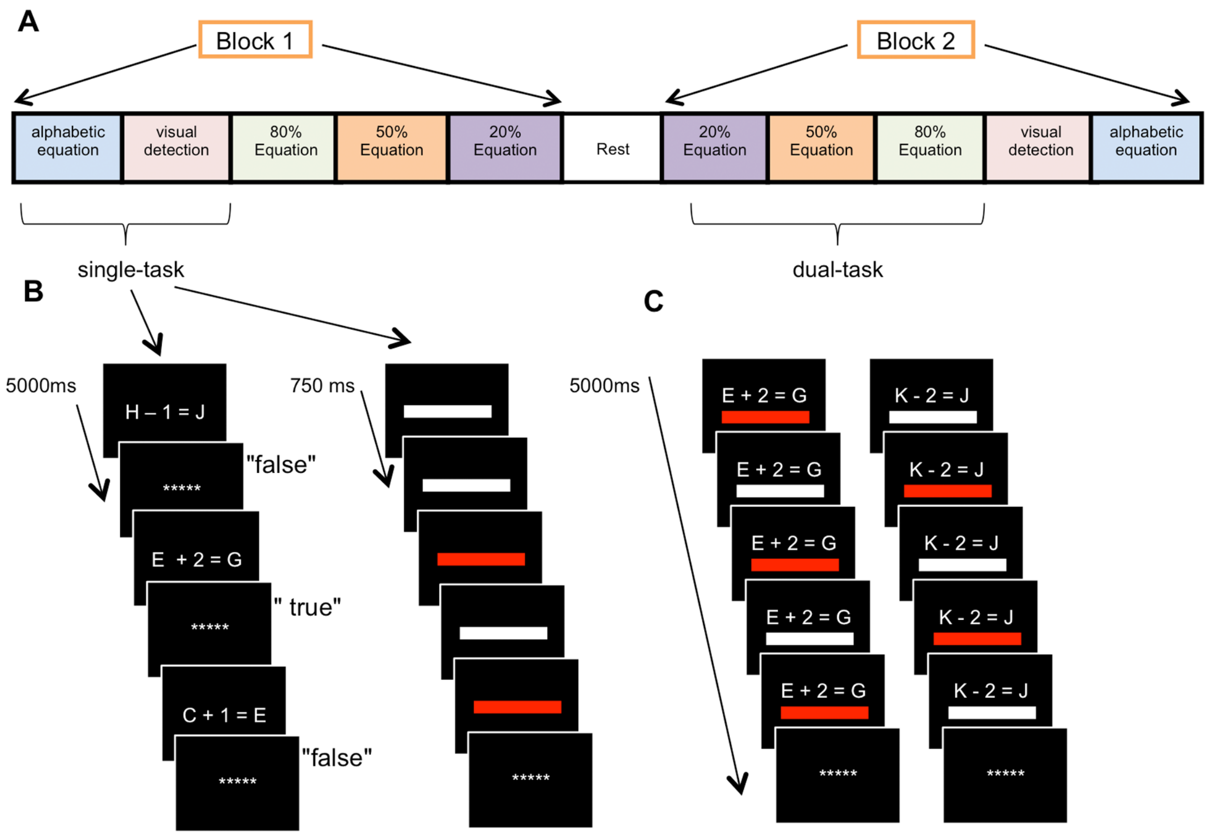

Figure 2. Experimental paradigm. Schematic representation of the task conditions order in fMRI (A), as well as the alphanumeric equation and visual detection tasks in both single-task (B) and dual-task (C).

In the **alphanumeric equation task**, participants were asked to judge the accuracy of a set of visually presented alphanumeric equations. They were addition or subtraction equations constructed by combining a letter and a number (1 or 2) in the form: *letter* +/- *number* = *letter* (e.g., P+2=R). The first letter was used as a starting point, and the number indicated the distance in terms of the number of intervening letters between the starting and end point. The sign indicated whether the end point was positioned before or after the starting point in the alphabet. In the example P+2=R, the starting point is P and R is the letter that stands two positions ahead in the alphabet. This equation is thus correct. Training equations contained only letters that were part of the second half of the alphabet (from N to Z). Half of the equations were correct. Incorrect ones were formed by selecting a letter that was 1 or 2 positions away from the correct result. Equations were presented visually in the centre of a 17" Viewsonic VE7106 Monitor, with white items over a black background. They were presented for a maximum of 3750 ms, with an interstimulus interval of 1500 ms filled with a centred fixation cross. Responses were made by pressing the “F” key with the left index finger when the equation was incorrect and the “J” key with the right index finger when the equation was correct.

In the **visual detection task**, participants were presented with series of white and red rectangles and were asked to detect the red one by pressing the space bar key with their left thumb. The rectangles were 3 inches high by 30 inches wide (1cm by 8cm) and were positioned just below the centre of the screen. They were presented for 500ms with an interstimulus interval (ISI) of 250ms. Forty percent of the rectangles were red, and they appeared in random order. In the divided attention conditions, five rectangles were presented while the equation was presented.

Training was provided in six one-hour sessions on weekdays over a period of two weeks, each separated by at least one day. Participants completed nine to 13 blocks per session depending on the training condition. The number of addition versus subtraction, one versus two steps, as well as correct versus incorrect equations were equivalent across blocks of trials. Accuracy and reaction time (RT) were recorded for both tasks. If a participant did not provide an answer within the maximum allotted time, the next equation was presented, and the trial was considered failed. To provide a baseline, all participants completed one block of each task under focused attention at the beginning and end of each session.

Participants received one of three training formats as described below.

Variable priority divided attention training ***(DIVIDED VARIABLE):*** Participants were asked to complete both tasks (alphanumeric equation and visual detection) simultaneously with divided attention. This was done under three conditions of attentional allocation: 80% Equation, 50% Equation, and 20% Equation. The 80% Equation condition required participants to allocate 80% of their attention to the alphanumeric equation task and 20% to the visual detection task (80/20), and vice-versa in the 20% Equation condition (20/80). In the 50% Equation condition, participants were asked to allocate an equal proportion of attention to both tasks (50/50). Each session comprised nine blocks of 20 trials of the dual-task (3 blocks per condition). Feedback was provided after each block. A histogram was presented to the participants, indicating their baseline level in focused attention, their performance on that trial, and the performance level that should have been attained according to the instructions. Participants were asked to draw their estimate of how they had performed, and their actual performance was then displayed with the histogram on the computer screen (see Figure 3). In this manner, participants were informed as to whether they had achieved the targeted allocation of attention, in order to better adjust their attention on the next block.

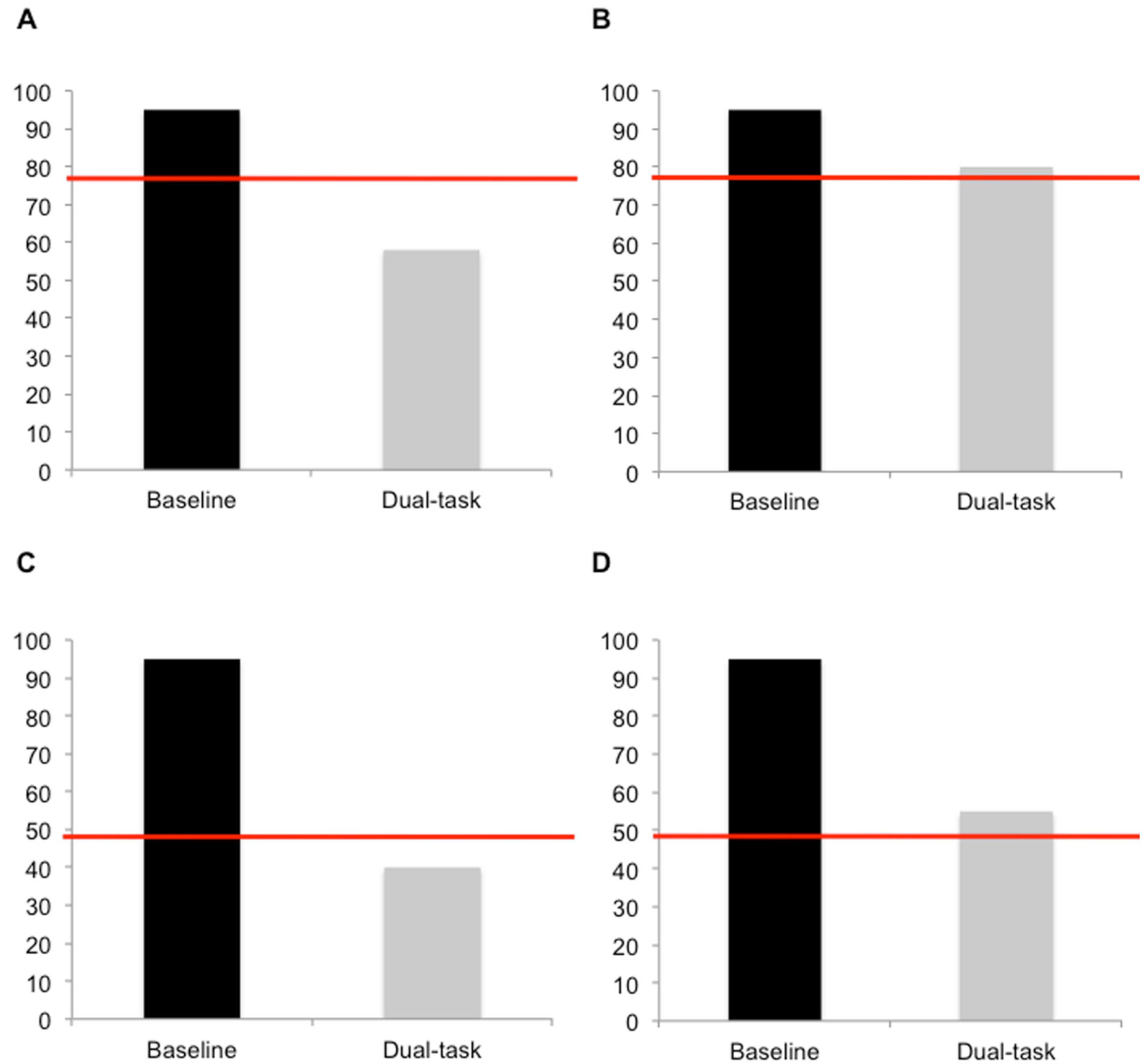

Figure 3. Feedback during variable training. Four examples of the histograms that provided visual feedback to the participants in the DIVIDED VARIABLE training group. The dark column represents the performance of alphabetical equation that was obtained under single-task baseline. The light column shows performance that was reached in the dual-task condition. The line represents the level of performance that was expected. (A; B) Examples of an 80% Equation trial where participants were asked to allocate 80% of their attention to the alphanumeric equation tasks: A) shows a trial where performance was below the expected threshold; (B) shows a trial where participants succeeded to obtain the expected level of performance. (C; D) Example of a 50% Equation trial where participants were asked to allocate 50% of their attention to the alphanumeric equation task: C) shows a trial where performance was below the expected threshold; (D) shows a trial where participants succeeded to obtain the expected level of performance.

Fixed-priority divided-attention training ***(DIVIVED FIXED)****:* In the DIVIDED FIXED condition, participants were asked to complete the two tasks simultaneously with divided attention. They were instructed to allocate an equal amount of attention to each task. There was no feedback provided. Each session comprised nine blocks of 20 trials of the task.

Repeated single task training ***(SINGLE REPEATED)****:* In the SINGLE REPEATED training condition, participants were asked to practice the alphanumeric equation task and the visual detection task individually under focused attention. Participants completed six blocks for one task and seven blocks for the other task in each session. The number of blocks was alternated across tasks, so that each task received the same amount of training overall. The order of tasks was alternated between sessions so that in a subsequent session, participants completed the opposite order. The starting task in session 1 was counterbalanced across participants. Thus, this training condition was similar to the other two training conditions except that the two tasks were not combined. Participants only received repeated practice on the individual tasks, and this was done under focused attention

5. fMRI methods

Task used in fMRI

Participants were scanned one week prior to and one week following training. The two tasks were completed separately in single-task and simultaneously in dual-task. The parameters of each task were identical to training except that the part of the alphabet used for the alphanumeric equation task was different (from A to M). The letter I was excluded so as to avoid confusion with the digit 1. The tasks were implemented using E-prime software (Psychology Software Tools, Inc.). Stimuli were presented using a projection system (Epson, EMP-8300), and they were visible to participants in a mirror attached to the head coil. Subjects' vision was corrected with goggles appropriate for MRI scanning as needed. Responses were given on fiber optic response pads (Brain Logics, BLBRS-FO-A) by pressing the appropriate button with the right index finger when the equation was incorrect, another button with the right middle finger when the equation was correct, and a third button with the right thumb when the red rectangle was shown.

Subjects performed the task in a blocked design with one run of five blocks. Each block was composed of a rest (20 sec) and the five task conditions (40 sec each): single-task alphanumeric equation, single-task visual detection, dual-task with equal division of attention (50% Equation: 50/50), dual-task with more emphasis on equation (80% equation: 80/20), and dual-task with more emphasis on detection (20% Equation: 20/80). Each task condition comprised eight trials, and the order of presentation for the different conditions was varied within subjects. The single-task versus dual-task followed an ABBA order, and the emphasis conditions an ABCCBA order. The order of presentation for each condition is shown in Figure 2. No feedback was given. The task instructions were provided prior to each block and remained on-screen for 5 sec in the rest condition and 7.5 sec in the task condition. One week prior to the pre-training scanning, participants were trained on the fMRI procedure and practiced the task in a simulator that mimicked the fMRI environment (in terms of task, body position, sound, etc.).

Scanning parameters

Participants were scanned on a Siemens TIM Trio 3 T magnetic resonance imaging (MRI) system (Siemens Medical Solutions, Erlangen, Germany), using the Siemens 12-channel receive-only head coil at L'Unité de Neuroimagerie Fonctionnelle (UNF) du Centre de recherche de l'Institut universitaire de gériatrie de (http://www.unfmontreal.ca/siteweb/Home_en.html). Blood oxygenation level-dependent (BOLD) signal was acquired using a standard T2*-weighted gradient-echo EPI sequence (TR: 2500, TE: 30 ms, flip angle 90°, FOV 192 x 192 mm^2 , 38 slices, voxel size 3 x 3 x 3 mm^3 with a gap of 0.6 mm-distance factor [20%], matrix size 64 x 64). Acquisition was in axial orientation co-planar with AC-PC, whole brain coverage. Order of acquisition was ascending. The functional images were acquired in one run, and the first three volumes were automatically discarded by the fMRI scanner. A structural image was acquired after the functional run using a high-resolution T1-weighted MPRAGE sequence (TR/TE 2300/2.98 ms, flip angle 9°, FOV: 256 mm 176 slices, voxel size 1 mm^3 , matrix size 256x 256).

Image processing and analysis

Data were analyzed in MATLAB 7.1.2 (http://www.mathworks.com), using the statistical parametric mapping (SPM8) software (http://www.fil.ion.ucl.ac.uk/spm). The preprocessing consisted of the following steps: 1) motion correction, the temporal processed volumes of each subject were realigned to mean volume to remove the head motion, a mean realigned volume was created for each session, and the participants with more than 3 mm of translation in x, y, or z axis and 1° of rotation in each axis for one of the two sessions were removed; 2) slice-timing correction, the differences of each individual's slice acquisition times were corrected by slice timing to the middle volume, using SPM8 Fourier-phase shift interpolation; 3) co-registration of each subject's functional and anatomical data; 4) spatial normalization, the realigned volumes were spatially standardized into the Montreal Neurological Institute (MNI) space by normalizing with the EPI template via their corresponding mean image, and all the normalized images were resliced by 3 mm^3 voxels; 5) smoothing, the normalized images were smoothed with a Gaussian kernel of 9 mm full width at half-maximum (FWHM). The two sessions (pre and post) were pre-processed separately.

The first level of statistical analysis carried out for each smoothed individual image was fixed effects analysis based on the general linear model (GLM) with a box-car response (HRF). GLM analysis was performed using regressors, generated by convolving the time course of the condition onsets and duration with canonical hemodynamic response function (HRF). There were six experimental conditions: rest (cross-fixation), single-task alphanumeric equation, single-task visual detection, dual-task 80%Equation (80/20), dual-task 50% Equation (50/50) and dual-task 20% Equation (20/80). The instruction before each condition was also modeled as a condition of no interest. Movement parameters estimated during realignment (translations in *x*, *y* and *z* directions, and rotations around *x*-, *y*- and *z*-axes) and a constant were also included in the matrix scanning run as variables of no interest. High-pass filter was implemented using a cut-off period of 256 s to remove the low-frequency drifts from the time series. Serial correlations in the functional MRI signal were estimated using an autoregressive (order 1) plus white noise model and a restricted maximum likelihood (ReML) algorithm. After estimating the parameters of the model, eight linear contrasts were calculated for each participant.Cerebral activation during single-tasking was calculated with the contrast *(single-task alphanumeric equation > rest; single-task visual detection > rest)*. Activation during dual-tasking was measured by separately calculating for each dual-task condition (80% Equation; 50% Equation; 20% Equation) with a simple contrast (dual-task > rest) and an interaction contrast: *(dual-task > single-task alphanumeric equation) - (single-task visual detection > rest).* This interaction contrast was used because it was shown to be the most appropriate method for comparing activity in the dual-task to that of the single-task [25,26]. It allows for isolating the activation associated with dual-task, because it subtracts the activation associated with both tasks when performed individually.

The subject-specific contrast images were then further spatially smoothed (Gaussian kernel 6 mm full-width at half-maximum) and entered into a second-level random-effects analysis. First, activation associated with attention and attentional control was measured by pooling and analyzing the data from all participants during pre-training. One-sample *t*-tests were performed to measure the activation associated with dual-tasking in the different attention conditions, and paired t-tests were performed between dual-task 80% Equation (80/20) and dual-task 20% Equation (20/80) conditions to obtain effects of attentional control. We used paired t-tests to analyze the effects of training on activation under single-tasking comparing the contrasts *single-task alphanumeric equation > rest* and *single-task visual detection > rest* from pre- and post-sessions for each training group. To analyze the effects of training on activation during dual-tasking, we compared the contrast, *(dual-task > single-task alphanumeric equation) - (single-task visual detection task > rest),* obtained in pre- and post-training of each condition *(80% Equation (80/20), 50% Equation (50/50) and 20% Equation (20/80)) and* for each training group. The resulting set of voxel values for each contrast constituted a map of the *t*-statistic [SPM(T)] that was thresholded at an uncorrected $P < 0.001$ with 10 contiguous voxels. Again, this was done to isolate the changes in activation associated with the target conditions, relative to the changes in the baseline or single-task conditions.

Correlational analyses were used to assess whether the brain activation that occurred after training scans was associated with better performance on the behavioural tasks. The average beta values of the regions of interest (ROI) were extracted with MarsBaR [27] for each participant. The ROI is functionally defined as it corresponds to the regions that showed intervention effects in each condition. Performance on the critical dependent variables (RT on alphanumeric equation in single-tasking and dual-tasking cost) was then correlated with activation in brain regions found to be modified by the intervention. Pearson's correlations were performed using SPSS 19.0 (http://www.spss.com).

Results

1. Clinical and cognitive results

Eight participants were excluded from the analyses; six experienced adverse reactions in the simulator and refused to continue with the fMRI examination, and two were excluded because of excessive head motion during the scan. The clinical and cognitive characteristics of the remaining 40 participants are shown in Table I as a function of the training condition to which they were assigned. As shown in Table I, the three groups were comparable in terms of demographic and clinical characteristics.

Table I. Mean age, mean education, and mean score on clinical measures

	SINGLE REPEATED Training n= 12	DIVIDED FIXED training n= 14	DIVIDED VARIABLE training n=14	T value	P
Age	68.58 (8.16)	69.57 (5.81)	68.79 (5.13)	0.51	0.60
Education	14.17 (2.76)	15.21 (2.49)	16.00 (3.70)	1.32	0.28
Moca	28.25 (1.71)	27.43 (1.60)	27.29 (2.40)	0.58	0.57
GDS	1.63 (2.18)	1.43 (1.28)	2.21 (3.33)	0.87	0.43
Similarities WAIS-III subtest	12.25 (1.42)	12.14 (1.83)	12.36 (1.74)	0.06	0.94
Digit Symbol-Coding WAIS-III subtest	13.36 (1.36)	11.93 (1.59)	11.86 (1.99)	2.99	0.06

Standard deviations in parentheses

Table II presents behavioral performances in single-task alphanumeric equation and dual-task cost score (see below for computation of dual-task score), prior to and after training[1].

The training effect on performance when each task was completed under single-tasking was tested separately for each task (alphanumeric equation; visual detection) with Training condition (SINGLE REPEATED, DIVIDED FIXED, DIVIDED VARIABLE) x Time (Pre, Post) ANOVAs using Reaction time (RT) and Accuracy (AC) as dependent variables. The analysis showed a main effect of Time for the alphanumeric equation task on both RT, $F(1, 34)=9.75$, $p < .001$ ($\eta^2 = 0.22$),, 95% CI [63.99, 299.75] and AC, $F(1, 34) = 14.8$ ($\eta^2 = 0.30$), $p < .001$, 95% CI [5.40, 17.52]. As shown in Table II, all groups improved their alphanumeric performance when it was completed in single-task. No effect was found on the visual detection task.

Table II. Performance in single-task alphabetic equation (reaction time and accuracy) and dual-task cost in pre- and post-sessions for each training group

	Single-task performance				Dual-task cost[+]	
	Reaction time		Accuracy			
	Pre	Post	Pre	Post	Pre	Post
REPEATED training	2383 (121)	2307 (127)**	84.1 (3.1)	86.8 (3.1)**	0.45 (.04)	0.38 (.06)
Divided FIXED training	2315 (105)	2146 (84)**	75.2 (4.6)	90.0 (3.6)**	0.53 (.05)	0.40 (.02)**
Divided VARIABLE training	2466 (73)	2154 (100)**	77.3 (5.5)	89.8 (2.0)**	0.45 (.05)	0.39 (.04)*

[+] Pooled across conditions
*Task x Condition x Time Interaction, $p < 0.05$
**Main Time effect, $p < 0.01$
Standard deviations in parentheses

[1] As this paper focuses on brain activation, only summary analyses of behavioural data are presented here (see Bier et al. 2014, for more details).

To analyze the training effect on dual-tasking, a dual-task cost score was computed by combining the reaction time (RT) and accuracy (AC) for each task in the dual-task condition (DIVIDED) relative to the performance in single-tasking (SINGLE), with the following equation: {[(RT DIVIDED – RT SINGLE) / RT SINGLE] + [(AC SINGLE – AC DIVIDED) / AC SINGLE]}. In the equation, RT single and AC single represent performance in single-tasking for reaction time and accuracy. RT divided and AC divided represent performance in the dual-task conditions (80% Equation, 50% Equation or 20% Equation) for reaction time and accuracy.

This dual-task cost represents the proportional loss of performance in the dual-task condition as a function of performance in the single-task condition. A larger score represents a larger divided attention cost. A cost is determined separately for each task (i.e., alphanumeric equations vs. visual detection). This allows for examining the effect of attentional emphasis since the dual-task score should vary as a function of the way in which each task is prioritized. For instance, the dual-task score for the alphanumeric equations task should be lower when participants are instructed to emphasize the equations over the visual detection task (80% Equation) than when instructed to emphasize the visual detection over the equations task (20% Equation). Dual-task cost was used as a dependent variable in a repeated measure ANOVA with Time (pre, post), Priority instruction (80% Equation, 50% Equation and 20% Equation), and Task (alphanumeric equation; visual detection) as within-subject factors, and Training (SINGLE REPEATED, DIVIDED FIXED, DIVIDED VARIABLE) as a between-subject factor. The analysis revealed a four-way interaction, $F(1, 34)=3.26$, $p < .01$ ($\eta^2 = 0.16$). To interpret the interaction, Time x Priority instruction x Task ANOVAs were done separately for each training condition. The SINGLE REPEATED training condition resulted in no improvement with dual-tasking (no main effect of time or Time x Priority instruction x Task interaction ($\eta^2 = 0.00$); p = .32 & ; p =.81, respectively). The DIVIDED FIXED group showed a reduced overall dual-task cost from pre- to post training (main time effect, $F(1, 34) = 6.97$, $p < .001$ $\eta^2 = 0.45$, 95% CI [0.04, 0.23]. Importantly, no Time x Priority instruction x Task ($\eta^2 = 0.027$) was obtained indicating that participants did not improve their ability to vary their level of attention after training (p = .35). The DIVIDED VARIABLE condition group showed a Time x Priority instruction x Task interaction, $F(2, 33) = 5.17$, $p < .001$ $\eta^2 = 0.34$. After training, participants in that group showed a lower cost on the alphanumeric equation task when instructions required that the task was to be emphasized (80% Equation), and they showed a lower cost on the visual detection task when it was that task that was asked to be emphasized (20% Equation) (main effect of Priority instruction, $F(2, 33) = 8.83$, $p < .001$ $\eta^2 = 0.20$), 95% CI [-0.31, -0.08]. This was not found prior to training. This indicates that after training participants in that group were able to modify their attentional priority in dual-tasking as a function of task instruction.

2. Brain activation related to attention (pre-training)

To determine whether training resulted in the activation of new brain areas or areas that were already activated prior to training, we first used the pre-training data from the entire group of participants to identify the areas of activation associated with dual-task (Figure 4 and Table III). As shown in Figure 4 and Table III, a network of prefrontal activation was recruited in the dual-task condition. The network was more active as persons moved their attentional priority from more attention on alphanumeric equations (80% Equation) to more attention on visual detection (20% Equation). Thus, activation related to *modulation of attention* was obtained by subtracting dual-task in the 80% Equation condition (80/20) from activation in the dual-task

20% Equation condition (20/80). Of note is the fact that the dual-task 50% Equation condition (50/50) showed an intermediate pattern of activation.

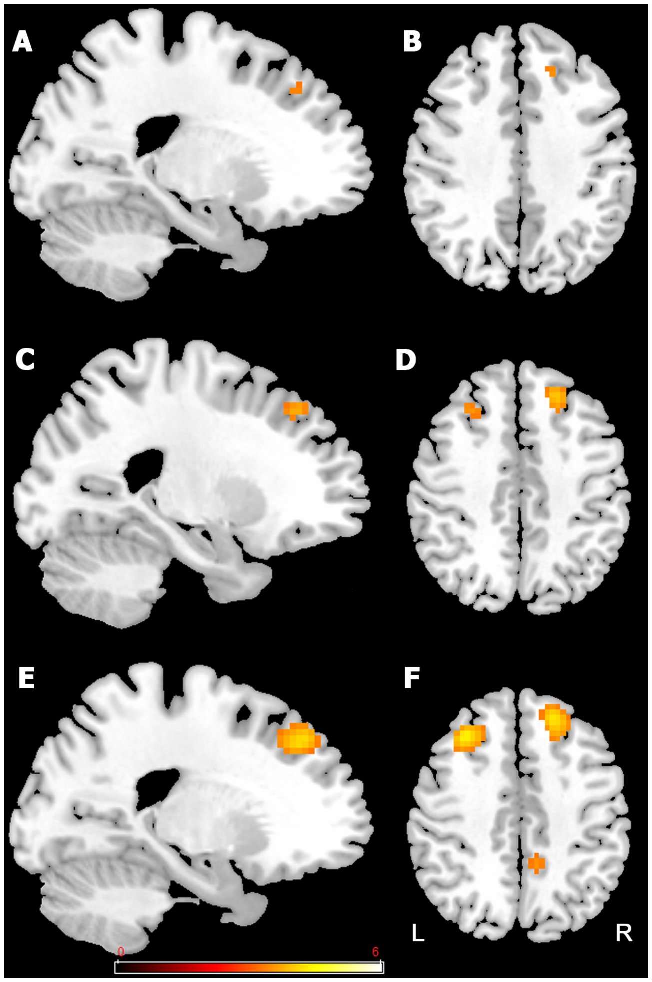

Figure 4. Activations related to dual-tasking prior to training (pre-training session). Network of prefrontal activation in dual-task, with more emphasis on equation (80% Equation (80/20)) in A and B; equal division of attention (50% Equation (50/50)) in C and D; and more emphasis on detection (20% Equation (20/80)) in E and F. The threshold for display is $p < 0.001$, uncorrected, 10 voxels. Coloured bar is representative of t scores mentioned in Table III. "L" denotes the left side of the brain, while "R" denotes the right side.

Table III. Brain regions associated with dual-task at pre-training by pooling all participants

Activated areas (Brodmann area)	Cluster size	*x*	*y*	*z*	*t*-value
Dual-task 80% Equation (emphasis on equation)					
Right superior and middle frontal gyrus	15	21	32	38	3.67
Dual-task 50% Equation (equal division of attention)					
Right middle frontal gyrus (8,9)	37	24	32	41	3.97
Left middle frontal gyrus (8)	21	-27	26	47	3.64
Dual-task 20% Equation (emphasis on detection)					
Left middle frontal gyrus (8,9)	118	-30	23	44	4.56
Left superior frontal gyrus (9, 10)	71	-18	53	26	4.28
Right superior , medial and middle frontal gyrus (8,9,10)	223	21	32	38	4.27
left cerebelum	44	-18	-79	-43	3.81
Left anterior cingulate (24,32)	52	-6	32	8	3.78
Right precuneus and cingulate gyrus (7, 31)	35	15	-37	47	3.72
Right cerebellum	12	3	-49	-52	3.57

During modulation of attention (Figure 5 and Table IV), clusters of activation were found in the left superior, medial frontal gyrus and anterior cingulate (areas 8-9-10), left inferior frontal gyrus (area 45), left cingulate (area 31), and left middle frontal gyrus (area 8). There was also activation in the left parietal and superior temporal gyrus (39-22) and left cerebellum. Many of these areas are typically involved in controlled attention [28].

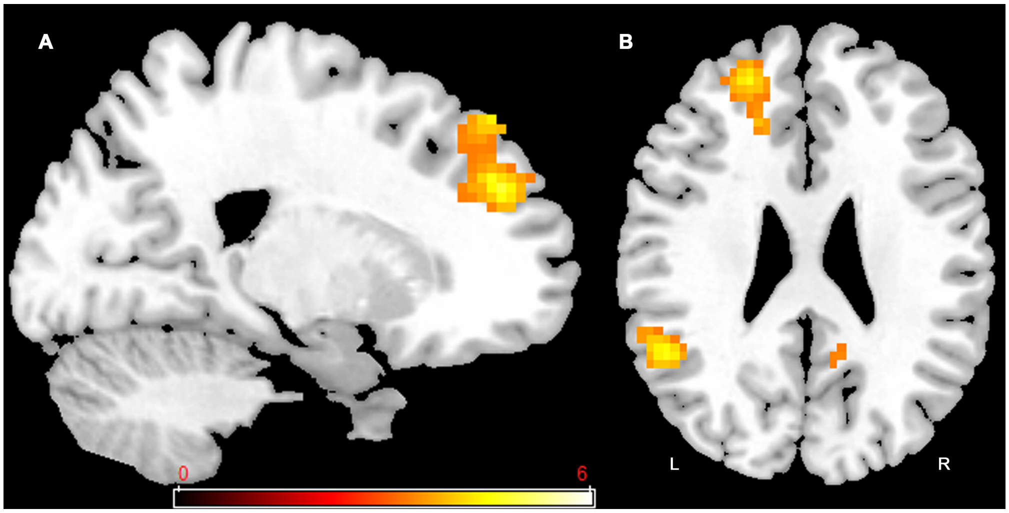

Figure 5. Activation-related to modulation of attention prior to training (pre-training session). Subtracting dual-task 80% Equation (80/20) from dual-task 20% Equation (20/80) involves activation in the left superior and medial frontal gyrus (A and B), and left superior temporal and left cingulate gyrus (B). The threshold for display is p < 0.001, uncorrected, 10 voxels. Coloured bar is representative of t scores mentioned in table IV, "L" denotes the left side of the brain, while "R" denotes the right side.

Table IV. Brain regions associated with the modulation of attention at pre-training by pooling all participants (dual-task 20% Equation > dual-task 80% Equation)

Activated areas (Brodmann area)	Cluster size	*x*	*y*	*z*	*t*-value
Left superior temporal gyrus (39,22)	162	-48	-55	17	5.65
Left cerebellum	44	-9	-49	-43	5.17
Left superior , medial frontal gyrus (8,9,10), anterior cingulate	235	-18	44	26	4.83
Left cingulate gyrus (31)	172	-3	-49	35	4.60
Left inferior frontal gyrus (45)	70	-51	26	8	3.92
Left middle frontal gyrus (8)	34	-42	14	50	3.79

3. Brain activation related to training

The effect of training on brain activation was measured by comparing activation prior to training with activation after training and determining whether there was increased (Post>Pre) or decreased (Pre>Post) activation after training. This was done while participants performed each task under single-tasking and while they performed the two tasks in dual-tasking. The data is presented below for each training condition. Contrast estimates (mean and standard deviation) for all training conditions on significant contrasts are presented in Figure S1 (Supplementary material).

SINGLE REPEATED task training (SINGLE REPEATED)

The group trained in the single training condition (SINGLE REPEATED) showed areas of decreased post-training activation (Pre>Post) when completing the task under single-tasking, as shown in Figure 6 and Table V. The paired t-test analyzing performance on the single-task alphanumeric equation indicated decreased post-training activation (Pre>Post) in the inferior and middle frontal gyri bilaterally and in the left thalamus (Figure 6). There was no post-training decrease in activation on either the visual detection task or when performing the two tasks under dual-task. In this group, there was no evidence for increased activation after training (Post>Pre) under single- and dual-task.

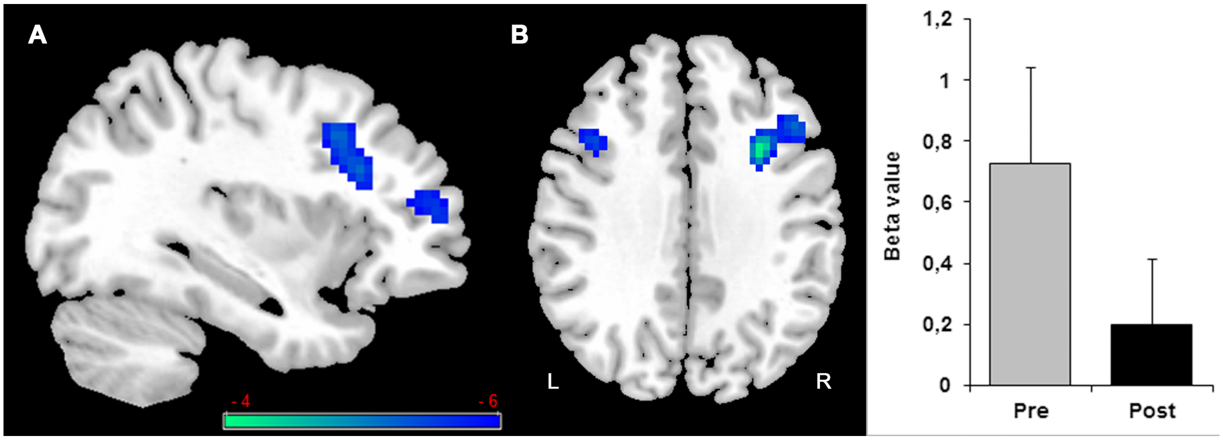

Figure 6. SINGLE REPEATED training effect. Decreased (Pre < Post) activation in single-task with alphanumeric equation is found in the right inferior and middle frontal gyrus (A and B) and left middle frontal (B). Histogram in (C) indicated the Beta value (activity estimates ± SE) in right inferior and middle frontal gyrus. The threshold for display is p < 0.001, uncorrected, 10 voxels. Coloured bar is representative of t scores mentioned in Table V. "L" denotes the left side of the brain, while "R" denotes the right side.

Table V. Brain regions associated with training (Pre<Post or Post<Pre)

Activated areas (Brodmann area)	Cluster size	*x*	*y*	*z*	*t*-value
SINGLE REPEATED training					
Single-task alphabetical equation Pre>post					
Right inferior and middle frontal gyrus (46,9,10,45)	315	33	8	35	5.91
Left thalamus	96	-9	-31	8	5.37
Left middle frontal (9)	21	-36	14	32	4.57
DIVIDED FIXED training					
Single-task visual detection Pre>Post					
Rignt cerebellum	*11*	3	-79	-25	4.73
Right middle occipital gyrus (37,18,19)	*34*	33	-82	-1	4.68
Dual-task 50% Equation Post>Pre					
Left middle frontal gyrus (11,47)	13	-27	32	-16	4.52
Right superior and middle frontal gyrus (11)	16	27	35	-16	4.41
DIVIDED VARIABLE training					
Dual-task 80% Equation Post>Pre					
Right cerebellum	15	42	-76	-28	4.79
Dual-task 50% Equation Post>Pre					
Right superior and middle frontal gyrus (10)	12	27	56	23	4.78
Dual-task 20% Equation Post>Pre					
Right superior and middle frontal gyrus (10)	30	30	56	20	5.35

P < 0.001 uncorrected, K=10

DIVIDED FIXED priority attentional training

Participants in the DIVIDED FIXED attention training condition showed decreased post-training activation in the right cerebellum and right middle occipital gyrus (see Table V), when completing the visual detection task under single-tasking (Pre>Post). No change was observed in post training activation on the single-task alphanumeric equation. When completing the dual-task 50% Equation (50/50), the group showed only small increases in post-training activation in the right and left middle frontal gyrus (area 11 and 47) (Table V). Furthermore, there was no post-training change in activation when performing dual-task 80% Equation (80/20) or dual-task 20% Equation (20/80).

DIVIDED VARIABLE priority attentionnal training

The group trained in DIVIDED VARIABLE attention showed neither reduced (Pre>Post) nor increased (Post>Pre) activation while completing the alphanumeric equation or visual detection tasks under single-tasking. While completing the dual-task, this group showed increased post-training activation (Post>Pre) in the prefrontal areas, as shown in Figure 7 and Table V. The post-training (Post>Pre) in the 20% Equation dual-task condition was associated with a significant increase activation in the right middle frontal gyrus (area 10) (Figure 7 and Table V). This group also showed increased post-training activation in the same right middle frontal gyrus (area 10) when completing the 50% Equation dual-task (Table V). Finally, there was a small locus of increased post-training activation in the right cerebellum during the 80% Equation in dual-task (Table V). In this group, completing the dual-task was not associated with reduced activation after training (Pre>Post).

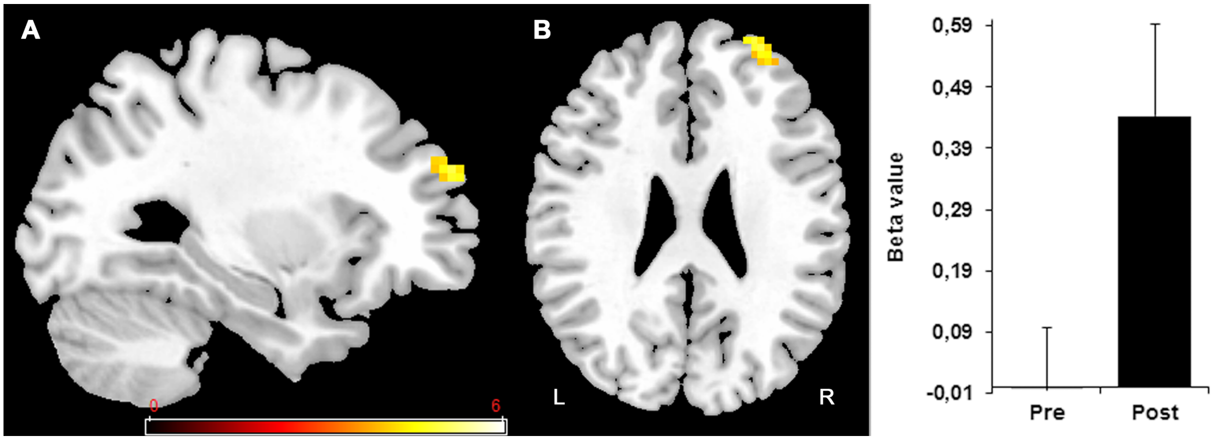

Figure 7. DIVIDED VARIABLE training effect. Increased (Post > Pre) activation in dual-task with more emphasis on detection (20% Equation (20/80)) is found in the right superior and middle frontal gyrus (10). Histogram in (C) indicated the Beta value (activity estimates ± SE) in the region showing increase activity in right superior and middle frontal gyrus during pre- and post-training session. The threshold for display is $p < 0.001$, uncorrected, 10 voxels. Colored bar is representative of t scores mentioned in Table V. "L" denotes the left side of the brain, while "R" denotes the right side.

Figure 8 shows the BOLD signal found in the DIVIDED VARIABLE training in Right area 10 - the region showing the most consistent post-training effect - during the pre- and post-training sessions for single-task (visual detection > rest; alphanumeric equation > rest) and for each dual-task condition (80% Equation (80/20) > rest, 50% Equation (50/50) > rest and 20% Equation (20/80) > rest).

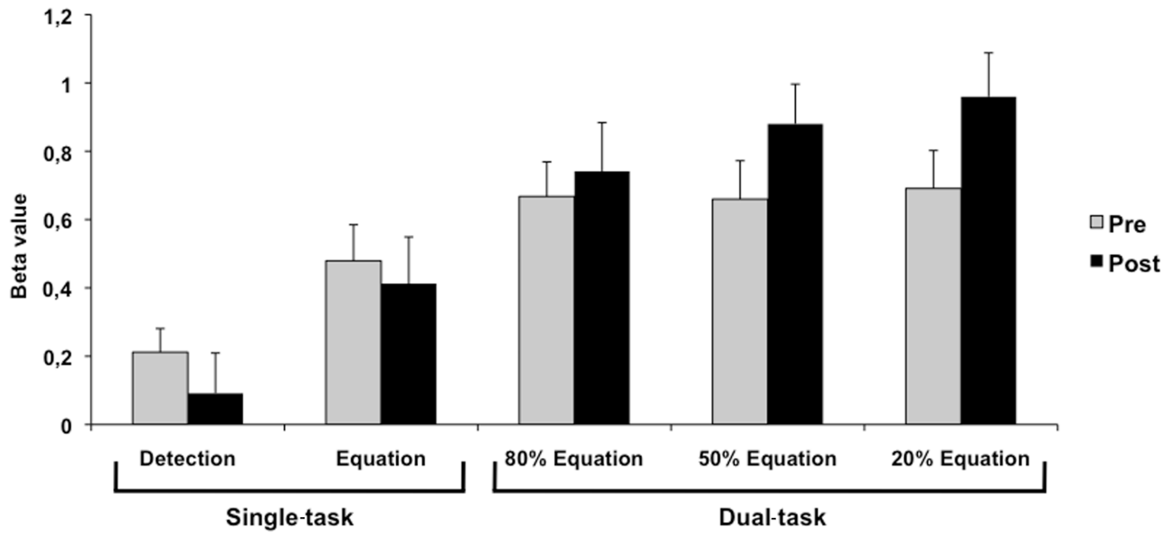

Figure 8. BOLD signal pre- and post-intervention for the DIVIDED VARIABLE training. Beta value (activity estimates ± SE) in pre- and post-training sessions for single-task (visual detection > rest; alphanumeric equation > rest) and for each dual-task condition (80% Equation (80/20) > rest, 50% Equation (50/50) > rest and 20% Equation (20/80) > rest) in right area 10 – the regions showing post-training effect.

Correlation between performance and training-related activation

Table VI shows the correlations for each group between post-training performance (RT in alphanumeric equation task) and activation in the right inferior and middle frontal gyrus (Brodmann's areas 46, 9, 10, 45), a region of interest for single-tasking, and between post-training attentional cost and activation in the right superior and middle frontal gyrus (Brodmann's area 10), a region of interest for the dual-task condition. Those regions were selected because they were changed by the training condition in the group analysis. We were also interested in looking at Brodmans's area 10 as the literature had identified it as being specifically related to multitasking. Only participants in the SINGLE REPEATED training condition showed a significant positive correlation between activation of the right inferior and middle frontal gyrus and performance in single-tasking, r = .56; $p < .05$. This positive correlation indicates that, at post-training, better performance in single-tasking (shorter RT) was associated with lesser brain activation in the right inferior and middle frontal gyrus. Similarly, only participants in the DIVIDED VARIABLE training condition showed a significant correlation at post-training between attentional cost and activation of Brodmann area 10, $r=-.55$, $p<.05$; see Table VI. In this case, the negative correlation indicates that better post-training performance (i.e., lower dual-tasking cost) was associated with greater brain activation at post-training. Importantly, no correlation was found between dual-tasking cost and activation of this area prior to training ($r = -.02$, NS).

Table VI. Correlation between performance and post-training activation in single- (a) and dual-task (b).

a) Correlations between performance (reaction time (RT) on equations) and the beta value obtained in the right inferior and middle frontal gyrus during single-task (alphabetic equation) at post-training. The positive correlation indicates that smaller RTs are associated with less activation.

b) Correlations between attentional cost and the beta value obtained in the right superior and middle frontal gyrus (area 10) during dual-task at post-training. The negative correlation indicates that smaller attentional costs are associated with more activation.

a)

Training condition	Correlation value
SINGLE REPEATED training	0.56*
DIVIDED FIXED training	0.08
DIVIDED VARIABLE training	0.39

b)

Training condition	Correlation value
SINGLE REPEATED training	-0.31
DIVIDED FIXED training	-0.26
DIVIDED VARIABLE training	-0.55*

*significant at $p < 0.05$

Discussion

In this study, we used fMRI to shed light on the brain processes involved in three different attentional training programs in healthy older adults. Overall, we found that the aging brain is highly plastic and that it responds in a coherent manner to different training methods. We also found that the type and loci of the brain response are largely dependent on the type of training provided as described below.

Different training formats result in different behavioural and neural changes

Repeated practice on individual tasks (SINGLE REPEATED) made participants faster and more accurate when asked to solve the alphanumeric equations under single-tasking. In terms of neural changes when completing such a task, the SINGLE REPEATED training group showed reduced activation in the right inferior frontal gyrus, right middle frontal gyrus, left middle frontal gyrus, and in the left thalamus. Furthermore, correlations showed that better performance under single-tasking was associated with lesser activation of these regions at post-training, indicating that the effect found at the group level was coherent with that of the individual level. This suggests that the brain changes found here reflect successful compensation. Cabeza and Dennis [29] have indeed theorized that one empirical indication for successful compensation is a correlation between the brain changes and performance. In spite of their stronger performance on the individual alphanumeric Equations task, the SINGLE REPEATED training group did not improve their ability to combine the Equations task with the visual detection task in the dual-tasking condition. Thus, the dual-task cost was left unchanged by the training. Consistent with behavioural data, the SINGLE REPEATED training group showed no activation changes associated with dual-tasking.

Thus, and as hypothesized, training involving repeatedly practicing a task results in reduced brain activation. This is coherent with the INTERACTIVE model suggesting that as participants gain experience, there is a reduced need for activation because of increased efficacy of the recruited brain regions. In this case, the efficiency gained through experience did not result in a qualitative change in the way the task was completed or use of a different strategy because activation reduction is logically found in brain regions that were active prior to training. Similar findings were observed when younger adults practiced working memory tasks [14]. Erikson and collaborators [12] also reported post-training decreases in activation in the right prefrontal cortex - a region close to the one found here. It is interesting to note that areas showing decreased activation have been associated with monitoring processes of working memory. In particular, Stuss [30] and Stuss and collaborators [31] have proposed a model that relates different regions of the anterior frontal lobe to different executive functions. In this model, the dorsolateral cortex is involved in the online monitoring function of working memory. The alphanumeric equation task is a rather complex task that requires monitoring and updating the content of working memory. Our results suggest that enhancing capacity to solve the alphanumerical equations reduces the need for those controlled processes. It is remarkable that improvements following single-task training were only found on the alphanumeric equation task. This was found for all training groups; all of them improved on the equations task but not on the detection task. The detection task is very similar to a visual reaction time task and because it is an easy task, it mostly reflects processing speed. The literature shows that there is potential for processing speed to be increased in older adults. However, studies that have shown improved processing speed among older adults have typically used training programs that explicitly manipulate basic dimensions of the task; for instance, the time allowed for providing their response or the preparatory intervals (see Baron and Mattila [32]; Bherer and Belleville [33]). Lack of improvement on the detection task may be due to the fact that it was a very simple task, and that mere practice does not impact performance on such basic tasks. In turn, the alphanumeric equation tasks involve complex processes including working memory, monitoring, and updating, and these processes have been shown to be relatively plastic.

Repeated practice under divided attention in the DIVIDED FIXED attentional training condition also resulted in a better ability to complete the alphanumeric equation task alone, as well as to divide attention between the alphanumeric equation and visual detection tasks when asked to combine the two. Thus, a lower dual-task cost was found post-training. In terms of brain changes, practicing under dual-tasking was followed by reduced activation when completing the visual detection task under single-tasking. It also resulted in small areas of increased activation in the middle frontal gyrus bilaterally during the 50% Equation (50/50) dual-task.

In the DIVIDED VARIABLE training condition, participants were trained to variably control their attentional focus, to exert top-down control on the locus of their attention, and to improve their metacognitive abilities. We predicted that this training would increase their attentional control and lead to new or larger engagement of regions that are involved in multitasking and metacognition. As was the case for the other two training groups, participants in this group improved their ability to complete the alphanumeric equation task in the single-tasking condition. Critically, however, this training condition was the only one to improve participants' ability to modulate their attentional priority according to task instructions. When participants were asked to prioritize the equations task, their dual-tasking score was reduced; the opposite was found when asked to prioritize the detection task. In terms of brain changes, the DIVIDED VARIABLE training resulted in increased activity in area 10 of the right prefrontal cortex, and this was found in two of the dual-tasking conditions (50% Equation and 20% Equation). None of these effects were found in the other two training conditions. Importantly, we observed a correlation between greater activity in this region and better dual-tasking after DIVIDED VARIABLE training, indicating that the effect is coherent at the individual level. The correlation between increased brain activation and better dual-task performance also suggests that the activation changes found here reflect successful compensation [29].

Many studies in the attentional domain, have related area 10 to the coordination of multitasking [34,35,36,37]. In line with this literature, the region was activated bilaterally under dual-tasking prior to training. In addition, Stuss [30] has proposed that this region is involved in orchestrating the basic executive functions needed to accomplish novelty tasks and is critical for metacognition. That it became more active following DIVIDED VARIABLE training indicates that older adults who were trained in this condition increased their reliance on brain regions associated with multitasking, perhaps because they engaged the coordinating processes necessary for completing such complex tasks. Interestingly, DiGirolamo and collaborators [38] have found that the brains of older adults recruit the medial frontal cortex even when not multi-tasking, perhaps as a way to compensate when task demands are important. Thus, this region might be an interesting component of compensatory processes in older adults.

Models of Age-Related Brain Compensation

It is informative to relate patterns of brain loci modified by training to current theoretical frameworks of age-related brain compensation. One important question is whether activation results in reduced or increased activation. Another is whether training modifies activation in regions that were involved in the task prior to training (referred to here as specialized regions) or whether it modifies recruitment of regions that are not normally involved in the task (referred to here as alternative or latent regions [39,40].

Current models of compensation related to brain lesions or age indirectly address these issues. For instance, Pruvolic and collaborators [41] and Clement and Belleville [5] have proposed that compensation occurs naturally in the early course of age-related neurodegenerative diseases, and this is reflected in increased activation of the structurally impaired specialized regions that are typically involved in the task. In turn, the degeneracy model [42,43] suggests that the complexity of brain interconnectivity makes different brain regions potentially apt at performing the same functions. Thus, loss of neurons in a specialized region might reveal latent systems in other regions that are either inhibited or left aside in non-impaired individuals. This latter view is coherent with current models of age-related compensation. The HAROLD model [3] proposes that the brains of older adults compensate by recruiting latent regions contralateral to those that are typically recruited by the task. The CRUNCH model [10] proposes that compensation is supported by increased activation of specialized brain regions and also by strategic recruitment of alternative regions. Thus, the degeneracy-type models predict that training should yield greater activation in alternative regions; that is, regions not engaged by the task prior to training. According to HAROLD, these would most likely be the contralateral homologues of the regions normally involved in the task.

The pattern of results we found is not easily reconciled with any of those models because the pattern varied widely as a function of the training format. DIVIDED VARIABLE training increased activation in right area 10, which is specialized for multitasking, and which was active bilaterally prior to training. At first sight, this pattern contrasts with the HAROLD model because this model suggests that the brains of older adults compensate by increasing activation in latent regions that are contralateral to those involved in the task. Similarly, the finding of reduced activation following repeated practice is not consistent with HAROLD, because the model suggests that compensation occurs through increased rather than decreased activation. Erikson and collaborators [12] have shown that attentional training reduces right prefrontal activation and increases left prefrontal activation in healthy older adults. This mixed pattern led to greater brain asymmetry post-training compared to pre-training, which is also contrary to the predictions of the HAROLD model. Interestingly, however, the reduced activity reported in the present study after repeated practice is found in the right hemisphere. It is possible that practice actually reduced the need to recruit from the contralateral region, which would then be consistent with HAROLD and the processing efficiency account proposed by the CRUNCH model.

INTERACTIVE: a model of training-induced brain plasticity

Our major finding is that training-induced activation changes following attentional training differ strikingly as a function of training types. Importantly, these aforementioned models are concerned with naturally occurring compensation, and for this reason, they are not directly concerned by the effect of training. As a result, they have inherent limitations in accounting for findings related to differences of training-induced activation as a function of training types. In turn, the result is coherent with analyzing the type of cognitive processes that are engaged or modified by the training format. In this case, activation changes are considered to be not only biologically determined but also, determined by the cognitive mechanisms that are engaged or modified by training format. The training literature in aging shows results consistent with such an interpretation. For instance, Hampstead [44] reported increased activation in the hippocampus following training that increased associative memory capacities. Similarly, Belleville et al. [8,17] and Nyberg et al. [19] reported increased activation in regions that are known to be involved in mental imagery and semantic elaboration, after training on imagery-based and elaborative encoding strategies. Braver, Paxton, Locke, and Barch [20] found that after strategy training on task maintenance and updating, older adults showed a combination of increased activation in response to the cue and reduced activation in response to the probe, which normalized their pattern of brain activity. In those cases, a task analysis of the training format and of the processes that it engages or changes would best determine the pattern and loci of brain changes following training.

INTERACTIVE is a training model that expends models of naturally-occuring compensation to interpret the data arising from training-induced activation changes. It suggests that activation changes depends on training modalities as well as on a complex interaction between those and the characteristics of the participants; for example, the type and extent of their brain changes, the availability of their cognitive reserve, and their level of expertise In terms of training modalities, the INTERACTIVE model hypothesizes that repeated practice will result in decreased activation due to more efficient processing in specialized regions, whereas metacognitive training will result in activation of networks involved in controlled processing. In addition, the model distinguishes between training methods that promote compensation – by focusing on preserved functions- and training methods that promote restoration of impaired functions. Training protocols based on teaching mnemonics or promoting metacognition induce compensatory strategies and are more likely to result in increased activation. In contrast, restoration approaches focus on the impaired function and most often aim to increase the function by providing intensive and repeated practice and this might reduce activation in specialized regions. This might affect the choice of an appropriate training format, which may depend on whether the goal is to *increase* functioning in dysfunctional brain regions or to encourage *compensation* by making use of residual brain regions [45].

INTERACTIVE also identifies pre-training proficiency level as a factor in determining the pattern of change following training and this may interact with the type of training used. Metacognitive strategies could be taught to persons who already make use of those strategies. This might result in decreased activation as the training makes them more adept at using such strategies. For instance, we found that teaching mnemonics that promote deeper encoding reduced encoding-related activation in healthy older adults, but it increased encoding-related activation in persons with MCI [17]. We proposed that reduced activation occurred because older adults were attempting to use those strategies prior to training and they became more efficient at using them following training. Thus, activation changes not only depend on the type of training provided, but also on whether similar strategies were mastered prior to training and the level of mastery that was required. Clinical status is also an important parameter. Different clinical populations might be more sensitive to metacognitive, restoration, and compensation approaches. For instance, when the target region for restoration is too impaired at the structural level, one may wish to promote compensation processes that rely on unimpaired regions. In either cases, selection of the appropriate training program requires that the pattern of brain changes induced by a particular training format be well understood [9,13].

Limitations and remaining issues

We would like to recognize some of the limitations in this study and address remaining issues to explore. First, the sample size is relatively small when compared to typical randomized control trials. Note, however, that this sample size is in the upper range of those found for studies of training-induced brain changes in older adults [12,15,17,18,20,44,46,47,48]. Brain imaging studies are costly and demanding, and these constraints impose limitations on sample size, particularly for intervention studies where multiple scans are required and participants need to be split across different conditions. However, future studies will benefit from more powerful designs to broaden impact and increase generability of findings. More powerful designs will facilitate conducting studies that require a large number of participants (e.g., whole-brain connectivity), as well as investigating the impact of moderating variables on patterns of brain changes. With a larger sample size, we could have also used corrected p-values or direct group comparisons. Another important issue is that of generalization. One of the key concerns with training is showing transfer of benefits, not only to tasks very similar to the training itself, but also to untrained cognitive domains. It has been suggested that training basic cognitive processes, such as speed of processing or perceptual grouping, might result in greater transfer than training more complex processes. Measuring transfer was not the goal of this paper; however, knowing whether the neural changes found in the present study can support transfer to untrained cognitive tasks is an important question that should be addressed in future studies. Some of our findings can speak to this issue. Indeed, activation changes resulting from repeated practice are extremely different from those resulting from complex metacognitive training. However, the effect of repeated practice was found to be quite specific and limited to the task and condition that was trained, and results were not transferred to the dual-tasking condition.

Summary

In summary, the attentional system of healthy older adults is highly plastic and behavioural and brain changes can be fostered by implementing relatively short training regimens. Importantly, however, the type of training appears to be a critical factor in determining the pattern of brain activation, as training formats vary in the effects they have on the brain. Practice reduces activation, perhaps through increased efficiency of the brain network implicated in the task for which expertise is developed. In turn, a training program that involves compensatory processes through the teaching of new metacognitive abilities is associated with increased activation. These findings can have a tremendous impact when selecting or designing training programs to prevent cognitive decline in older adults, as well as for those involved in rehabilitation of brain-damaged persons, because they provide a fine-grained analysis of the brain-related changes that can occur in response to different training formats. By showing that different programs can have dramatically different effects on cerebral activity, the results indicate that readaptation approaches should take into account not only the behavioural effects of particular intervention programs, but also their effects on the brain. Finally, these results and the model that we propose to account for them, can contribute to theories of brain compensation in aging and in age-related neurodegeneration.

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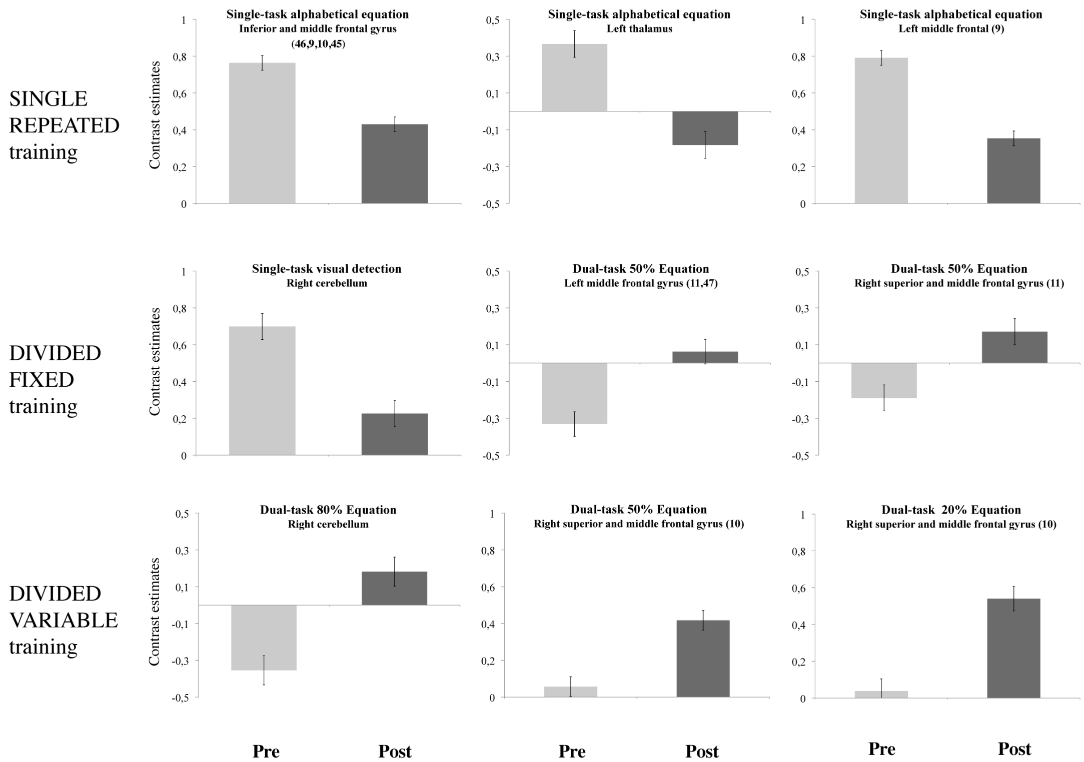
Supplementary material

Article 4: The pattern and loci of training-induced brain changes in healthy older adults are predicted by the nature of the intervention

Supplementary material



Supplementary figure S1. Contrast estimates (mean and standard error) for all training programs on significant contrasts (see in Table V)

CHAPITRE VI

Article 5: *Timecourse of brain and cognitive changes following two types of computerized attentional training programs: A three-time point fMRI intervention study in older adults*

Article 5: Timecourse of brain and cognitive changes following two types of computerized attentional training programs: A three-time point fMRI intervention study in older adults

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Manuscrit en rédaction

Abstract

Background: There is considerable interest regarding the role of cognitive training as a way to improve cognition in older adults and to build resilience against age-related cognitive decline. However, we need to better understand the neurobiological basis of cognitive training and how its effects develop with increasing dose. The aim of the study was to assess the timecourse of the dose-response on behavior and brain activation resulting from two types of attentional cognitive training programs.

Method: Thirty healthy older adults were randomized to eight one-hour training sessions of either: 1) SINGLE attention training which comprised the repeated practice of one of two tasks (visual detection; alphabetical verification) under focused attention, or 2) VARIABLE priority training, where participants learned to control their attentional priority while performing the two tasks concurrently. Participants were assessed with behavioral measures and task-related fMRI at three time points: one week prior to training (BASELINE), following the 4^{th} training session (4TH), and following the 8^{th} training session (8TH).

Results: During VARIABLE priority training, there was a cognitive gain in divided attention performance from BASELINE to 4TH, but no further improvement from 4TH to 8TH. A similar timecourse was found for activation: increased activation was found from BASELINE- to 4TH only in areas involved in the right frontal BA10 and superior parietal regions, bilaterally, regions that were involved in multitasking and attentional control. SINGLE-task training was associated with a rapid performance gain on the alphabetical task in focused attention from BASELINE- to 4TH and no further improvement from 4TH to 8TH. This was accompanied by an increased activation of the anterior and posterior cingulate gyrus bilaterally and pre-central and post-central gyri from BASELINE- to 4TH, followed by an activation decrease at 8TH.

Conclusion: The two training programs led to specific improvement of the cognitive process targeted by the intervention. In both cases, the time course of the behavioral training effect is characterized by a rapid change in performance over the first few sessions after which the gain levels off. The region and pattern of brain activation changes, differ according to training type but a non-linear time course was found in both cases. VARIABLE priority training increases activation in brain regions associated with multitasking with a plateau that parallels performance. In turn, activation related to SINGLE-task training shows an inverse U-shape function. The results show that the effect of dose is not linear and that different cognitive training have different effects on behavior and the brain: strategic training leads to increase activation reflecting the newly learned strategy, whereas repeated practice leads to decrease activation at later stages of training reflecting better efficiency. These findings further stress the importance of fMRI studies to better understand the neural substrate involved in the older adult brain following training.

Keywords: Cognitive training, timecourse, brain changes, dose effect, dual-task, aging, brain aging,

Introduction

There is now increasing evidence that brain plasticity is a lifelong phenomenon and that the aging brain is malleable and can be modified by cognitively stimulating life experiences (Cabeza, 2002; Clément & Belleville, 2012; Clément, Gauthier, & Belleville, 2013; Reuter-Lorenz & Cappell, 2008). Functional brain imaging studies measuring brain activation in healthy older adults have revealed brain changes associated with compensatory mechanisms (Cabeza, 2002; Reuter-Lorenz & Cappell, 2008; Reuter-Lorenz & Park, 2014). Training can be used as a way to better understand brain reorganization and compensation (Belleville, Mellah, de Boysson, Demonet, & Bier, 2014; Lustig, Shah, Seidler, & Reuter-Lorenz, 2009). Results from functional magnetic resonance imaging (fMRI) studies can provide invaluable information on the regions or networks that are active when performing a task and can also reveal the cognitive processes and brain reorganization that are triggered by cognitive interventions (Belleville & Bherer, 2012). This could have a tremendous impact for clinicians when selecting the appropriate training program, as different cognitive training programs may engage different processes.

Studies that have assessed brain activation changes in younger and older adults following training show inconsistent results. Some studies found decreased activation post-training (Brehmer, Westerberg, & Bäckman, 2012) and others a mix of increased and decreased activation (Belleville et al., 2011; Belleville et al., 2014; K. Erickson et al., 2007; Erickson et al., 2010; K. I. Erickson et al., 2007a, 2007b). A decrease in activation associated with improved performance indicates that less activation is necessary to reach a similar or even better level of accuracy and was interpreted as reflecting superior brain efficiency (Chein & Schneider, 2005). In turn, new or increased activation was interpreted as reflecting a reliance on a process that was not used to complete the task (e.g., learning a new strategy) prior to training or a greater reliance on a previously used process (Belleville et al., 2011; Belleville et al., 2014). The type of programs used to measure training-related brain changes was highlighted as a critical factor to help determine efficacy as well as the program's impact on the brain (Lustig et al., 2009; Belleville et al, 2011; 2014). This hypothesis was supported empirically by Belleville et al. (2014) who showed that training with repeated practice on a Working Memory (WM) task resulted in decreased activation in the right inferior and middle frontal gyri and in the left thalamus, two regions expected to be involved in the task that was practiced. In contrast, when using strategic training targeting attentional control abilities with the same material, it resulted in increased post-training activation in the right prefrontal cortex (area 10), a region which has been linked to metacognitive and control capacities (Badre & Wagner, 2004; Burgess, Scoth, Frith, 2003; Dreher, Koechiln, Tierney & Grafman, 2008; Stuss, 2000). These findings suggest that training-induced plasticity can result from repeated practice or strategic training, but that they will induce different types of brain changes. This has tremendous consequences. To develop neurobiologically motivated training approaches, it is critical to understand how different program characteristics determine different brain changes.

In addition to training format, training dose is an important characteristic that may determine differences in brain effects. Dose can be measured by the amount of sessions or number of training hours received by the individual. Importantly, studies of motor skill learning indicate that the pattern of brain activity elicited by a task changes throughout the course of training (Doyon & Benali, 2005; Doyon, Penhune, & Ungerleider, 2003). Those studies indicate that motor skill learning is characterized by a fast initial learning phase where different networks are recruited, and after which, in the later stages of learning, these networks become more specialized, and underlies specific aspects of the learned skill. In a recent study, Wenger et al., (2016) examined the time course of training-related structural changes over seven weeks and 18 structural MRI. They reported an inverse-U shaped function following motor training: grey matter volume increased during the first four weeks of training and then renormalized partially. Thus, motor skill learning is first accompanied by increased recruitment followed by a reduced, more efficient and focal pattern of brain activity as the skill is automatized.

Little is known regarding the pattern of brain activation changes accompanying cognitive training, though, one might expect that a similar pattern of increased followed by decreased activation would be found upon training complex cognitive functions. In particular, the INTERACTIVE model (Belleville et al., 2014) proposed that training content and dose should interact to determine differences in brain changes. As mentioned above, the model proposes that training involving repeated practice would result in reduced activation in specialized networks due to better processing efficiency, and that strategic learning would result in greater or new activations in the regions that would reflect the newly learned strategy. Additionally, the INTERACTIVE model proposes that this will interact with the learning phase (Belleville et al, 2011; 2014). Accordingly, increased activation is expected to occur early in the learning stage when training is more likely to engage novel processing. However, activation should stabilize when the participant is provided with additional hours of training. It might also decrease even if the program involves learning new strategies, as automatization is likely to occur when a sufficient amount of training is provided. One may therefore observe a decrease followed by stabilization or an inverse-U shape function of activation. Finding an inverse-U shape function for strategic training in the regions that were found to initially increase, would suggest late increase efficiency for those newly learned cognitive skills.

Most studies that have looked at training-induced activation changes relied on pre- and post-training designs. Because they included only two measurement time points, those studies fail to inform on the activation changes that occur while participants are engaged in training. Hempel et al., (2004) study was one of the rare studies to include three time points in fMRI. They looked at cerebral activations during a visual spatial working memory task before, during and after four weeks of daily training in a small group of younger adults (N = 9). They show that training-related cerebral activation changes followed an inverse U-shaped function. Some of the regions involved in performing the tasks showed an initial activation increase with improved performance, followed by a subsequent activation decrease with consolidation of performance gains.

In this study, we will assess the time-course of the dose response on behavior and brain activation resulting from two types of attentional training: a VARIABLE priority training vs. a SINGLE-task training. To our knowledge, no cognitive interventions have relied on more than PRE-POST assessment points to test activation trajectories as a function of training types. Healthy older adults were randomized to one of the two training types. In VARIABLE priority training, participants are asked to vary the amount of attention placed on each task performed concurrently (alphanumeric equation and visual detection). In SINGLE-task training, participants perform both tasks individually in focused attention. Participants were assessed with behavioral measures and task-related fMRI at three time points: one week prior to training (BASELINE), following the fourth training session (4TH), and following the eighth training session (8TH). In line with Belleville et al. (2014) and Bier, de Boysson, and Belleville (2014) we hypothesized that VARIABLE training would increase performance on attentional control and that SINGLE training would increase performance in focused attention. In both cases, the time course of the behavioral effect was expected to be characterized by a rapid change in performance from BASELINE to the 4TH, after which the gain should level off. Concerning brain activation, we expect that VARIABLE priority training would result in increased activation from BASELINE to 4TH followed by a maintenance or reduction of activations from 4TH to 8TH. A reduction of brain activation with stable or increased performance between the 4TH to 8TH scan would suggest that the strategy has become automatized. In contrast, we expect that the SINGLE training group would show a linear decrease in activation from BASELINE to 8TH in regions involved in performing each task individually. To our knowledge, this is the first study to use a study design with more than two measurement time points in functional brain imaging over the course of training in healthy older adults.

Materials and Method

Participants

Thirty healthy, community-dwelling older adults were recruited through advertisements in senior centers, magazines for seniors and the CRIUGM participant bank. They underwent a telephone interview to provide initial selection information. Participants were included if they were French-speaking, living in the Montreal area, right-handed, and had normal or corrected-to-normal hearing and vision. Exclusion criteria included: dementia, alcoholism or substance abuse; presence or history of a neurological disorder or stroke; presence or history of a severe psychiatric disorder (e.g., depression, schizophrenia, bipolar disorder); general anesthesia in the past six months, medication that could impact cognitive and cerebral functioning, and MRI incompatibility. To evaluate cognitive functioning, eligible participants were invited to come to the laboratory for a standardized clinical and neuropsychological battery. The battery included the Montreal Cognitive Assessment (Nasreddine et al., 2005), a general measure of cognitive functions, the Geriatric Depression Scale (Yesavage & Sheikh, 1986), one test of "fluid" intelligence (Wechsler, 2008) and one test of "crystallized" intelligence (Wechsler, 2008). Participants were excluded if their MoCA score was below the cut-off stratified by age and educational attainment for the North American population (Rossetti, Lacritz, Cullum, & Weiner, 2011), as a way to exclude participants who were suspected to suffer from mild cognitive impairment or dementia. Furthermore, participants with a GDS score above 5/15 were excluded.

Study Design

Participants were randomly assigned by an independent research assistant to one of the two training conditions (VARIABLE or SINGLE-task training). Randomization was stratified by education and age to reduce the likelihood that groups would be unbalanced with respect to these factors. Training was provided in eight one-hour sessions on weekdays over a period of two weeks in groups of two or three participants. Participants were scanned at three time points: one week prior to the first training session (BASELINE), following the fourth training session (4TH), and one week following the last training session (8TH). One week prior to the BASELINE training session, participants were trained on the fMRI procedure and practiced the task in a simulator that mimicked the fMRI environment (in terms of task, body position, sound, etc.).

Training method

Participants received either a VARIABLE priority training or a SINGLE-task training. Training was conducted with a visual detection task and an alphanumeric equation task and was completed in either focused or divided attention depending on the training condition (Belleville et al., 2014; Bier et al., 2014; Zendel, de Boysson, Mellah, Démonet, & Belleville, 2016). Each training session comprised 12 blocks of 20 trials of the task. Accuracy (AC) and reaction time (RT) were recorded for both tasks. Participants received one of the two training condition described below.

In the VARIABLE condition, participants were asked to complete the two tasks simultaneously for eight blocks; however, their attentional allocation priorities varied between the blocks. For four of the blocks, participants were asked to allocate 80% of their attention to the alphanumeric equation task and 20% to the visual detection task (80%-Equation). For the other four blocks, participants were asked to allocate 20% of their attention on the alphanumeric equation task and 80% on the visual detection task (20%-Equation). To provide a baseline, all participants completed two blocks of each task under focused attention at the beginning and end of each session for a total of 12 blocks. To enable better understanding, instructions were supported by an illustration representing the percentage of attention required by each task. After each block, a histogram was presented to the participants indicating their baseline level for the training session (as measured earlier in the focused attention condition) and the expected accuracy given the emphasis instruction condition. Before displaying their actual performance on the histogram, participants were asked to draw their own estimate on a paper histogram (see Bier et al. (2014) and Belleville et al. (2014) for more details).

In the SINGLE-task condition**,** participants were asked to practice both tasks separately under focused attention. Participants completed six blocks for each task and the overall order (i.e., visual detection first or alphanumeric equation first) was counterbalanced across participants.

Tasks used for training

The alphanumeric equation task requires the participant to verify the accuracy of a set of visually presented alphanumeric equations. Equations were constructed by combining a letter (from N to Z) and a number (1 or 2) in the form of an addition of a subtraction (e.g., N + 2 = P; E – 1 = D…). To verify the equation, participants needed to use the first letter as a starting point, the + or – signs indicated the direction of the equation, and the digit revealed the number of "steps" needed to reach the correct answer. For example, in equation S - 1 = Q, the starting point is S, and the letter Q is not one letter down from S in the alphabet, thus this equation incorrect. Each equation was presented in the center of the screen for a maximum period of 3750-ms with 1500-ms inter-stimuli intervals. Half of the equations were correct. Incorrect ones were formed by selecting a letter that was one or two positions away from the correct result. In each block, the number of equations that used addition or subtraction and that had a digit of 1 or 2 was equivalent.

In the visual detection task, participants were presented with a series of red or white rectangles (1 cm x 8 cm) that appeared randomly just below the center of the computer screen for 500-ms each with an inter-stimuli interval of 250-ms. Participants were asked to press the spacebar every time the rectangle was red, and they were to do so as quickly and as accurately as possible.

fMRI methods

Task used in fMRI

All participants were asked to perform the visual detection task and the alphanumeric equation tasks separately (focused attention) and in combination (divided attention). When performed in combination, participants were asked to either emphasize the visual detection task

(20%-Equation) or the alphanumeric equation task (80%-Equation). The material was similar to that used in training, except that the equations contained letters from a different part of the alphabet (A to M rather than N to Z) to reduce potential practice effects. The tasks were implemented using E-prime software (Psychology Software Tools, Inc.). Stimuli were presented visually to participants using a mirror attached to the head coil. Participant's vision was corrected with MRI compatible goggles when needed. Responses were provided on MRI compatible response devices (ResponseGrip; *NordicNeuroLab*) by pressing the appropriate buttons (right and left index fingers for correct and incorrect equations, respectively, and the right thumb when the red rectangle was shown).

Each condition (focused and divided) was presented in six blocks of eight trials (for a total of 48 trials; lasting four seconds each, followed by a cross of 500 or 1000 ms). Each task block was followed by a rest period of 18 seconds (cross fixation). No feedback was provided during the task. Task instructions were presented prior to each block and remained on the screen for four seconds for each task condition. Three different versions of the experimental task were created for the three time-points and were counterbalanced across participants.

fMRI parameters

Participants were scanned on a Siemens TIM Trio 3T magnetic resonance imaging (MRI) system (Siemens Medical Solutions, Erlangen, Germany), using the Siemens 32 channel receive-only head coil at the neuroimaging unit of the research centre of the Institut universitaire de gériatrie de Montréal (http://www.unfmontreal.ca/siteweb/Home_en.html).

Functional data were acquired with an echo planar imaging (EPI) pulse sequence (305 acquisitions, TR: 2500 ms, TE: 30 ms, flip angle 90°, FOV: 192 x 192 mm, 41 slices, voxel size 3 mm^3 matrix size: 64 x 64 pixels). Acquisition was in axial orientation co-planar with AC-PC, whole brain coverage. Order of acquisition was ascending. The functional images were acquired in two runs and the first three volumes were automatically discarded by the fMRI scanner. The structural MRI image was acquired after the functional run using a ME-MPRAGE 4-Echo sequence (176 slices, 1 mm^3 voxels, TR = 2530 ms, TE = 1.64/3.5/5.36/7.22 ms, flip angle = 7°), which has a low distortion and high signal-to-noise ratio (van der Kouwe, Benner, Salat, & Fischl, 2008).

fMRI image processing

Data were analyzed in MATLAB R2015b (http://www.mathworks.com), using the statistical parametric mapping (SPM12) software (http://www.fil.ion.ucl.ac.uk/spm). First, images were motion corrected; the temporal processed volumes of each subject were realigned to mean volume to remove the head motion. Second, images were slice-time corrected to the middle slice, using SPM12's Fourier phase shift interpolation. Third, images were co-registered with each subject's anatomical MRI image. Fourth, images were spatially normalized to the echo-planar imaging (EPI) template via their corresponding mean image, resliced by 3 mm^3 voxels, and smoothed with a Gaussian kernel of 8-mm FWHM.

fMRI statistical analysis

The first level of statistical analysis was fixed-effects analysis based on the general linear model (GLM) with a box-car response. GLM analysis was performed using regressors, which were generated by convolving the time course of the condition's onsets and duration with canonical hemodynamic response function (HRF). There were four experimental conditions: rest (cross-fixation), focused alphanumeric equation, focused visual detection and divided attention (combining both 20%-Equation; 80%-Equation blocks). The instructions before each condition were modeled as a condition of no interest. Movement parameters estimated during realignment (translations in x, y and z directions, and rotations around x-, y- and z-axes) and a constant were also included in the matrix scanning run as variables of no interest. High-pass filter was implemented using a cut-off period of 256 s to remove low frequency drifts from the time series. Serial correlations in the functional MRI signal were estimated using an autoregressive (order 1) plus white noise model and a restricted maximum likelihood (ReML) algorithm. After estimating the parameters of the model, three linear contrasts were calculated for each participant. Cerebral activation in the focused attention condition was calculated with a contrast *(focused alphanumeric equation ≥ rest; focused attention visual detection ≥ rest)*. Activation during divided attention was measured with an interaction contrast: *(divided attention ≥ focused alphanumeric equation) – (focused visual detection ≥ rest)*. This interaction contrast was used in one of our previous studies to extract divided attention performance activation (Belleville et al., 2014) and was shown to be the most appropriate method for comparing activity in the divided attention to that of the focused attention (Szameitat, Schubert, & Müller, 2011).

The data were pooled from all participants at BASELINE and one sample t-test was performed to measure brain activation associated with focused attention (alphanumeric equation and visual detection) and divided attention.

The effect of training on brain activation was assessed first with whole-brain analyses. To measure the effect on focused attention activation, paired t-tests compared the contrasts *focused alphanumeric equation ≥ rest* and *focused visual detection ≥ rest* in BASELINE- vs. 4TH and in 4TH vs. 8TH. To measure the effect on divided attention, paired t-tests compared the contrast *(divided attention ≥ focused alphanumeric equation) – (focused visual detection ≥ rest)* in BASELINE- vs. 4TH and in 4TH vs. 8TH. We examined both increased and decreased activation in relation to measure time. Results of the *t*-statistic [SPM(T)] maps were interpreted if they reached both a voxel-wise threshold of $p < 0.001$ (uncorrected) and a threshold of $p < 0.05$ (corrected) at the cluster level.

We then used Analyses of variance (ANOVA) with functionally defined regions of interest (ROI) to further analyze the timecourse of the activation changes. We used the clusters with significant reduced or increased activation change from BASELINE- to 4TH as ROIs. The average beta value of each ROI for each time point (BASELINE; 4TH; 8TH) was then extracted per participant with MarsBar region of interest toolbox for SPM (Brett et al. 2002).

Finally, correlational analyses were also used to assess whether post-training brain activation was related with task performance. Pearson's correlations were computed between the extracted beta values from each ROI found to be modified by the intervention and the AC and RT performance for the alphanumeric equation task and dual-task cost. Pearson's correlations and ANOVAs were performed using SPSS 21.0 (http: //www.spss.com).

Results

Demographic and clinical characteristics

Three participants were excluded from the analyses; one participant refused to continue with the fMRI examination following the first scanning session, and two were excluded because of excessive head motion during the scan and technical difficulties in the scanner. The demographic and clinical characteristics of the 27 remaining participants are shown in Table I, as a function of the training condition to which they were assigned. As shown in Table I, the two groups were comparable in terms of demographic and clinical characteristics.

Table I. Demographic and clinical characteristics for all participants included in the final sample

	VARIABLE training n= 15	SINGLE-task Training n= 15	F value	P
Age	69.70 (5.13)	73.05 (6.36)	0.51	0.60
Gender	10 W, 3 M	12 W, 2 M	-	-
Education	14.77 (2.68)	14.85 (4.63)	0.04	0.95
Moca (/30)	28,92 (1.38)	28,14 (1.20)	0.16	0.68
GDS (/15)	1.69 (2.01)	0.92 (1.27)	0.87	0.43
Vocabulary WAIS-IV subtest	12.46 (1.12)	11.50 (2.10)	2.14	0.15
Digit Symbol-Coding WAIS-IV subtest	14.15 (2.51)	14.85 (1.47)	3.03	0.09

Standard deviations in parentheses

Behavioral performance

Tables II and III show the BASELINE-, 4TH and 8TH dual-task cost score (see below for computation of the dual-task cost score) and behavioral performances on both task performed in the scanner in focused attention (alphanumeric equation and visual detection). As this paper focuses on brain activation, only summary analyses of behavioral data are presented here (see Bier et al., in revision, for more details).

<u>**Behavioral performance - divided attention**</u>

To analyze the training effect on dual tasking, a dual-task cost score was computed with the following equation: {[(RT DIVIDED – RT FOCUSED) / RT FOCUSED] + [(AC FOCUSED – AC DIVIDED) / AC FOCUSED]}. This dual-task cost represents the proportional loss of performance in the divided attention condition as a function of performance in the focused attention condition. A higher score represents a larger dual-task cost.

To analyze the training effect on dual-task cost, mixed ANOVAs were used separately for each task with Time (BASELINE, 4TH, 8TH) as a within-subject factor, and Training type (VARIABLE, SINGLE-task) as a between-subject factor. For the visual detection task, the analysis revealed a Time x Training type interaction, $F(1, 25) = 6.02$, $p < .01$ ($\eta^2 = 0.20$). Decomposition of the interaction revealed that only VARIABLE-priority training reduced dual-task cost. Indeed, a main effect of Time $F(1, 25) = 5.60$, $p < .001$ $\eta^2 = 0.55$, was found for VARIABLE-priority training. Mean comparisons indicated reduced dual-task cost from BASELINE- ($M = 1.00$) to 4TH ($M = 0.78$) ($p < .05$) and no further improvement from 4TH to 8TH ($p = .09$) (see Table II and Figure 1A). There was however no main effect of Time for the SINGLE-task training ($F<1$). For the alphanumeric equation task, no main effect of Time, Training type and no interaction were found ($F<1$ in all cases) on dual-task cost (see Table II and Figure 1B).

Table II. Dual-task cost for both alphanumeric equation and visual detection in BASELINE, 4TH and 8TH sessions for each training type

	Dual-task cost					
	SINGLE-task training			VARIABLE training		
	BASELINE	4TH	8TH	BASELINE	4TH	8TH
Alpha	0.27 (.14)	0.28 (.16)	0.28 (.13)	0.21 (.10)	0.21 (.12)	0.24 (.12)
Detect	1.05 (.17)	0.96 (.15)	0.94 (.16)	1.00 (.17)	0.78 (.14) *	0.71 (.20)

*Group x Time interaction, $p < 0.01$
Standard deviation in parentheses

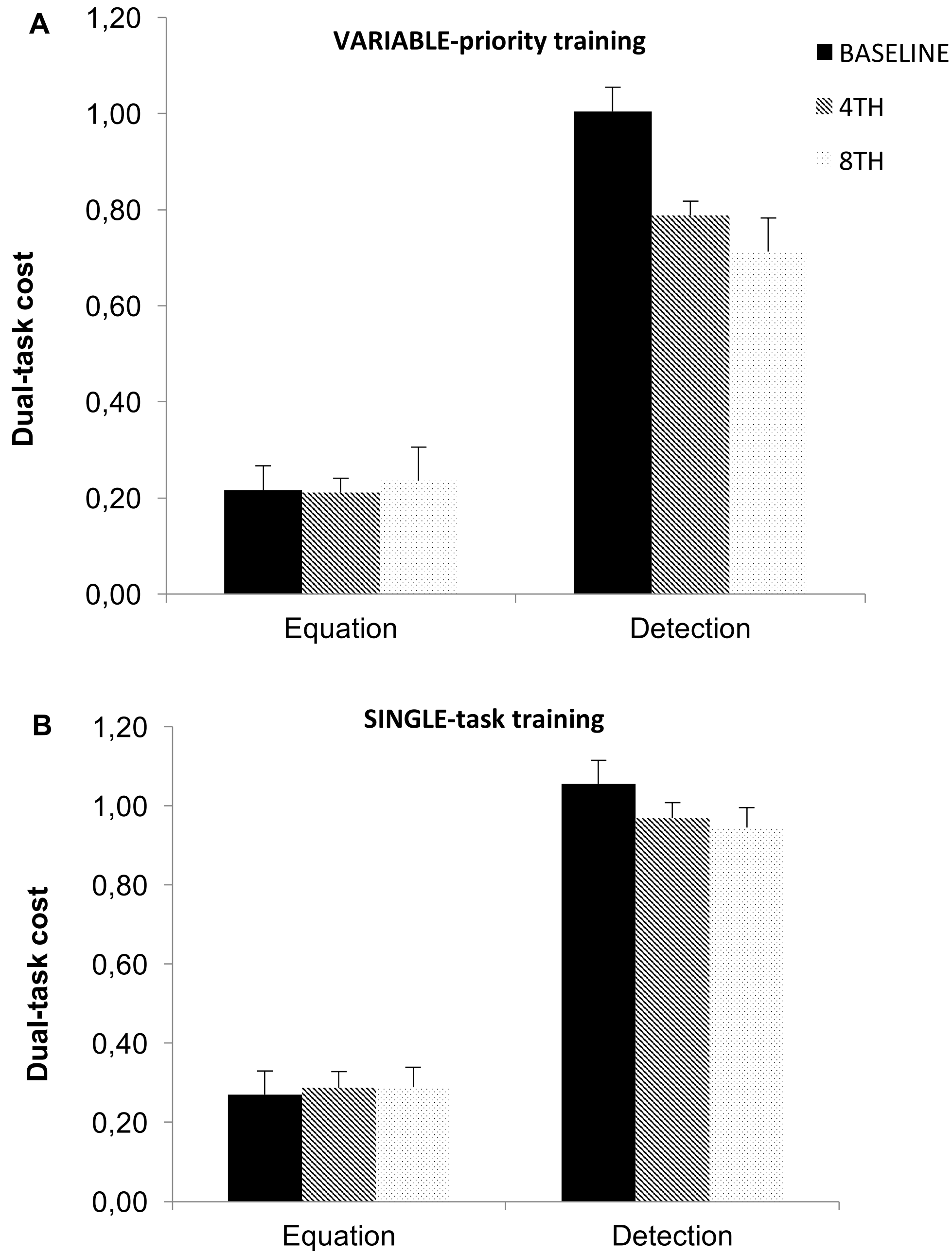

Figure 1. Divided attention cost on each task (alphanumeric equation; visual detection) at BASELINE, 4TH and 8TH for A) VARIABLE-priority training and B) SINGLE-task training.

Behavioral performance - focused attention

To assess the effects of training on single task performance, separate mixed ANOVAs with Time (BASELINE, 4TH, 8TH) as a within-subject factor and Training group (VARIABLE, SINGLE-task) as a between-subject factor were performed, using reaction time (RT) and accuracy (AC) as dependent variables when each task was completed in the focused attention condition. For the visual detection task, a main effect of Time was found on RT, F (1, 25) = 15.96, $p < 0.05$ ($\eta^2 = 0.38$). Mean comparisons and Table III indicate that all participants were faster following training, reducing their RT from BASELINE- to 4TH ($p < 0.05$), but no further improvement was detected from 4TH to 8TH ($p = 0.41$). There was no main effect of Training group and no interaction involving that factor for either variable ($F<1$ in all cases). For the alphanumeric equation task, the analysis showed a main effect of Time on both AC, F (1, 25) = 3.03, $p < 0.05$ ($\eta^2 = 0.11$), and RT, F (1, 25) = 45.10 ($\eta^2 = 0.57$), $p < 0.001$. Mean comparisons and Table III indicate that both groups increased their AC and reduced their RT from PRE- to POST-4 ($p < 0.05$ & $p < 0.001$, for AC and RT, respectively), but no further improvement from 4TH to 8TH was found ($p = 0.24$, $p = 0.41$, for AC and RT respectively). No main effect of Training group and no interaction involving that factor were found for either AC or RT on the alphanumeric equation task ($F < 1$ in all cases).

Table III. Performance in single-task alphanumeric equation and visual detection (reaction time and accuracy) in BASELINE, 4TH and 8TH sessions for each training type

		SINGLE-task training			VARIABLE training		
		BASELINE	4TH	8TH	BASELINE	4TH	8TH
Alpha-equation	AC	81.24 (9.35)	84.62* (12.37)	81.72 (18.94)	72.76 (13.33)	79.76* (13.78)	84.1 (3.1)
	RT	2548.72 (298.33)	2088.49* (284.02)	2110.52 (413.27)	2739.98 (448.67)	2408.82 * (414)	2282.99 (388.51)
Visual detection	AC	94.68 (2.36)	94.78 (1.58)	95.07 (2.24)	92.84 (3.24)	94.28 (2.63)	94.47 (2.57)
	RT	445.07 (27.29)	440.33 * (23.74)	440.83 (37.88)	457.85 (32.45)	449.94* (41.81)	442.53 (40.15)

*Main Time effect, $p < 0.05$
Standard deviation in parentheses

Brain activation in pre-training

<u>**Brain activation in divided attention**</u>

The divided attention condition (Table IV and Figure 2) activated regions typically involved in dual-tasking and controlled attention (Cabeza & Nyberg, 2000): the left and right superior and middle frontal gyrus (areas 9-10) and bilaterally in the precuneus (area 7), cingulate gyrus (area 31) and superior and temporal gyri (areas 39-40).

Table IV. Brain regions associated with divided attention at BASELINE by pooling all participants

Activated areas (Brodmann area)	Cluster size	*x*	*y*	*z*	*t*-value
Right and left precuneus and cingulate gyrus (7, 31)	897	9	-52	32	9.01
Right and left middle and superior frontal gyrus and anterior cingulate gyrus (10, 32)	282	3	56	-10	8.48
Right and left superior and middle frontal gyrus (8,9,10)	259	-18	44	32	9.01
Left angular gyrus, left superior and temporal gyrus (39,40)	134	-54	-61	23	7.43
Right angular gyrus, right superior and temporal gyrus (39,40)	114	51	-61	32	8.79

p<0.05 (FWE) K=100 voxels

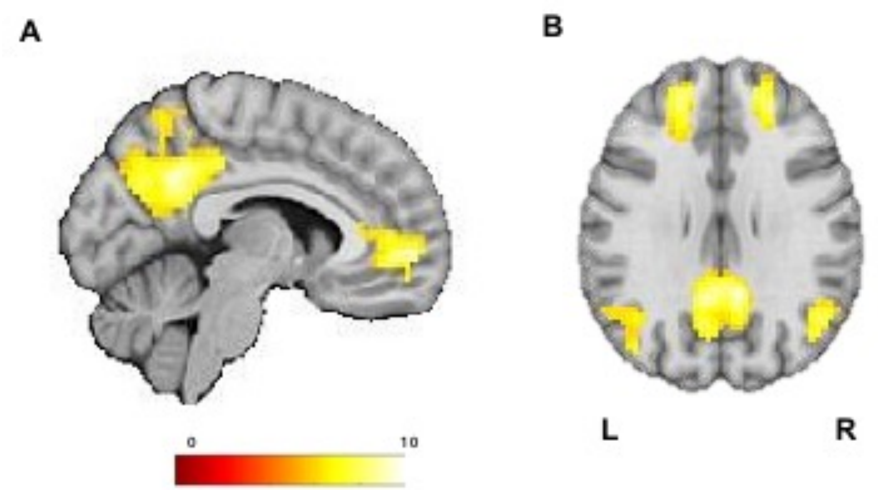

Figure 2. Activation-related to divided attention prior to training (BASELINE). Combining both 20%-Equation; 80%-Equation blocks involves activation in the left and right superior and medial frontal gyrus (A and B), and left and right superior temporal, cingulate gyrus and precuneus (B). The threshold for display is $p < 0.05$, FWE, k= 100 voxels. Colored bar is representative of t scores mentioned in table IV, “L” denotes the left side of the brain, while “R” denotes the right side.

<u>Brain activation in focused attention</u>

We used the pre-training data from the entire group of participants to identify the areas of activation associated with performing the alphanumeric equation and visual detection task. As displayed in Table V, for the alphanumeric equation, main loci of activations were found in the left fronto-parietal areas, occipital areas and in the cerebellum. Bilateral activations were also found in frontal and prefrontal regions. For the visual detection tasks, bilateral activations were found mainly in frontal-parietal areas, occipital regions and in the cerebellum.

Table V. Brain regions associated with focused attention at PRE-training by pooling all participants for the alphabetic equation and detection task

Activated areas (Brodmann area)	Cluster size	*x*	*y*	*z*	*t*-value
Focused Alphabetic equation					
Left superior and inferior parietal lobule, fusiform gyrus, inferior occipital gyrus, cerebellum anterior lobe (6, 7, 17, 18, 40)	3988	12	-91	-4	21.07
Left inferior and middle frontal gyrus, precentral gyrus (6, 8,44,45,46,47)	1247	-39	2	32	13.47
Right and left Cingulate gyri, right and left middle and superior frontal gyrus (6,8,24,32)	474	-6	11	50	13.37
Right insula and inferior prefrontal gyrus (13, 47)	242	33	23	-1	11.56
Focused Visual detection					
Left superior and middle frontal gyrus, left precentral and postcentral gyri, left inferior and middle parietal lobule, left cingulate, precuneus(3, 4, 6, 7, 24, 32, 40).	2670	3	-1	59	11.49
Left and right middle and inferior temporal gyrus, middle and inferior occipital gyrus, left lingual gyrus, cuneus, and left and right cerebellum, culmen and uvula lobe (17, 18, 19, 20, 37)	2166	-33	-58	-28	12.73
Right middle and inferior frontal gyrus, precentral gyrus and right insula (6, 13, 44, 47)	917	51	8	35	10.41
Right superior and inferior parietal lobule, precuneus, supramarginal gyrus (7, 40)	524	27	-61	47	11.16

p<0.05 (FWE), K=100 voxels

Brain activation related to training type and dose effect

Divided attention

Participants in the VARIABLE-priority training showed increased activation when completing the divided attention task from BASELINE- to 4TH in the right middle frontal (area 10) and superior frontal gyri (area 8), and in the superior and inferior parietal gyri (area 7, 40) bilaterally, as shown in Figure 3 and Table VI. There was no further increase or reduction of activation between the 4TH and 8TH time points. When examining the beta value of the four ROIs with repeated measure ANOVAs, followed by mean comparisons, we found a main Time effects for all four clusters, indicating that participants increased their activation from BASELINE- to 4TH ($p < 0.001$ in all cases), but no further changes were found from 4TH to 8TH (see Figure 3).

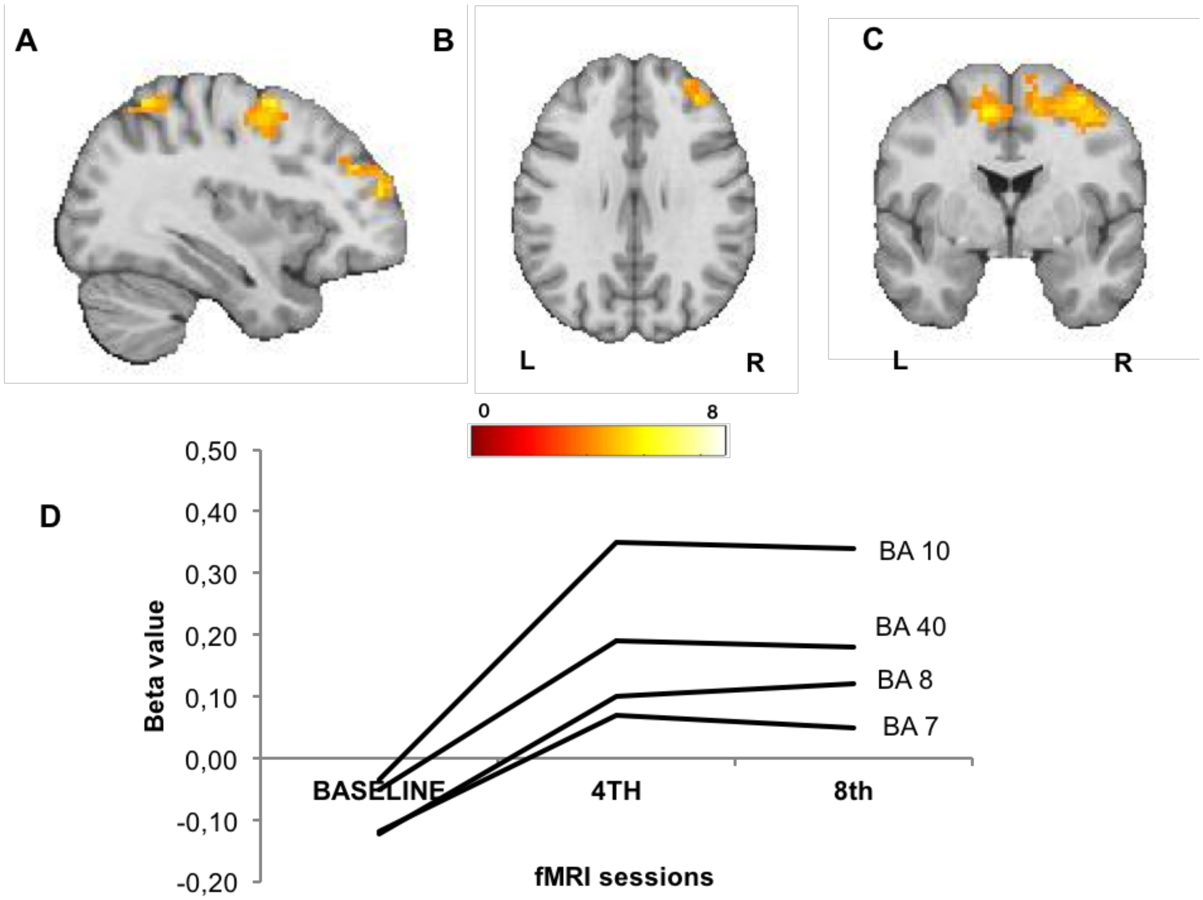

Figure 3. VARIABLE-priority training effect in condition of divided attention. Increased (4TH > BASELINE) in the (A, B) right middle frontal (area 10) and superior frontal gyri (area 8) (A, C), and in the superior and inferior parietal gyri (area 7, 40) (A, C). Graphic in (D) indicated the Beta value (activity estimates ± SE) in the region showing increase activity in right superior and middle frontal gyrus and in the superior and inferior parietal gyri bilaterally during BASELINE and 4TH training session. The threshold for display is $p < .001$, cluster corrected (FWE). Colored bar is representative of t scores mentioned in Table VI. "L" denotes the left side of the brain, while "R" denotes the right side.

For the SINGLE-task training, the whole-brain analysis indicated no activation changes when performing both tasks concurrently in divided attention.

Focused attention

When completing the tasks under focused attention, the only change that was found in the VARIABLE training group was a reduced activation associated with performing the visual detection task (Table VI). Reduced activation was found from BASELINE- to 4TH in the superior and inferior parietal gyri (areas 7, 40) bilaterally, and in the right superior and middle frontal gyri (areas 6, 8).

Table VI. Brain regions associated with training (BASELINE < 4TH or 4TH < BASELINE; 4TH < 8TH or 8TH < 4TH) for the VARIABLE-priority training

Activated areas (Brodmann area)	**Cluster size**	***x***	***y***	***z***	***t*-value**
Focused attention visual detection BASELINE > 4TH					
Left inferior and superior parietal (7,40)	330	-33	-58	47	4.11
Right inferior and superior parietal (7,40	194	33	-49	50	3.89
Right superior and middle frontal gyrus (6,8)	126	33	5	56	4.44
Divided attention 4TH > BASELINE					
Right superior and middle frontal gyrus, anterior and posterior cingulate gyri (8,24,32)	609	15	8	56	8.85
Right superior and middle frontal gyrus (10)	76	39	53	17	5.85
Right inferior parietal (7)	65	24	-67	59	7.04
Left superior parietal (40)	56	-21	-61	47	5.24

$p < 0.001$ uncorrected, cluster corrected (p<0.05, FWE)

For the SINGLE-task training, changes in activation were found in the alphanumeric equation task and were associated with an increase in activation. As shown in Figure 4 and Table VII, increased activation was found from BASELINE- to 4TH in the anterior and posterior cingulate gyri (area 23, 24) bilaterally, and in the precentral and postcentral gyri (area 6, 43) in the right hemisphere. The whole-brain analysis indicated no differences between 4TH to 8TH.

When examining the beta value of the two ROIs with repeated measure ANOVAs followed by mean comparisons, we found a main Time effect for the two clusters. Mean comparisons and Figure 4 indicated an increased activation from BASELINE- to 4TH ($p < 0.001$ in all cases) followed by a decrease 4TH to 8TH ($p < 0.001$ in all cases). The whole-brain analysis indicated no activation changes when performing the visual detection task.

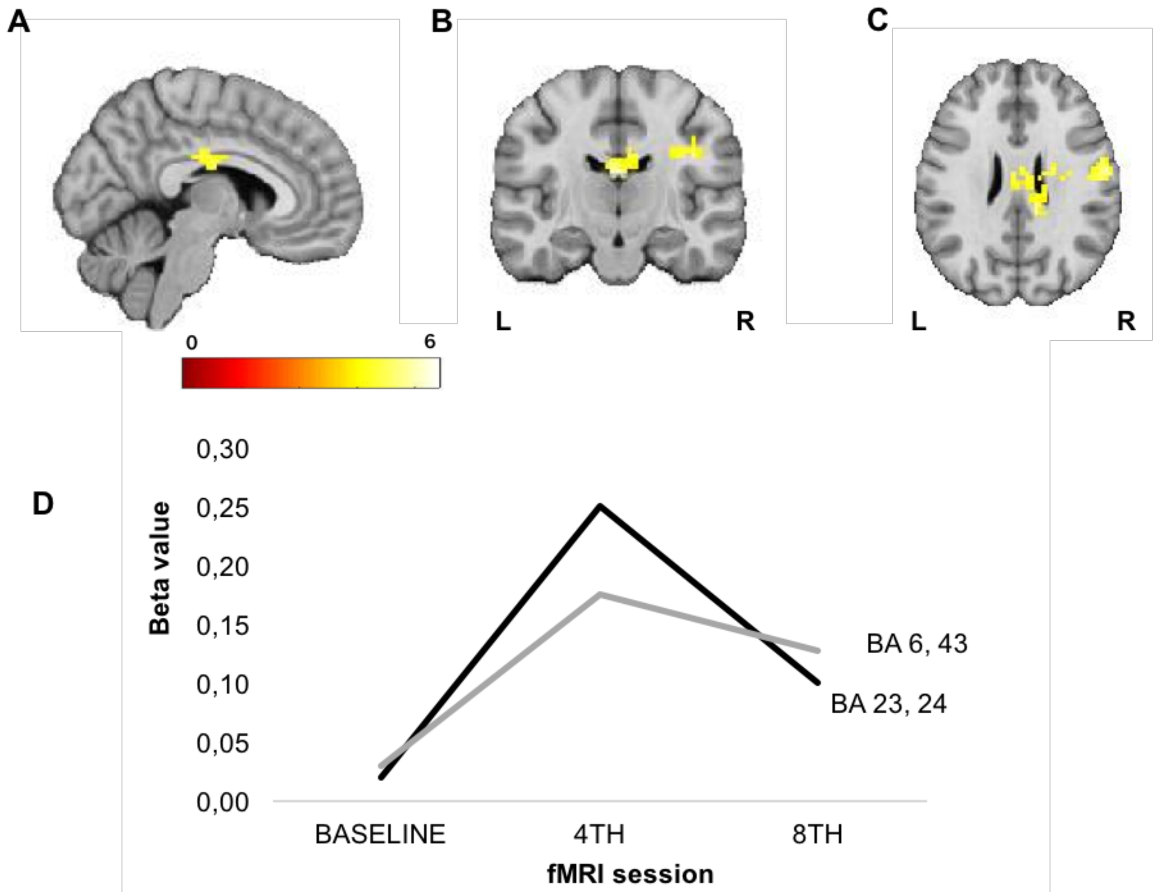

Figure 4. SINGLE-task training effect in condition of focused attention for the alphanumeric equation task. Increased (4TH > BASELINE) in the anterior and posterior cingulate gyri (area 23, 24) bilaterally and in the precentral and postcentral gyri (area 6, 43) in the right hemisphere (B, C). Histogram in (D) indicated the Beta value (activity estimates ± SE) in the regions showing increase activity from BASELINE to 4TH.The threshold for display is p <.001, cluster corrected (FWE). Colored bar is representative of t scores mentioned in Table VII. "L" denotes the left side of the brain, while "R" denotes the right side.

Table VII. Brain regions associated with training (BASELINE < 4TH or 4TH < BASELINE; 4TH < 8TH or 8TH < 4TH) for the SINGLE-task training.

Activated areas (Brodmann area)	Cluster size	*x*	*y*	*z*	*t*-value
Focused attention alphanumeric equation 4TH > BASELINE					
Right postcentral gyrus and precentral gyrus (6, 43)	181	24	-1	32	3.90
Right and left cingulate gyrus (23, 24)	98	0	-13	20	4.07

$p < 0.001$ uncorrected, cluster corrected ($p<0.05$, FWE)

Correlation between performance and training-related activation

Correlations were conducted between activations showing increase activity from BASELINE to 4TH for the SINGLE-task training group (Brodmann's areas 23, 24, 6, 43) and performance on the alphanumeric equation task in focused attention (AC and RT). Correlations were also conducted between activations showing increase activity from BASELINE to 4TH for the VARIABLE-priority training group (Brodmann's area 7, 8, 10, 40) and the dual task cost performance. Participants in the SINGLE- task training showed a significant positive correlation between activation of the cingulate gyri in both hemispheres and the alphanumeric equation task (RT) at Post-8, $r = .56$; $p < .05$. This positive correlation indicates that, at 8TH, better performance (shorter RT) was associated with less activation in the right and left cingulate gyri. Participants in the VARIABLE-priority training condition showed a significant negative correlation at 4TH between attentional cost and activation in the right middle frontal gyrus (area 10), $r= -.64$, $p < 0.05$. In this case, the negative correlation indicates that better performance (lower dual-task cost) was associated with greater brain activation at 4TH.

Discussion

In this study, we investigated the time-course of the dose response on behavior and brain activation resulting from two types of attentional cognitive training programs in older adults and examined the interaction between the type of training provided and the training dose. Overall, we found that different training formats result in different behavioral and neural changes. We also found that these changes vary depending on the dose of training provided, as described below.

Training specific behavioral gains and dose effect

As predicted, the two training types that we tested resulted in specific behavioral improvements of attention. In the VARIABLE priority training, participants were trained to variably control their attentional focus and exert top-down control on the locus of their attention, and to improve their metacognitive abilities, while in the SINGLE-task training, participants performed both tasks individually in focused attention. As expected, the older participants trained in the VARIABLE-priority training were the only ones who reduced their dual-task cost following training when performing both tasks concurrently. Furthermore, they were better able to control their attentional priority. No improvement on dual tasking was found for the SINGLE-task training group, although they were faster and more accurate when asked to solve the alphanumeric equation and faster when performing the visual detection task in focused attention after training. This finding is in line with previous studies reporting selective training effects with similar intervention programs and the efficacy for VARIABLE-priority training to improve attentional control abilities (Belleville et al., 2014; Bier et al., 2014; Zendel et al., 2016). One new component of the present study was the use of a three time-point design to assess the effect of the dose response of both VARIABLE and SINGLE training at BASELINE, 4TH and 8TH session. Interestingly, for both training types, the major training gains in performance were found from BASELINE to the 4TH session, after which the gain levels off. These findings are consistent with those of Lampit et al., (2014) who examined cognitive outcomes during and after 36 sessions of a computerized cognitive training targeting memory, speed of processing, attention, language, and reasoning in healthy older adults. They observed a dose-dependent response displayed by a large gain in performance (loading dose) after relatively few training sessions, followed by a peak performance and maintenance until a few weeks following training (Lampit et al., 2014). They also found that despite a decrease in training gains, some were preserved for as long as 12 months after the completion of training. These findings are vital in understanding the impact of cognitive training, as they provide new insights into dose response relationships and help distinguish different phases in the training process. This could have a tremendous clinical impact if one wants to provide an individualized approach, knowing when the peak response occurs and guiding clinicians as to when it is the appropriate moment to provide booster sessions.

Training specific neural changes and dose effect

A non-linear dose effect was found, as the training-related changes in brain activation were characterized by two different time-courses specific to each training type. As predicted, the participants in the VARIABLE-priority training group were the only ones to show training-related brain changes in the divided attention condition. We found increases in activation from BASELINE to the 4TH session in regions typically involved in attentional control and dual tasking (Cabeza & Nyberg, 2000; Joyce & Hrin, 2015; Stuss, 2011; Stuss & Alexander, 2000): the right middle frontal (area 10) and superior frontal gyri (area 8), and the superior and inferior parietal gyri (area 7, 40), bilaterally. Importantly, we observed a correlation between greater activity in area 10 and better dual-tasking performance at the 4TH session. This correlation suggests that the increase in activation found here may reflect successful compensation (Cabeza & Dennis, 2012). This finding is in line with a previous study conducted by Belleville et al., (2014) who found a specific increase in area 10 in parallel with performance changes in dual-tasking following a VARIABLE-priority training program in healthy older adults. Increased activation in this region was suggested to reflect the engagement of coordination processes necessary for completing such a complex task. This region was also shown to be involved in compensatory processes when task demands are important, in metacognition, and in orchestrating the basic executive functions needed to accomplish novel tasks (Belleville et al., 2014; Burgess, Scott & Frith, 2003; Gilbert, Frith & Burgess, 2005; Stuss, 2011). Therefore, this region might be an interesting component of compensatory processes in older adults and an interesting target for future interventions.

Interestingly, the increases in activations were followed by a maintenance of brain activation from the 4^{th} to 8^{th} session. A similar pattern was found for the behavioral results, as performance in dual tasking was also maintained from the 4^{th} to the 8^{th} session. This suggests that participants engage new brain regions involved in coordination and attentional processes necessary to improve performance, after which these increases in brain activation are maintained to support cognitive performance.

Consistent with the behavioral data, which indicated no gain in performance for divided attention following SINGLE training, that group showed no activation changes associated with dual tasking. Brain activation results showed an inverse U-shape function when performing the alphanumeric equation task in focused attention. Those changes were found in regions typically involved in working memory: the anterior and posterior cingulate gyri, bilaterally and the precentral and post-central gyri, bilaterally. The dose response of these two clusters was non-linear, showing an initial activation increase, followed by a subsequent decrease in activation. The increase in activation from BASELINE to the 4TH session could be explained by the fact that the alphanumeric equation task is a rather complex working memory task requiring a recruitment of regions related to controlled processes or the use of strategy to complete the task. The decreased activation suggests that as participants cumulated experience in the task, the recruitment became more efficient and resulted in a decrease in activation. These results are interesting, as a previous study using similar tasks and training procedure found only a decrease in activation when performing the alphanumeric equation task, using a PRE- POST-test design. Interestingly, using three time-point measures in fMRI enabled us to observe non-linear changes in brain activation.

Our results are in line with a previous study, conducted in a small group of younger adults, showing that training-related cerebral activation changes, following a four-week daily training of working memory, was best characterized by an inverse U-shaped quadratic function (Hempel et al., 2004). Studies focusing on plasticity-induced gray matter changes described this trajectory as an expansion-renormalization process (Lövdén, Wenger, Mårtensson, Lindenberger & Bäckman, 2013; Wenger et al., 2016). Indeed, in the course of training, learning is accompanied by an initial increase in parallel to an increase in the pool of neural resources from which the most efficient wiring can be selected (Reed et al., 2011). This process was proposed to be presumably a more efficient way for the brain to reorganize and adjust than a constant growth process (Kühn & Lindenberger, 2016).

Of note is the fact that participants in the VARIABLE-priority training showed reduced activation from BASELINE to the 4TH session when performing the visual detection task in focused attention. This was found in the superior and inferior parietal gyri (areas 7, 40), bilaterally, and in the right superior and middle frontal gyri (areas 6, 8). This could be explained by the fact that at baseline, participants prioritized the alphanumeric equation, but learned to engage more of their attention to visual detection with VARIABLE-priority training. Therefore, participants were more efficient in performing the visual-detection task after training.

The results for both training groups are coherent with the INTERACTIVE model. First, the model proposes that the pattern of brain changes in activation should align with the cognitive processes that are mobilized by the training and the type of training provided. This is what we found. An attentional control training focusing on learning compensatory strategies leads to changes in regions involved in attention, executive processes, and metacognition, whereas repeated practice on a working memory task leads to changes in regions involved in working memory. Second, the model proposes that the pattern of training-induced brain changes would be modulated by the number of training trials or dose that participants receive, which is also in line with our findings. Interestingly, the present paper underlines that the type of training we choose (strategic vs. repeated practice) will engage different brain processes, and that the pattern observed is non-linear. Indeed, our results show that cognitive and brain processes undoubtedly shift as people automatize the task during training. The inverse U-shape function found after repeated practice may represent a general neuroplasticity principle (Wenger et al., 2016) and a more efficient way for the brain to reorganize. This is not the pattern we found for the strategic training. However, we can hypothesize that the increase in activation at the onset of training could reduce after they reach a performance peak and plateau, as they eventually automatize the strategy that they have learned.

Limitations and future research

Some methodological limitations should be considered. First, the study sample was relatively small when compared to typical randomized control trials. However, considering the cost and constraints imposed by fMRI intervention studies (split across different conditions; multiple scans) and when looking at other cognitive intervention studies focusing on training-induced brain changes in older adults, our sample size is quite reasonable (Belleville et al., 2011; Belleville et al., 2014; Braver & West, 2008; Erickson et al., 2007; Hampstead, Stringer, Stilla, Giddens & Sathian, 2012; Zendel et al., 2016). Be this as it may, large sample studies should be encouraged to include fMRI measures to broaden impact and increase generalization of findings. Second, as no follow-up analyses were conducted in the current study, no conclusions about the stability over time of the observed training effects can be made at this point. It might be important to investigate how these changes and improvements are maintained over time.

Our results have potential implications for the use of fMRI in cognitive training studies, as it was shown to be sensitive to training-related changes, particularly regarding the effect of dose. Indeed, we found specific changes in activation for both training groups between the 4TH and the 8TH session, whereas no differences were found when looking only at the behavioral data. Importantly, the changes observed using fMRI were clinically relevant as they were correlated with the cognitive outcome. Apart from being sensitive to change, fMRI is also known to be reliable over time (Clément & Belleville, 2009; Putcha et al., 2011). This aspect is important, as training efficacy is assessed by repeated measurements.

Furthermore, the question of whether the time-course of cerebral activation changes may be modified by individual characteristics, such as age, education level, or gender is still to be answered. Due to possible individual variability, being aware of the trajectory of the effect of training dose may be advantageous on a clinical standpoint, for example to introduce a booster session or adjust the number of sessions to provide to each participant.

Conclusion

The current study investigated the timecourse of the dose response on behavior and brain activation resulting from two types of attentional cognitive training programs. The innovative aspect of this study was the use of three time-points measures in fMRI. We found that the effect of dose on behavior and training-related brain changes is not linear and this is true for both training types. Behaviorally, both training types result in a rapid change in performance after which the gain levels off. Those changes were specific to the cognitive processes that were mobilized by each training type. For the brain activation changes, training focusing on the use of compensatory strategies (VARIABLE-priority) rapidly increases activation in brain regions associated with attentional control and metacognition, but the brain changes level off in parallel with performance. In turn, repeated practice training (SINGLE-task) shows an inverse U-shaped function, indicating that practice eventually leads to a certain form of automaticity and results in a more efficient system. Importantly, the results of the present study underline the fact that fMRI may be a sensitive and reliable tool to assess the effect of cognitive training over time and provide direct information regarding the impact that environmental stimulation exerts on brain function. Our results emphasize the prospect of investigating cerebral mechanisms underlying training effects.

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CHAPITRE VII : Discussion générale

1. Rappel des objectifs et synthèse des résultats

Ce travail de thèse examine l'effet des interventions cognitives sur le contrôle attentionnel en faisant appel à des mesures comportementales et à des mesures d'IRMf. Cinq études ont découlé de ce travail. Un résumé de leurs objectifs respectifs et une synthèse des principaux résultats sont présentés dans la présente section.

La première étude visait à mieux comprendre la source des différences reliées à l'âge au niveau du contrôle attentionnel et évaluer si ces différences étaient expliquées par une baisse des ressources attentionnelles disponibles avec l'âge, ou par des difficultés à modifier l'emphase attentionnelle en fonction des demandes externes. Pour cela, des participants jeunes et âgés ont effectué deux tâches en attention divisée, soit une tâche d'empan de chiffres et une tâche visuo-spatiale de poursuite d'une cible. Les capacités de contrôle attentionnel étaient évaluées en demandant aux participants de varier la proportion d'attention à accorder à l'une ou l'autre des deux tâches réalisées conjointement selon la consigne d'emphase attentionnelle. Dans une seconde partie de l'étude, les deux tâches devaient être réalisées conjointement et le niveau de difficulté d'une des deux tâches était manipulé de façon paramétrique et individuelle pour chaque participant. Les résultats suggèrent que les participants âgés présentent plus de difficultés que les jeunes adultes à varier le niveau d'attention à allouer à chacune des tâches selon la consigne d'emphase attentionnelle, reflétant un problème de contrôle attentionnel. Par ailleurs, bien que les âgés présentent une performance globale plus faible que les jeunes adultes en condition de double-tâche, aucune interaction entre l'âge et le niveau de difficulté de la tâche n'a été observée. L'effet d'âge observé sur le coût attentionnel n'est donc pas amplifié par le fait d'augmenter le niveau de difficultés de la tâche, ce qui ne va pas dans le sens d'une diminution des ressources, mais plutôt d'une difficulté à réaliser les deux tâches conjointement. Enfin, les résultats de cette étude suggèrent que le contrôle attentionnel pourrait jouer un rôle dans l'explication des différences reliées à l'âge en contexte de double-tâche.

La deuxième étude visait, quant à elle, à comparer l'efficacité de trois types d'entraînement attentionnel chez la personne âgée : 1) un entraînement en pratique simple (*SINGLE*), où les participants pratiquaient deux tâches en attention focalisée, soit une tâche de vérification alphanumérique de type (A + 2 = C) et une tâche de détection visuelle, 2) un entraînement à priorité fixe (*FIXED*), où les participants devaient réaliser les deux mêmes tâches de façon concurrente en portant autant d'attention aux deux et 3) un entraînement à priorité variable (*VARIABLE*) dans lequel les participants étaient appelés à varier le niveau d'attention à allouer à chacune des tâches à travers plusieurs blocs. Les résultats montrent des effets spécifiques selon l'entraînement reçu. En effet, seuls les participants âgés ayant suivi l'entraînement *VARIABLE* améliorent leurs capacités de contrôle attentionnel suite à l'entraînement. Cette amélioration est reflétée par une meilleure habileté à varier le niveau d'attention selon la consigne externe. Les participants du groupe *FIXED* améliorent, quant à eux, leur performance globale en double-tâche, alors que les participants du groupe *SINGLE* ne s'améliorent que sur les tâches réalisées en attention focalisée. Cependant, et contrairement à nos hypothèses, des effets de transfert similaires ont été obtenus pour les trois groupes d'entraînement. En effet, ils ont tous amélioré leur performance sur une tâche de mémoire de travail réalisé avant et après l'entraînement.

Dans le cadre de la troisième étude, nous nous sommes intéressés au transfert de *contexte*, en mesurant si les effets des entraînements attentionnels se transféraient à des tâches similaires à la vie quotidienne. Le transfert de *contexte* était évalué en utilisant un paradigme de double-tâche immersive en RV. Les résultats de cette étude montrent qu'un entraînement *VARIABLE* améliore les capacités de contrôle attentionnel et, pour la première fois, que les effets bénéfiques de cet entraînement peuvent se transférer à un paradigme de double-tâche en RV chez une population âgée. De plus, nous montrons que les âgés bénéficient autant, voire même plus que les jeunes adultes, d'une intervention visant le contrôle attentionnel et que l'âge n'influence pas les effets de transfert obtenus. Également, et de manière similaire aux résultats de la deuxième étude, les effets obtenus sont spécifiques à l'entraînement reçu. Les participants entraînés en *SINGLE* n'améliorent pas leur capacité de contrôle attentionnel et ne montrent pas d'effet de transfert sur le paradigme de double-tâche en RV.

La quatrième étude examinait, quant à elle, l'impact des entraînements attentionnels sur les changements d'activation en IRMf. Les résultats montrent que le cerveau est hautement plastique, même à un âge avancé, et que les changements d'activation obtenus diffèrent selon le type d'intervention reçu. Un entraînement *VARIABLE*, visant l'apprentissage de stratégies de contrôle attentionnel et les capacités métacognitives, produit des augmentations d'activation dans une région frontale impliquée dans la coordination multi-tâche et le contrôle attentionnel (BA 10). Le recrutement accru de cette région cérébrale reflèterait des processus compensatoires, puisque corrélé positivement aux performances en condition de double-tâche. L'entraînement *FIXED*, quant à lui, produit des augmentations d'activation bilatérale au niveau du gyrus frontal médian seulement lors des conditions où les tâches sont réalisées conjointement sans variation de l'emphase attentionnelle (50%-50%). Par ailleurs, l'entraînement *SINGLE*, visant la pratique répétée, produit plutôt des diminutions d'activations en condition d'attention focalisée. De plus, ces diminutions sont corrélées à de meilleures performances lors de la réalisation de la tâche en attention focalisée, indiquant une utilisation plus efficace des régions cérébrales. Ainsi, cette étude montre que le type d'intervention donné est un facteur déterminant des changements d'activation.

La cinquième étude est l'une des rares études à avoir évalué le décours temporel des changements d'activation à l'aide de trois séances en IRMf : 1) avant l'entraînement (*BASELINE*), 2) après la 4^{e} séance d'entraînement (séance 4), et 3) après la 8^{e} et dernière séance d'entraînement (séance 8). Les résultats montrent que les changements d'activation sont non linéaires au cours de l'entraînement et, de façon similaire aux résultats obtenus dans la quatrième étude, modulés par le type d'intervention donné. L'entraînement *VARIABLE* entraîne des augmentations d'activation, du *BASELINE* à la session 4, dans des régions frontales et pariétales impliquées dans la coordination multitâche et le contrôle attentionnel. Plus particulièrement, l'augmentation d'activation dans la région frontale BA 10 est corrélée à de meilleures performances en situation de double-tâche. Comme pour les performances comportementales, les activations atteignent un plateau de la session 4 à la session 8. Par ailleurs, et contrairement à nos hypothèses, le patron d'activation lors de l'entraînement *SINGLE* est caractérisé par une courbe en U inversée. Ainsi, en condition d'attention focalisée, une amélioration des performances ainsi qu'une augmentation d'activation dans les régions impliquées dans la tâche sont d'abord observées du *BASELINE* à la session 4. Les performances comportementales sont ensuite maintenues de la session 4 à la session 8, mais une diminution d'activation est notée de la session 4 à la session 8. Les augmentations d'activation sont interprétées comme reflétant l'utilisation de stratégies pour compléter la tâche, qui est au départ relativement complexe. Les stratégies utilisées deviennent alors plus efficaces, suivant la session 4, et s'automatisent, se traduisant par une diminution d'activation et un recrutement plus efficace des régions impliquées.

Dans les prochaines sections, les principaux résultats des études qui constituent la thèse seront incorporés à la littérature existante dans une discussion intégrative. Ensuite, les limites de ce travail seront abordées pour ouvrir enfin sur les implications cliniques et perspectives futures.

2. Bénéfices d'un entraînement à priorité variable

Un des objectifs majeurs de la thèse était d'examiner les bénéfices d'un entraînement à *priorité variable* pour améliorer les capacités de contrôle attentionnel chez la personne âgée. L'article 2 et 4 de la présente thèse visait donc à comparer l'efficacité d'un entraînement à *priorité variable* (*VARIABLE*) en utilisant, pour la première fois, deux groupes contrôles actifs ciblant, 1) la performance aux tâches en attention divisée sans modulation attentionnelle (*FIXED*) et 2) la performance aux tâches en attention focalisée (*SINGLE*). Les résultats combinés de ces deux articles mettent en évidence que le type d'entraînement attentionnel peut avoir des impacts très différents sur les capacités attentionnelles, et que les effets obtenus sont cohérents avec les processus cognitifs visés par chaque entraînement. Nos résultats montrent qu'un entraînement *VARIABLE*, visant l'apprentissage de stratégies de contrôle attentionnel et favorisant les capacités métacognitives des participants, est le seul qui permet d'améliorer les capacités de contrôle attentionnel chez la personne âgée. Malgré la présence de difficultés marquées en pré-entraînement, les participants âgés sont en mesure, suite à l'entraînement *VARIABLE*, de varier le niveau d'attention à allouer à chacune des tâches selon la consigne donnée.

Nos résultats sont aussi les premiers à montrer que l'amélioration du contrôle attentionnel n'est pas due à la pratique aux tâches simples. Nous montrons aussi que le fait d'être entraîné à performer les deux tâches en attention divisée (sans modulation attentionnelle) ne permet pas d'améliorer les capacités de contrôle attentionnel des âgés. Ces résultats sont corroborés par certaines études ayant montré les bénéfices d'un entraînement à *priorité variable,* lorsque comparés à un entraînement à *priorité fixe* (Gagnon & Belleville, 2012; Kramer et al., 1995; Lussier et al., 2016). Cependant, certains auteurs n'ont montré aucune différence entre les deux types d'entraînement (Bherer et al., 2005). Une hypothèse explicative pourrait être reliée à la nature des tâches à combiner. En effet, l'ensemble des résultats du présent travail mettent en évidence qu'un entraînement *VARIABLE* semble plus efficace dans les conditions où les tâches à combiner sont plus difficiles et impliquent une certaine liberté dans la coordination des deux (*self-paced tasks*). D'ailleurs, les études n'ayant pas réussi à montrer la supériorité d'un entraînement *VARIABLE* semblent avoir combiné des tâches de nature plus simple (par exemple, deux tâches de discrimination visuelles) qui demandaient peu de capacité de coordination (Bherer et al., 2005 ; 2008). Nous avons aussi montré qu'un entraînement *VARIABLE* semble plus efficace dans un contexte où les deux tâches diffèrent d'un point de vue de la saillance. Par exemple, lorsque l'on conduit une voiture tout en poursuivant une conversation animée avec le passager.

Une des forces du présent travail est d'avoir montré que les bénéfices d'un entraînement *VARIABLE* sont aussi visibles au niveau cérébral et qu'ils se distinguent des deux autres types d'entraînement. En effet, les résultats des articles 4 et 5 montrent que seuls les participants âgés du groupe *VARIABLE* recrutent davantage, suite à l'entraînement, la région BA 10 qui est impliquée dans la coordination multitâche et les capacités métacognitives. L'augmentation d'activation dans cette région est reliée à de meilleures performances au plan comportemental suggérant que les changements d'activation observés reflètent des processus de compensation réussie.

Il est tout de même important de nuancer nos résultats en lien avec les études 3 et 5 de ce travail, qui ne comparait pas directement les trois types d'entraînement attentionnel. L'objectif de ces deux études n'était pas de montrer la supériorité d'un entraînement à *priorité variable* ou de comparer deux types d'entraînement en attention divisée, mais d'utiliser, à la lumière des résultats de nos études précédentes (Belleville, Mellah, de Boysson, Demonet & Bier, 2014; Bier, de Boysson & Belleville, 2014), l'entraînement le plus efficace pour améliorer les capacités de contrôle attentionnel. Nous avons donc décidé de ne comparer qu'un entraînement *VARIABLE* à un entraînement visant la pratique aux tâches en attention focalisée (*SINGLE*), sachant qu'il produirait des effets différents. Les résultats de ces deux études mettent aussi en évidence des effets spécifiques selon le type d'entraînement, et ce à la fois au niveau comportemental et cérébral. En effet, l'entraînement *VARIABLE* est le seul qui permet l'amélioration des capacités de contrôle attentionnel et qui entraine le recrutement de régions attentionnelles/exécutives.

Le présent travail supporte l'utilisation d'un entraînement *VARIABLE* pour améliorer les capacités de contrôle attentionnel chez la personne âgée. De plus, la pertinence de cet entraînement chez la personne âgée est justifiée par les résultats des articles 1 et 3, montrant que le contrôle attentionnel semble être au cœur des difficultés attentionnelles chez cette population. Enfin, l'ensemble des résultats apporte un éclairage intéressant sur l'importance de bien connaître l'ingrédient actif de nos entraînements afin d'en prévoir les effets.

3. Transfert des entraînements attentionnels : où en sommes-nous ?

3.1 L'âge est-il un facteur modérateur des effets de transfert ?

Un autre objectif de ce travail était d'évaluer si les effets de transfert mesurés diffèrent selon l'âge des participants ; nous souhaitions explorer la possibilité que les personnes âgées montrent un transfert moins important que les jeunes adultes. Cependant, nos résultats suggèrent que ce n'est pas le cas. On observe l'effet inverse, c'est-à-dire que les participants âgés montrent un transfert plus important sur la tâche de RV que les jeunes adultes. Bien que ces résultats puissent sembler surprenants, l'effet d'âge obtenu sur la capacité de transfert est cohérent avec les effets de l'entraînement. En effet, nos résultats suggèrent que les participants âgés ont davantage bénéficié de l'entraînement *VARIABLE*, se traduisant par un effet plus important sur les capacités de contrôle attentionnel suite à l'entraînement. Ceci pourrait s'expliquer par le fait que les participants âgés présentaient plus de difficultés à varier le niveau d'attention à allouer à chacune des tâches en pré-entraînement, ce qui aurait pu laisser plus de place à l'amélioration.

Ces résultats sont particulièrement intéressants, surtout à la lumière des études suggérant qu'une diminution des capacités plastiques du cerveau avec l'âge aurait pour effet de limiter la capacité des âgés à généraliser leurs apprentissages (Dahlin et al., 2008; Derwinger et al., 2003; Neely & Backman, 1993). Nos résultats vont plutôt dans le sens d'une préservation des capacités plastiques du cerveau avec l'âge et corroborent les résultats de quelques études montrant un effet de transfert similaire pour les deux groupes d'âge suite à des entraînements en mémoire de travail et en attention divisée (Bherer et al., 2005 ; Li et al., 2008). Ces résultats sont aussi importants puisqu'il souligne que le type d'entraînement donné et les effets de transfert obtenus peuvent différer selon la population ciblée.

3.2 Entraînement à priorité variable : transfert de contenu vs de contexte

Les articles 2 et 3 de la présente thèse avaient comme objectif d'évaluer la capacité des entrainements attentionnels à produire un transfert de *contenu* vs un transfert de *contexte*. Rappelons que le transfert de *contenu* survient lorsque l'apprentissage d'une habileté mène à l'amélioration d'une nouvelle habileté, tâche ou fonction cognitive non directement visée par l'entraînement (Austin, 2009; Butterfield & Nelson, 1991; Mayer & Wittrock, 1996; Noack et al., 2009). Le transfert de *contexte,* quant à lui, survient lorsqu'un comportement ou une stratégie apprise dans un contexte est appliqué avec succès dans un contexte différent de celui entraîné (Bransford et al., 2000; Lobato, 2006; Perkins & Salomon, 1992). Les résultats de ce travail montrent la présence des deux types de transfert suite aux entraînements attentionnels.

En ce qui concerne le transfert de *contenu*, les résultats de l'article 1 montrent des effets de transfert similaires pour les trois groupes entraînés (*VARIABLE* ; *FIXED* ; *SINGLE*). Le transfert de *contenu* a été évalué à l'aide d'une tâche de *N-Back*, qui implique la mise à jour, le *monitoring* et la manipulation d'information en mémoire de travail (Owen, McMillan, Laird & Bullmore, 2005). Contrairement à nos hypothèses, le transfert des bénéfices d'un entraînement *VARIABLE* n'était pas supérieur lorsque comparé aux deux autres entraînements. Ces résultats peuvent paraître surprenants compte tenu des études qui suggèrent qu'un entraînement *VARIABLE* devrait produire plus d'effet de transfert (Gopher, 2007; Kramer et al., 1995; Lussier et al., 2016). Plusieurs explications sont possibles. La première serait reliée au fait que les trois groupes étaient entraînés à réaliser une tâche de vérification alphanumérique, qui implique, comme pour la tâche de *N-Back*, la manipulation d'information en mémoire de travail. Ainsi, l'exposition à une tâche avec une forte composante en mémoire de travail aurait permis un transfert dans une tâche de mise à jour. Ensuite, ces résultats pourraient être expliqués par la présence d'un effet test re-test, puisque les participants ont réalisé les tâches en pré- et post-entraînement. Le fait que nous n'ayons pas de groupe contrôle sans contact ne nous permet pas de confirmer ou non cette hypothèse. Ces résultats sont corroborés par quelques études ayant montré des effets de transfert de *contenu* suite aux entraînements attentionnels (Bherer et al., 2005, 2008; Kramer et al., 1999; Kramer et al., 1995; Lussier et al., 2016). Ces études ont utilisé des tâches de transfert où l'on modifiait le type de réponse, la nature ou la modalité de présentation des stimuli. Bien qu'aucun effet du type d'entraînement n'ait été montré sur la mesure de transfert choisie, nos résultats sont encourageants puisqu'ils montrent une possibilité de transfert des entraînements attentionnels sur des tâches relativement différentes de celles entraînées et impliquant d'autres habiletés cognitives (par exemple, la mise à jour).

Nous étions aussi particulièrement intéressés aux effets de transfert des entraînements attentionnels dans un environnement plus proche de la vie quotidienne (transfert de *contexte*). Pour ce faire, nous avons développé un paradigme de double-tâche immersive (*promenade en voiture virtuelle*) dans le lequel le participant est passager d'une voiture et doit guider le conducteur en cherchant des indications sur la route tout en complétant une tâche auditivo-verbale complexe. L'article 3 visait à comprendre si un entraînement *VARIABLE* amenait des effets de transfert plus importants qu'un entraînement en pratique simple (*SINGLE*). Pour la première fois, nos résultats mettent évidence des effets de transfert de *contexte* sur un paradigme de double-tâche en RV chez la personne âgée. Les participants âgés entraînés en condition *VARIABLE* sont les seuls à montrer un transfert en condition de double-tâche dans l'environnement virtuel. En effet, ils obtiennent de meilleures performances, suite à l'entraînement, sur les deux tâches lorsqu'elles sont réalisées conjointement. Nous montrons aussi que les gains obtenus suite à l'entraînement *VARIABLE* sont corrélés au gain à la tâche de *promenade en voiture virtuelle,* suggérant un transfert réel des apprentissages et non un effet test re-test. Ces effets ne sont pas observés chez le groupe *SINGLE*. Cependant, ce dernier améliore ses performances sur l'une des deux tâches en RV (détection visuelle), lorsque celle-ci est réalisée en attention focalisée. Les deux groupes entraînés sont donc en mesure de transférer leur acquis dans un nouveau contexte, mais les effets de transfert sont spécifiques au type d'entraînement. Ces résultats sont particulièrement importants, puisque le transfert des apprentissages à un nouveau contexte, plus représentatif du quotidien, est essentiel d'un point de vue clinique et a été relativement peu évalué chez la personne âgée.

Notre étude incite aussi à se questionner sur l'impact de l'ingrédient actif de nos entraînements (contrôle attentionnel vs pratique aux tâches simples) sur les effets de transfert attendus. En effet, un entraînement qui permet de développer les capacités métacognitives, de coordonner de multiples tâches en amenant les participants à redistribuer leurs ressources attentionnelles entre celles-ci, semblerait se transférer davantage à un nouvel environnement qui implique des processus attentionnels complexes, qu'un entraînement visant la pratique répétée de tâche en attention focalisée. Des études effectuées chez le jeune adulte semblent aussi aller dans cette direction (Gopher, 1996; Gopher et al., 1994). Gopher et al., (1994) et Hart & Battiste (1992) montrent qu'un entraînement à *priorité variable* améliore les performances de jeunes cadets lors d'une tâche complexe réalisée en contexte réel (performance en vol). Il est donc possible qu'un entraînement *VARIABLE* soit un choix intéressant si l'on veut avoir un impact sur les activités complexes du quotidien.

3.3 Mesurer le transfert dans la vie de tous les jours : apport de la réalité virtuelle

Tel que mentionné dans l'introduction, l'étude du transfert des entraînements dans les activités de la vie de tous les jours ou hors du laboratoire a été peu abordée chez la personne âgée et représente un défi important. Un des objectifs de ce travail était de trouver un outil qui nous permettrait d'évaluer le transfert de façon objective et qui traduirait la complexité des tâches que l'on peut rencontrer au quotidien. Nous nous sommes intéressés aux systèmes de RV à cet égard, puisque ce sont des systèmes prometteurs qui permettent de créer des situations proches des activités réelles sans compromettre le contrôle expérimental (pour une revue voir : Plancher, Nicolas & Piolino, 2008; Schultheis, Himelstein & Rizzo, 2002). La RV consiste à programmer des environnements informatisés riches et multi-sensoriels, qui permettent de mesurer les comportements lors de différentes situations ou tâches qui s'apparentent fortement à des situations réalistes du quotidien (Plancher et al., 2008). Grâce à sa validité écologique, la RV est de plus en plus reconnue comme une technique utile pour l'évaluation et la rééducation des processus cognitifs (Plancher, Nicolas & Piolino, 2008 ; Schultheis, Himelstein & Rizzo, 2002). À notre connaissance, notre étude est la première à avoir utilisé cette technologie comme mesure pour évaluer les effets de transfert chez la personne âgée.

Les résultats de ce travail montrent qu'il est possible d'utiliser la RV chez une population âgée et que celle-ci semble être une mesure sensible pour évaluer les effets de transfert. En effet, nous avons obtenu des effets de transfert spécifique dans l'environnement virtuel, c'est-à-dire une amélioration des performances en double-tâche seulement pour le groupe *VARIABLE*, alors que ces effets distinctifs n'ont pas été observés sur un questionnaire auto-rapporté. Ce dernier mesurait la fréquence à laquelle les participants commettent des erreurs dans la réalisation de tâches attentionnelles au quotidien. Ces résultats sont particulièrement encourageants puisque peu d'études ont montré des effets de transfert sur des tâches plus représentatives du quotidien.

À la lumière de nos résultats, la *promenade en voiture virtuelle* pourrait aussi être utilisée comme une mesure plus écologique pour évaluer les capacités des personnes âgées à partager leurs ressources attentionnelles entre différentes informations. D'ailleurs certaines études chez la personne âgée ont montré que les performances aux tâches virtuelles étaient fortement corrélées aux performances lors de tâches réalisées dans un environnement « réel » (Allain et al., 2014; Cushman, Stein & Duffy, 2008; Plancher, Gyselinck, Nicolas & Piolino, 2010). Par exemple, Cushman et al., (2008) ont montré une corrélation entre les difficultés de navigation mesurées dans le lobby du *Strong Memorial Hospital* et une reproduction virtuelle de cet environnement. Plancher et al., (2010) ont aussi montré que, par rapport à un test standard de mémoire, les performances de mémoire lors du rappel d'éléments vu lors de l'exploration d'une ville virtuelle étaient corrélées à la plainte mnésique chez les participants âgés.

En somme, la RV est une technologie en pleine expansion, qui est de plus en plus accessible et abordable. Elle ouvre un large champ d'investigation futur aussi bien pour mesurer les effets de transfert des entraînements que pour l'évaluation des fonctions cognitives et même, à titre d'entraînement cognitif (voir section 6).

4. IRMf et entraînement cognitif

4.1 Interprétation des résultats en lien avec les modèles de compensation dans le vieillissement normal

Différents modèles ont été proposés pour rendre compte des effets des entraînements cognitifs sur le cerveau des personnes âgées (Cabeza, 2002; Reuter-Lorenz & Cappell, 2008; Reuter-Lorenz & Park, 2014). Ceux-ci font souvent appel à la notion de compensation ou de plasticité cérébrale. La plasticité cérébrale renvoie à la capacité qu'a le cerveau de se réorganiser et de se modifier en fonction de changements ou de stimulations provenant de l'environnement externe (par exemple, apprentissage de nouvelles stratégies) et/ou de demandes endogènes (par exemple, une lésion cérébrale ou les changements associés au vieillissement normal). La majorité des modèles se sont toutefois basés sur la compensation qui s'opère de façon « naturelle » au cours du vieillissement, plutôt que suite aux entraînements cognitifs. Parmi ceux-ci, le modèle HAROLD proposé par Cabeza (2002) suggère qu'au cours du vieillissement la compensation s'opère via le recrutement de régions alternatives (latentes) et controlatérales à celles typiquement recrutées par la tâche. Selon le modèle, cette augmentation d'activation serait une forme de compensation réussie, puisqu'elle permettrait de pallier la diminution de l'efficacité des régions spécialisées suite au vieillissement et de soutenir la réalisation optimale de la tâche (Cabeza, 2002). Le modèle CRUNCH (Reuter-Lorenz & Cappell, 2008), quant à lui, suggère que la compensation est supportée par des augmentations d'activation, soit dans les réseaux spécialisés dans les processus sollicités par la tâche, soit dans de nouvelles régions (alternatives), qui ne sont pas normalement impliquées dans la tâche.

La comparaison de nos résultats avec ces modèles s'avère toutefois difficile, puisque les patrons d'activation varient considérablement selon le type d'entraînement donné. Les résultats des articles 4 et 5 de ce travail montrent qu'un entraînement *VARIABLE* entraîne des augmentations d'activation dans des régions reliées au contrôle attentionnel et aux capacités métacognitives. Plus spécifiquement, les deux articles montrent un recrutement supérieur à droite dans la région BA 10, celle-ci étant bilatéralement activée en pré-entraînement. Ce patron contraste avec le modèle HAROLD, puisque ce dernier suggère que le cerveau compense en augmentant l'activation dans les régions alternatives, controlatérales à celles impliquées dans la tâche.

De plus, ces modèles permettent difficilement d'interpréter les diminutions d'activation observées suite à l'entraînement *SINGLE*, puisqu'ils suggèrent que la compensation s'opèrerait plutôt par l'entremise d'augmentations d'activation et non de diminutions. Les résultats des articles 4 et 5 montrent une diminution de l'asymétrie suite à l'entraînement *SINGLE*. Ces diminutions, pour la plupart dans l'hémisphère droit, sont notées au sein de régions qui étaient bilatéralement activées lors de la réalisation de la tâche en pré-entraînement. Il est toutefois possible que la pratique répétée ait permis de réduire le besoin de recruter les régions controlatérales, ce qui pourrait être compatible avec le modèle HAROLD.

4.2 Interprétation des résultats selon le modèle INTERACTIVE

Le présent travail a permis de contribuer au développement d'un nouveau modèle plus adapté pour l'interprétation des effets des interventions cognitives sur le cerveau. Le modèle INTERACTIVE, suggère que les changements d'activation induits par les interventions cognitives dépendent d'une interaction complexe entre 1) les caractéristiques de l'entraînement, c'est-à-dire le type (ou la nature), la dose et les processus cognitifs visés et 2) les caractéristiques de l'individu, par exemple le niveau d'éducation, la présence ou non d'atteintes cognitives, la sévérité et la localisation de lésions cérébrales, ou le niveau cognitif de base. Dans le cadre de ce travail, nous nous sommes particulièrement intéressés aux effets du type d'entraînement (stratégique vs répétée) et de la dose (nombre de séances données) sur les changements d'activation.

Concernant l'effet du type d'entraînement, les résultats des articles 4 et 5 de ce travail supportent la proposition du modèle voulant qu'une intervention se basant sur l'apprentissage de stratégies compensatoires ou visant des capacités métacognitives (ici l'entraînement *VARIABLE*), entraine des augmentations ou de nouvelles activations dans des régions qui reflètent les stratégies apprises, alors qu'une intervention visant la pratique répétée (ici l'entraînement *SINGLE*) entraine plutôt des diminutions d'activations dans les régions préalablement impliquées dans la réalisation de la tâche. Ces diminutions ont été montrées comme étant associées à de meilleures performances et reflèteraient un recrutement plus efficace et une meilleure utilisation des circuits neuronaux nécessaires à la réalisation de la tâche. Des résultats similaires ont été rapportés chez le jeune adulte suite à la pratique de tâches en mémoire de travail (Chein & Schneider, 2005) et en attention divisée chez la personne âgée (Erickson et al., 2007).

Le modèle propose aussi que les patrons d'activation cérébraux doivent être reliés aux processus visés par l'entraînement. Les résultats des deux derniers articles de ce travail montrent qu'une intervention visant les capacités de contrôle attentionnel et métacognitives, entraîne des changements au sein de régions attentionnelles/exécutives, alors qu'un entraînement visant la pratique répétée d'une tâche de mémoire de travail produit plutôt des changements dans des régions impliquées en mémoire de travail. Par conséquent, prédire l'effet d'une intervention donnée sur le cerveau demande une connaissance précise des processus cognitifs impliqués dans l'entraînement et des mécanismes modulés par ceux-ci.

Concernant l'effet de la dose, l'article 5 de ce travail est la première étude, à notre connaissance, à avoir évalué le décours temporel des changements d'activation chez une population âgée à l'aide de trois temps de mesure en IRMf. Les résultats de ce dernier article sont importants et corroborent ceux des études dans le domaine de l'apprentissage moteur soulignant que les changements d'activation sont modulés au cours de l'entraînement (Doyon & Benali, 2005; Wenger et al., 2016). Nous montrons que, suite à un entraînement cognitif, les changements d'activation sont non-linéaires et que le décours temporel de ces changements diffère selon le type d'intervention reçu. Contrairement à nos hypothèses voulant que la diminution d'activation soit linéaire plus la tâche devient automatisée et bien apprise, le décours temporel des changements d'activation suite à la pratique répétée d'une tâche de mémoire de travail (*SINGLE*) est plutôt caractérisé par une courbe en U inversée. Les participants présentent d'abord des augmentations d'activation en lien avec l'utilisation de stratégie leur permettant de réaliser la tâche. Ces activations diminuent ensuite, malgré un maintien des performances. Ceci peut s'expliquer par le fait que la tâche s'automatise et que le réseau devient plus efficace. Ce patron est corroboré par quelques études ayant utilisé des mesures répétées en imagerie structurelle (Wenger et al., 2016) ou en IRMf chez le jeune adulte (Hempel et al., 2004). Cette courbe en U inversée n'est toutefois pas observée suite à l'entraînement stratégique en contrôle attentionnel (*VARIABLE*). Les résultats montrent plutôt des augmentations d'activation dans les régions reliées aux stratégies apprises suivies d'un plateau, ce dernier étant parallèle au maintien des performances.

Ces résultats supportent la notion que les processus cognitifs et cérébraux se modifient plus la tâche devient automatisée et bien apprise. La courbe en U inversée est peut-être une façon efficace qu'a le cerveau de se réorganiser. On peut penser que les changements d'activation suite à l'apprentissage de nouvelles stratégies pourraient éventuellement s'automatiser et se traduire par une baisse d'activation dans les régions liées à la stratégie apprise.

4.3 Contribution de l'IRMf

L'utilisation de l'IRMf dans le cadre de ce travail a permis d'amener un éclairage nouveau sur l'impact des interventions cognitives sur le cerveau des personnes âgées. Nos études montrent que cette technique est une mesure sensible et fiable des effets des interventions cognitives. En effet, les régions cérébrales modifiées par les entraînements sont cohérentes avec le type d'entraînement reçu et les processus cognitifs visés. Nous avons aussi été en mesure de montrer, à l'aide de l'IRMf, des changements non-linéaires au cours de l'entraînement. Ceci n'aurait pas été possible en utilisant que les données comportementales, puisque nous montrons que les changements au niveau cérébral s'opèrent malgré la présence d'un plateau dans les performances. Tel que mentionné plus haut, l'IRMf a aussi permis d'enrichir les modèles de compensation « naturelle » dans le but d'interpréter de façon plus précise l'effet des entraînements sur le cerveau.

Un des apports importants de ce travail est d'avoir montré qu'une connaissance plus précise des mécanismes cérébraux pourrait guider le choix du type d'entraînement cognitif pour une prise en charge individualisée. Les interventions stratégiques (ou compensatoires) entrainent des augmentations d'activation en lien avec les stratégies apprises et ont pour but de contourner les déficits cognitifs en enseignant de nouvelles techniques ou méthodes pour réaliser la tâche. Les interventions en pratique répétée (ou restauratrices) entrainent plutôt des diminutions dans les régions spécialisées et visent l'amélioration du domaine cognitif altéré en favorisant une stimulation élevée de celui-ci. Sachant cela, il est possible d'émettre l'hypothèse qu'en présence d'atteintes structurelles trop sévères, il soit préférable d'encourager l'utilisation d'interventions compensatoires via l'utilisation de régions cérébrales résiduelles ou alternatives. L'utilisation de l'IRMf permet donc de guider le choix des interventions cognitives selon la population ciblée, ce qui pourrait en faire un outil clinique particulièrement intéressant.

5. Limites de ce travail

Cette thèse présente certaines limites qu'il est important de souligner. Premièrement, les participants rencontrés pour l'ensemble des études étaient pour la plupart inscrits sur la liste de la Banque de participants du Centre de Recherche de l'Institut Universitaire de Gériatrie de Montréal. Il est fort probable que les caractéristiques des personnes qui participent à des études soient différentes de celles qui ne participent pas, par exemple, en lien avec la motivation, la santé, le niveau d'éducation ou le fonctionnement cognitif. De plus, l'ensemble des études de cette thèse comportait un nombre beaucoup plus élevé de femmes que d'hommes. Enfin, notons que les limites citées ici sont inhérentes aux recherches dans le domaine du vieillissement.

Une autre limite pourrait tenir au nombre de participants relativement restreint par groupe d'entraînement. Bien que la taille des échantillons nous ait permis de détecter des effets robustes suite aux entraînements, cela aurait pu aussi cacher certains effets. Rappelons que les études d'intervention sont coûteuses, particulièrement avec l'utilisation de l'IRMf. De plus, le recrutement peut s'avérer difficile et les projets d'intervention comportent de nombreuses visites ce qui est exigeant pour les participants. Nos échantillons sont toutefois comparables aux autres études dans la littérature ayant intégré des techniques d'imagerie cérébrale (Belleville, Clément, et al., 2011; Belleville et al., 2014; Braver & West, 2008; Erickson et al., 2007; Hampstead et al., 2012; Zendel, de Boysson, Mellah, Démonet & Belleville, 2016). Il serait intéressant d'encourager les études avec de grands échantillons d'inclure des techniques d'imagerie dans leur protocole expérimental.

Une autre limite, concernant plus particulièrement notre troisième étude, est en lien avec la nature écologique de la tâche de transfert choisie. Bien que le paradigme de double-tâche en RV ait été développé pour être plus représentatif de la complexité des tâches que peuvent rencontrer les âgés au quotidien, celle-ci reste une tâche expérimentale réalisée en laboratoire dans un environnement standardisé.

Enfin, une autre limite, pouvant s'appliquer à l'ensemble des études décrites dans ce travail, est de ne pas avoir inclus de suivi à long terme des participants. Il aurait été intéressant d'inclure des séances *boosters* et un suivi à 1, 6 et 12 mois pour évaluer si les effets de nos entraînements se maintiennent ou diminuent dans le temps. Il a même été proposé qu'un intervalle de trois ans était le plus approprié pour évaluer la stabilité des effets à long terme suite aux entraînements (Salthouse, 2006).

6. Implications cliniques de ce travail et perspectives futures

Nous avons montré qu'il était possible d'améliorer le contrôle attentionnel des personnes âgées saines suite à un entraînement à *priorité variable,* et que ce dernier pouvait générer un transfert sur des mesures plus représentatives du quotidien. Qu'en est-il de l'impact de cet entrainement auprès d'autres populations cliniques ? L'efficacité d'un entraînement à *priorité variable* a été montrée auprès de participants avec un TCL qui présentait des déficits exécutifs en pré-entraînement (Gagnon & Belleville, 2012). Les auteurs rapportent aussi un effet de transfert de cet entraînement sur des tâches exécutives non-entraînées. Ces résultats sont intéressants puisqu'ils indiquent qu'une population clinique, présentant des troubles cognitifs, peut bénéficier d'un entraînement à *priorité variable,* et ce malgré la présence d'atteinte exécutive. Les implications cliniques sont importantes, puisque la présence de difficultés exécutives et attentionnelles peut avoir des répercussions significatives sur plusieurs activités de la vie quotidienne et exacerber les difficultés fonctionnelles des aînés (Daigneault et al., 2002; Gaspar et al., 2013; Li et al., 2010).

Un entraînement ciblant le contrôle attentionnel pourrait aussi être bénéfique auprès d'autres types de populations cliniques présentant des déficits attentionnels ou exécutifs, par exemple, les individus ayant subi un Traumatisme Cranio-Cérébral (TCC) ou un accident vasculaire cérébral (AVC). Nous savons que la plupart des personnes qui ont subi un TCC modéré ou sévère restent avec des séquelles importantes au plan attentionnel et exécutif (Arciniegas, Held & Wagner, 2002; Ashman, Gordon, Cantor & Hibbard, 2006; Barman, Chatterjee & Bhide, 2016; Brenner, 2011; Rabinowitz & Levin, 2014; Stierwalt & Murray, 2002). De nombreuses études ont aussi montré que les troubles dysexécutifs, le ralentissement et les difficultés attentionnelles sont les déficits prédominants dans les pathologies vasculaires cérébrales (Godefroy, Barbay, Toba & Roussel, 2017; Hochstenbach, Mulder, van Limbeek, Donders & Schoonderwaldt, 1998). Cependant, bien que des interventions cognitives aient été largement utilisées chez ces populations, peu d'études ont montré la généralisation des bénéfices à d'autres contextes (Barker-Collo et al., 2009; Fetta, Starkweather & Gill, 2017; Sohlberg, McLaughlin, Pavese, Heidrich & Posner, 2000; Palmese & Raskin, 2000; Park, 1999). Il serait donc intéressant, d'une part, d'examiner si un entraînement à *priorité variable* pourrait être efficace pour améliorer les capacités attentionnelles et exécutives chez ces patients et d'autre part, s'il favoriserait le transfert à des mesures plus représentatives du quotidien.

Il nous semblerait également intéressant d'utiliser la RV comme outil d'intervention. Les tâches utilisées au sein des interventions cognitives sont souvent peu écologiques et font difficilement le pont avec les activités du quotidien (Shuchat, Ouellet, Moffat & Belleville, 2012; Strobach & Karbach, 2016; Wahl, Iwarsson & Oswald, 2012). De nombreux avantages sont associés à la RV : (1) elle permet de créer des environnements contrôlés et sécuritaires qui se rapproche de la vie quotidienne (2) elle est flexible et permet la création d'une multitude d'environnements virtuels, familiers et interactifs (3) et elle favorise la motivation et le sentiment d'investissement des participants (Plancher, Nicolas, & Piolino, 2008; Shuchat et al., 2012)

Par ailleurs, il serait intéressant d'examiner l'impact des facteurs interindividuels, par exemple l'éducation, le statut cognitif au *baseline* et le type de personnalité, sur les effets des interventions cognitives et d'identifier quels sont les facteurs qui déterminent qu'un individu bénéficiera ou non d'une intervention donnée. Certains auteurs suggèrent que l'efficacité des entraînements cognitifs et les effets de transfert obtenus sont fortement modulés par ces différences interindividuelles (Belleville et al., 2014; Reuter-Lorenz & Park, 2014; Strobach & Karbach, 2016). L'identification de ces modulateurs représente une étape importante vers le développement d'intervention plus personnalisée.

La question des différences individuelles a été peu abordée dans ce travail. L'article 3 a toutefois mis en évidence, à l'aide d'effet de groupe, qu'un entraînement à *priorité variable* peut engendrer des effets différents d'une population à l'autre (jeunes adultes vs personnes âgées). Il serait donc intéressant de vérifier si les participants plus âgés avec un niveau de base inférieur ou un faible niveau d'éducation pourraient bénéficier davantage de ce type d'entraînement. Certaines études ont montré que les participants avec un haut niveau d'éducation bénéficieraient davantage d'un entraînement de type *stratégique* (Belleville et al., 2006 ; Rebok et al., 2013), alors qu'un entraînement visant la pratique répétée pourrait bénéficier davantage aux participants avec un niveau plus faible d'éducation (Clark et al., 2016).

Il serait aussi intéressant d'évaluer s'il existe une interaction entre la dose et certains facteurs individuels, comme le niveau d'éducation. En effet, connaître la trajectoire des effets des entraînements pourrait être intéressant d'un point de vue clinique, afin d'introduire des séances *booster* ou pour ajuster le nombre de séances à offrir à chaque participant. Par exemple, les individus avec un niveau d'éducation plus faible pourraient nécessiter plus de séances d'entraînement pour améliorer leur performance et ultimement rejoindre celle des individus ayant un haut niveau d'éducation.

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Annexe 1 : Article publié

Optimiser le fonctionnement cognitif au cours du vieillissement : facteurs de réserve, stimulation cognitive et plasticité cérébrale

Optimiser le fonctionnement cognitif au cours du vieillissement : facteurs de réserve, stimulation cognitive et plasticité cérébrale

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Résumé

Les préoccupations relatives à l'intégrité intellectuelle et cognitive prennent une place importante chez les aînés et celles-ci sont souvent reliées à l'éventualité de développer la maladie d'Alzheimer. Le déclin de la mémoire et des capacités cognitives suscitent de l'inquiétude chez la population vieillissante et dépeignent une vision négative du vieillissement cognitif. Le but de cet article est d'apporter divers arguments empiriques qui remettent en cause cette vision strictement négative en montrant que le vieillissement cognitif est multiple, qu'il peut être adapté et également hautement plastique. Cet article porte sur la notion de réserve cognitive, sur différents modes d'optimisation du vieillissement cognitif et sur les différents modèles de plasticité cérébrale au cours du vieillissement.

Mots-clés : Vieillissement ; réserve cognitive ; plasticité cérébrale ; entraînement cognitif ; intervention cognitive.

Introduction

Dans une étude sondant les besoins des femmes canadiennes en termes de soins de santé, les participantes indiquaient que la cognition – et plus particulièrement la mémoire – correspondait à leur priorité en matière de santé (Tannenbaum, Mayo, & Ducharme, 2005). Les résultats de cette étude illustrent l'importance de la santé cognitive pour les personnes âgées et indiquent que l'accent mis dans notre société sur la santé physique, bien que souhaitable et nécessaire, ne doit pas avoir préséance sur les préoccupations relatives à l'intégrité intellectuelle et cognitive. Ces résultats sont à mettre en lien avec l'inquiétude que suscite chez les aînés l'éventualité de souffrir de la maladie d'Alzheimer (MA). La perte de la mémoire et des capacités cognitives est perçue comme une menace pour la dignité et à l'identité personnelle. Qu'en est-il des changements cognitifs qui sont rapportés au cours du vieillissement dit « normal » ? Contribuent-ils à une vision négative et pessimiste du vieillissement ? L'importance de la vitalité cognitive pour les aînés et le fait qu'ils la placent au sommet de leur priorité de santé doivent-ils être interprétés comme une confirmation subjective d'un vieillissement cognitif négatif, monolithique et inexorable ?

Au contraire, nous montrerons dans cet article que le vieillissement cognitif est multiple, qu'il peut être favorable et adapté et qu'il est également hautement plastique. Le but de cet article est donc de mettre au défi une vision strictement déficitaire du vieillissement cognitif et d'apporter divers arguments empiriques qui remettent en cause une vision strictement négative du vieillissement cognitif. Nous aborderons d'abord la notion de réserve cognitive. Ensuite, nous présenterons des données qui indiquent différents modes d'optimisation du vieillissement cognitif. Enfin, nous présenterons et discuterons les modèles de plasticité cérébrale au cours du vieillissement.

La notion de réserve cognitive

La notion de réserve cognitive a été proposée pour rendre compte des différences interindividuelles observées dans l'effet clinique des lésions cérébrales. L'hypothèse de la réserve postule que certaines caractéristiques individuelles sont associées à une plus grande réserve cérébrale et permettent de résister aux conséquences nocives des changements cérébraux accompagnant le vieillissement normal, aux lésions cérébrales abruptes ou aux lésions progressives causées par les maladies neurodégénératives. Des différences individuelles dans le style de vie, la scolarité ou le type de hobby et des différences d'ordre génétique, comme le fonctionnement intellectuel, ont été associées à la réserve et ont donc été fréquemment utilisées comme des mesures de réserve.

Ainsi, les études épidémiologiques ont montré qu'un fonctionnement intellectuel élevé, un nombre plus important d'années de scolarité formelle ou le fait d'avoir mené un travail intellectuel stimulant, réduisent le risque de déclin cognitif associé au vieillissement ou le risque de démence (pour revue voir Stern, 2009; Villeneuve & Belleville, 2010). Par exemple, l'équipe de Stern et al., (1994) a recruté 593 individus volontaires non déments âgés de 60 ans ou plus. De ces 593 participants, 106 ont reçu un diagnostic de démence lors d'un suivi réalisé un an après le début de l'étude. Les auteurs indiquent que le risque de démence était environ deux fois plus élevé lorsque le niveau d'éducation (RR, 2.02) ou le niveau de réalisation professionnelle (RR, 2.25) était plus faible. De plus, le risque était près de trois fois plus élevé (RR, 2.87) lorsque les participants avaient à la fois un faible niveau d'éducation et d'accomplissement professionnel indiquant un effet cumulatif de facteurs de réserve. Stern et al., (1994) suggèrent qu'un niveau d'éducation et d'accomplissement professionnel élevé réduit le risque de développer la MA en permettant, par l'entremise d'une réserve, de retarder l'apparition de manifestations cliniques.

Les mécanismes neurocognitifs et neurobiologiques sous-tendant la réserve sont encore mal connus. Deux types de mécanismes neurobiologiques ont été proposés (Stern, 2002, 2009). La réserve pourrait dépendre de différences interindividuelles au niveau de la structure du cerveau, comme sa taille, l'épaisseur corticale ou le nombre de neurones et de synapses. Il s'agirait de la « réserve passive ». Ces différences structurales modifieraient le seuil de dommage cérébral suffisant pour produire un déficit cognitif observable. Par ailleurs, la réserve pourrait dépendre de différences dans la capacité qu'ont les individus à recruter de nouveaux réseaux neuronaux lorsqu'ils doivent réaliser des tâches complexes ou lorsqu'ils souffrent d'atteintes cérébrales. On réfère ici à la notion de « réserve active ». Les différences de réserve prédiraient des différences dans l'efficacité et la flexibilité avec lesquelles un individu sain utilise les réseaux neuronaux pour réaliser une tâche cognitive.

De très nombreuses études ont utilisé les variables classiquement associées à la réserve pour évaluer si ces facteurs modéraient l'importance et la rapidité du déclin cognitif chez la personne âgée normale et chez celle souffrant d'une maladie neurodégénérative (Stern, Alexander, Prohovnik, & Mayeux, 1992; Stern, Tang, Denaro, & Mayeux, 1995). Ces études montrent que les marqueurs de réserve classiques comme l'éducation modifient la relation entre l'atteinte cérébrale mesurée par des techniques de neuroimagerie et la sévérité de l'atteinte cognitive ou clinique. Par exemple, les études portant sur la démence ont comparé des groupes de patients équivalents sur le plan de la sévérité du dysfonctionnement clinique, mais qui varient sur le plan de leur scolarité. Toutes ces études rapportent que les patients ayant un plus haut niveau de scolarité souffrent de dommages cérébraux plus importants que ceux ayant un plus bas niveau de scolarité même si leur atteinte cognitive et clinique est équivalente (Garibotto et al., 2008; Perneczky et al., 2006; Stern, et al., 1992). Ainsi, Stern et al., (1992) ont mesuré le débit sanguin cérébral (rCMRglc) dans le cortex temporo-pariétal – normalement diminué dans cette région – chez 58 patients avec la MA. Ils montrent que la réduction du rCMRglc est plus importante chez les patients ayant un niveau d'éducation plus élevé. Cet effet en apparence contre-intuitif est extrêmement robuste et a également été rapporté chez des patients souffrant de démence de type Parkinson (Perneczky et al., 2007a) et de démence fronto-temporale (Borroni et al., 2009; Perneczky, Diehl-Schmid, Drzezga, & Kurz, 2007b). Il s'expliquerait par le fait que les personnes plus scolarisées sont en mesure de maintenir un fonctionnement clinique équivalent à celui de personnes moins scolarisées en dépit d'une plus grande altération neuronale (reflétée par la diminution du débit sanguin temporo-pariétal).

Les modes d'optimisation du vieillissement cognitif

Plusieurs études mettent en évidence différents phénomènes de plasticité cérébrale chez les personnes âgées, comme nous le verrons dans cette section. D'abord, des améliorations du fonctionnement cognitif ont été montrées à la suite de la participation à des programmes d'intervention non pharmacologique. L'entraînement cognitif a comme but principal d'améliorer les capacités cognitives, telles que la mémoire, l'attention ou la résolution de problèmes. Il prend généralement la forme d'un programme d'amélioration des fonctions cognitives dans lequel une ou des stratégies sont enseignées, ou dans lequel une consigne particulière, une rétroaction ou des conditions propres à la tâche permettent de maximiser la performance des participants. Il peut se faire sous forme d'exercices informatisés réalisés individuellement ou sous forme d'un enseignement structuré offert individuellement ou à un petit groupe de participants. L'entraînement implique souvent la pratique supervisée de stratégies et/ou d'habiletés permettant de cibler des difficultés cognitives (Belleville, 2008; Mowszowski, Batchelor, & Naismith, 2010). Stizer et al., (2006) proposent deux catégories d'entraînement cognitif. D'abord, les méthodes *compensatoires* ont pour but de contourner les déficits cognitifs en enseignant de nouvelles stratégies pour réaliser la tâche. Celles-ci peuvent être internes (p. ex. : catégoriser ou visualiser l'information à apprendre) ou externes (p. ex. : écrire l'information à retenir dans un carnet ou un calendrier). Les méthodes *restauratrices*, elles, visent l'amélioration du domaine cognitif altéré. Par exemple, les techniques qui consistent à répéter l'exécution de tâches d'attention ou de détection de cibles visuelles sont des méthodes restauratrices puisqu'elles visent l'amélioration de la fonction atteinte en favorisant une stimulation élevée de la fonction visée.

Les entraînements cognitifs peuvent aussi avoir différents objectifs. Ainsi, ils peuvent viser une optimisation des capacités cognitives afin de favoriser l'adaptation aux activités quotidiennes exigeantes sur le plan cognitif. Cette optimisation cognitive pourrait également réduire le stress et la frustration associés au sentiment de ne pas être optimal sur le plan cognitif et, par le fait même, favoriser le bien-être et la qualité de vie des aînés. Par ailleurs, certains auteurs ont proposé de faire appel à l'entraînement cognitif comme technique préventive, c'est-à-dire comme technique visant à réduire le déclin cognitif et à diminuer le risque de démence (Mahncke, Bronstone, & Merzenich, 2006a; Willis et al., 2006). Par exemple, Mowszowski et al., (2010) ont évalué plusieurs études afin de clarifier le potentiel préventif de l'entraînement cognitif et ils suggèrent que l'utilisation d'un entraînement cognitif à titre préventif pourrait être prometteuse chez une population à risque. Belleville (2008) rappelle qu'un entraînement cognitif peut améliorer les capacités cognitives des personnes atteintes de trouble cognitif léger

(MCI, mild cognitive impairment) et pourrait contribuer à prévenir et à ralentir le déclin cognitif chez cette population considérée comme étant à très fort risque de développer la MA. Bien que ces deux objectifs ne soient pas incompatibles, ils sont loin de s'équivaloir quand vient le temps de mettre en place des études visant à les évaluer. Les recherches souhaitant évaluer l'utilité d'un entraînement cognitif comme mode d'optimisation de la mémoire devront avoir recours à des mesures de transfert qui font état de son impact sur le fonctionnement cognitif quotidien de la personne âgée. En revanche, démontrer qu'une intervention cognitive a un impact préventif nécessite que les patients soient suivis suffisamment longtemps pour qu'une proportion importante d'entre eux ait développé une démence ou un déclin cognitif.

Études empiriques impliquant un entraînement cognitif chez les personnes âgées

Dans cette section, nous rapportons les résultats obtenus par les études ayant évalué l'efficacité à court terme d'une intervention cognitive chez les aînés dans une perspective d'optimisation. Celles-ci sont très nombreuses. Dans une méta-analyse de la littérature, Verhaeghen et al., (1992) se sont penchés sur l'efficacité d'un entraînement cognitif en analysant les résultats de 33 études ayant porté sur la mémoire. Leur analyse portait sur un échantillon global de 1539 personnes dont l'âge moyen était de 69.1 ans. Les auteurs ont examiné les données selon que les participants faisaient partie (a) d'un groupe qui avait suivi un entraînement spécifique de la mémoire; (b) d'un groupe placebo dont l'entraînement ne portait pas sur la mémoire; ou (c) d'un groupe contrôle qui ne recevait aucun entraînement. La méta-analyse indique que ceux ayant suivi un entraînement de la mémoire avaient une amélioration au post-test (0.73 SD, k=49) significativement supérieure à celle observée chez le groupe contrôle (0.38 SD, k=10) et chez le groupe placebo (0.37 SD, k=8). L'effet de l'entraînement était supérieur lorsqu'il était offert en groupe, lorsque les séances étaient courtes et lorsque les participants bénéficiaient d'un pré-entraînement (par exemple, un entraînement préalable portant sur l'imagerie mentale, le jugement ou sur la façon de réduire le stress). Ces résultats indiquent qu'un entraînement cognitif peut améliorer les capacités de mémoire chez la personne âgée et que ces capacités demeurent plastiques avec l'âge.

Certaines études suggèrent que des interventions cognitives peuvent améliorer les capacités d'attention divisée chez les personnes âgées normales. Dans l'une de ces études, Kramer et al., (1995) ont comparé les effets d'un entraînement à priorité fixe, dans lequel le participant devait combiner deux tâches, une tâche de monitoring où il devait surveiller et remettre à jour une jauge et une tâche d'équation alphanumérique de type G – 1 = ?, à un entraînement à *priorité variable*, dans lequel le participant devait combiner les deux tâches tout en variant le niveau d'attention alloué à chacune. Kramer et al., (1995) rapportent une amélioration de l'attention divisée chez les personnes ayant suivi l'entraînement à *priorité variable* et cette amélioration surpassait celle des personnes ayant suivi l'entraînement à *priorité fixe*. Ces résultats indiquent que les personnes âgées peuvent améliorer leur capacité de contrôle attentionnel, mais que certains types d'entraînement pourraient être plus efficaces que d'autres.

Bherer et al., (2005) ont confirmé l'efficacité d'un entraînement attentionnel chez les personnes âgées. Dans cette étude plus récente, les entraînements étaient structurés de la même façon que ceux de Kramer et al. (1995), mais les auteurs y combinaient une tâche de discrimination sonore (i.e., déterminer si le son est aigu ou grave) et une tâche de discrimination visuelle (i.e., déterminer si la lettre présentée à l'écran est un B ou un C). Les résultats de l'étude font état d'une amélioration de la capacité d'attention divisée après les interventions, mais l'effet ne variait pas ici en fonction des conditions d'entraînement. Cette différence pourrait provenir de ce que le protocole utilisé ici demandait moins de capacité de coordination.

Des entraînements similaires ont été menés dans notre laboratoire (de Boysson, Bier, Demonet, & Belleville, en préparation ; Gagnon & Belleville, en préparation). Une de ces études visait à déterminer les substrats neuronaux associés à l'entraînement du contrôle attentionnel chez des participants âgés qui recevaient (1) un entraînement à *priorité variable* ; (2) un entraînement en attention focalisée dans lequel le participant pratiquait chaque tâche en attention focalisée ; ou (3) un entraînement à *priorité fixe*. Les résultats montrent que le groupe ayant bénéficié de l'entraînement à *priorité variable* augmente davantage sa capacité à moduler son contrôle attentionnel que les deux autres groupes entraînés. De plus, ces participants montrent des augmentations d'activation dans les régions du cortex fronto-médian qui sont typiquement impliquées dans l'attention (Belleville, Bier, de Boysson, Mellah, & Demonet, 2010). Une autre étude (Gagnon & Belleville, en préparation) visait à évaluer l'efficacité d'une intervention cognitive ciblant le contrôle attentionnel chez une population MCI avec déficits exécutifs. Les participants recevaient un entraînement à *priorité variable* ou un entraînement à priorité fixe. Les résultats indiquent une amélioration de l'attention divisée chez les participants ayant suivi l'entraînement à *priorité variable* mais pas chez le groupe entraîné en *priorité fixe*.

Les études que nous avons rapportées plus haut visaient une optimisation de la mémoire ou de l'attention, puisqu'elles n'évaluaient pas si l'entraînement retardait le déclin cognitif ou l'apparition d'une démence. D'autres études ont tenté d'évaluer la valeur préventive de ces interventions en intégrant un suivi longitudinal des participants entraînés ou en examinant des populations à risque de démence.

L'étude ACTIVE (Advanced Cognitive Training for Independant and Vital Elderly) est un essai randomisé contrôle à simple aveugle dont l'objectif était de tester si trois entraînements cognitifs pouvaient améliorer les capacités cognitives et le fonctionnement quotidien et pouvaient réduire le déclin fonctionnel des aînés. L'étude a recruté 2832 personnes âgées de 65 à 94 ans sans troubles cognitifs. Les participants bénéficiaient pendant 5 à 6 semaines d'un entraînement cognitif portant sur la mémoire épisodique, le raisonnement inductif ou l'attention visuelle. Le type d'entraînement reçu était déterminé aléatoirement. Les résultats de l'étude indiquent que chacun des trois types d'entraînement est associé à une amélioration des performances sur les tests mesurant la fonction entraînée, mais pas sur les tests mesurant les fonctions non entrainées (Ball et al., 2002). Les auteurs rapportent que l'amélioration des performances correspond à une réduction de 7 à 14 ans des effets du vieillissement. Ils ne notent toutefois pas d'effet à court-terme sur l'autonomie fonctionnelle des participants. Les effets positifs des interventions sur les tests cognitifs sont maintenus lors d'un suivi réalisé cinq ans plus tard (Willis et al., 2006). Les auteurs rapportent également qu'après cinq ans, les groupes entraînés rapportent moins de difficulté à réaliser des activités quotidiennes complexes que le groupe non entraîné. Le suivi à long-terme indique donc que ce type d'intervention cognitive peut réduire le déclin cognitif associé au vieillissement et retarder le déclin fonctionnel.

Récemment, des études ont évalué l'efficacité d'interventions cognitives chez des personnes à risque de développer une démence, le plus souvent des personnes répondant aux critères de trouble cognitif léger (ou mild cognitive impairment-MCI; pour une revue voir Belleville (2008) ; Mowszowski et al., (2010). Plusieurs études ont fait appel à des programmes informatisés qui visaient un ensemble de fonctions cognitives. Günter et al., (2003) ont été parmi les premiers à faire appel à un entraînement informatisé auprès de personnes répondant aux critères de MCI. Leur étude comportait 19 participants MCI. Le programme d'entraînement durait 14 semaines et ses effets étaient mesurés immédiatement au terme de la dernière séance et 5 mois plus tard. Les résultats de l'étude montrent un effet positif de l'entraînement sur des mesures de mémoire épisodique et sur des mesures de mémoire de travail. De plus, l'effet positif est maintenu lors du suivi 5 mois plus tard. Günter et al., (2003) suggèrent qu'un programme d'entraînement cognitif informatisé pourrait être utilisé par une population âgée à titre préventif. Toutefois, les résultats de cette étude sont limités puisque les auteurs n'ont pas inclus une condition sans entraînement, qui aurait permis de contrôler pour l'effet de la répétition des mesures.

D'autres études (Cipriani, Bianchetti, & Trabucchi, 2006; Rozzini et al., 2007; Talassi et al., 2007) ont évalué l'effet d'un programme d'entraînement informatisé multifactoriel chez des participants satisfaisant les critères de MCI. Le programme d'entraînement visait un ensemble de fonctions cognitives dont la mémoire, l'attention, le langage, le raisonnement abstrait et les habiletés visuo-spatiales. Il était réparti sur trois blocs de 20 sessions d'environ une heure. Dans une étude randomisée (Rozzini et al., 2007) évaluant l'efficacité de ce programme, les auteurs ont montré un maintien des effets de l'intervention après un an chez 59 personnes avec MCI. Les participants recevaient l'entraînement cognitif plus un traitement pharmacologique (ChEIs), un traitement pharmacologique seulement ou aucun traitement. Les participants ayant reçu le traitement pharmacologique et cognitif ont amélioré leurs performances aux tests de mémoire et aux tests de résolution de problème, et montraient une réduction de la dépression, de l'anxiété et de l'apathie telles que mesurées par l'inventaire neuropsychiatrique (Cummings et al., 1994). Les auteurs suggèrent qu'un entraînement cognitif pourrait potentialiser les effets bénéfiques d'un traitement pharmacologique tant au niveau cognitif que comportemental.

Des résultats similaires ont été rapportés par Olzaran et al., (2004) dans une étude qui incluait des personnes avec MCI et des patients avec une MA avérée. Tous les participants de cette étude suivaient un traitement pharmacologique (ChEIs). Le programme d'intervention durait un an et comprenait 103 sessions réalisées en petits groupes. Les sessions étaient relativement longues (environ 3 h 30) et comportaient des exercices cognitifs, des activités d'interaction sociale et des exercices psychomoteurs. Le groupe recevant l'intervention cognitive était comparé à un groupe à qui on offrait des activités d'interaction sociale non structurées. L'étude rapporte une augmentation du fonctionnement cognitif, une diminution des symptômes d'agitation et d'irritabilité (NPI), une meilleure relation avec autrui et une diminution des perturbations du comportement (ADRQL) chez les participants du groupe ayant suivi l'intervention. Toutefois, il faut noter ici que l'étude ne distingue pas les résultats obtenus pour les personnes démentes et les personnes MCI. Il faut aussi souligner que ni l'étude d'Olazaran et al., (2004) ni celle de Rozzini et al., (2007) ne faisaient appel à un design complètement croisé et qu'elles ne comportaient pas de groupe recevant un traitement cognitif sans traitement pharmacologique. Il reste donc à déterminer si les deux traitements ont des effets additifs ou s'ils se potentialisent.

Certaines études ont évalué l'effet de programmes d'enseignements structurés menés en petits groupes et visant le plus souvent la mémoire chez des personnes à risque de démence. Dans l'étude de Rapp et al., (2002), des personnes avec MCI assistaient à six séances qui visaient l'apprentissage de stratégies mnémotechniques (catégorisation, chunking) à l'aide d'exercices réalisés de façon individuelle ou en groupe. L'efficacité du traitement était évaluée en utilisant des mesures objectives et subjectives de la mémoire. À la suite de l'entraînement, les personnes entraînées montraient une meilleure perception de leurs habiletés de mémoire que celles n'ayant pas suivi d'entraînement. Aucun effet n'était trouvé sur les mesures objectives de la mémoire. Toutefois, le programme utilisé dans cette étude pourrait ne pas avoir été optimal puisqu'il comportait relativement peu d'exercices de généralisation et qu'il ne comportait pas d'activités de pré-entraînement.

Belleville et al., (2006) ont développé un programme d'intervention multifactoriel conçu pour être adapté au MCI (Méthode d'Entraînement pour une Mémoire Optimale (MEMO), Gilbert, Fontaine, Belleville, Gagnon & Ménard, 2008). Le programme vise l'amélioration de la mémoire épisodique, la composante la plus altérée chez cette population. Il comprend l'apprentissage de différentes stratégies visant à promouvoir un encodage riche et élaboré. Les stratégies enseignées reposent sur l'imagerie interactive, les connaissances sémantiques et l'organisation verbale. Le programme propose également d'inclure un pré-entraînement visant l'amélioration du contrôle de l'attention en utilisant une technique similaire à celle proposée par Kramer et al., (1995) et Gagnon & Belleville (en préparation), un pré-entraînement portant sur la vitesse de traitement cognitif et un pré-entraînement visant l'amélioration de l'imagerie mentale. Le programme comprend également des conseils sur la gestion du stress, la familiarisation à des techniques de relaxation et des informations sur le vieillissement cognitif. Les participants complètent plusieurs exercices à la maison pour leur permettre de développer une expertise et pour favoriser la généralisation (Gilbert, Fontaine, Belleville, Gagnon & Ménard, 2008; Belleville et al., 2006). Le programme est offert au cours de huit rencontres hebdomadaires en petits groupes de 4 ou 5 participants. L'étude menée par Belleville et al., (2006) incluait 29 participants avec MCI (21 qui prenaient part à l'intervention et 8 qui ne recevaient aucun traitement). Les auteurs ont aussi inclus des participants âgés sains afin d'évaluer si l'intervention avait le même effet chez les personnes sans trouble cognitif. Belleville et al., (2006) rapportent un effet positif de l'intervention sur des mesures objectives de la mémoire épisodique (rappel différé d'une liste de mots, associations nom-visage) chez les MCI et chez les âgés sains. Ils rapportent aussi un effet positif sur des mesures reflétant l'impact dans les activités de tous les jours (questionnaire d'autoévaluation de la mémoire et sur le bien-être). La sévérité du déficit de mémoire chez les MCI (mesuré par le rappel d'histoire) et le déficit global de la cognition (mesuré par l'échelle MMSE et la Mattis Dementia Rating Scale) n'étaient pas reliés à l'effet de l'entraînement. Toutefois, l'éducation était corrélée aux effets de l'intervention, puisque les personnes plus éduquées, donc celles ayant une plus grande réserve, tiraient davantage profit du programme d'entraînement cognitif. Il est intéressant de souligner que l'effet de l'intervention était de même ampleur chez les personnes âgées sans trouble cognitif et chez les personnes avec MCI, ce qui suggère que les processus compensatoires sont toujours présents et demeurent mobilisables, même dans les phases très précoces de la maladie d'Alzheimer.

Les modèles de plasticité cérébrale et études empiriques en neuro-imagerie

La plasticité cérébrale renvoie aux modifications cérébrales qui font suite à des stimulations de l'environnement ou à des activités endogènes. Les phénomènes de plasticité pourraient avoir cours tout au long de la vie et sous-tendre les processus de réserve active. Ils peuvent aussi être stimulés par des interventions de courte durée comme celles décrites dans le chapitre précédent. L'imagerie cérébrale est une technique particulièrement intéressante pour évaluer les phénomènes de plasticité, car elle permet d'identifier et de caractériser les mécanismes cérébraux et cognitifs qui les sous-tendent.

Plusieurs études montrent que les activations cérébrales associées aux activités cognitives se modifient avec l'âge et que des mécanismes compensatoires déterminent certaines différences interindividuelles reliées à l'âge (Reuter-Lorenz & Lustig, 2005; Reuter-Lorenz, Stanczak, & Miller, 1999). Des modèles ont été proposés pour rendre compte de ces changements (Cabeza, 2002; Reuter-Lorenz & Lustig, 2005; Reuter-Lorenz, et al., 1999). Comme nous le verrons plus loin, ces modèles favorisent des processus de plasticité négative, des processus de plasticité positive, ou encore une combinaison des deux types de plasticité.

Le modèle de HAROLD (Hemispheric Asymmetry Reduction in Older Adults) vise à expliquer pourquoi l'activation du cortex préfrontal (CPF) est généralement moins latéralisée chez les âgés que chez les jeunes (Cabeza, 2002). Un certain nombre de données révèlent en effet que plusieurs tâches ne recrutant qu'un seul hémisphère chez les jeunes mobilisent les deux hémisphères chez les personnes âgées. Deux hypothèses pourraient expliquer cette diminution de l'asymétrie fonctionnelle avec l'âge (Cabeza, 2002; Reuter-Lorenz & Lustig, 2005). Selon l'hypothèse de la compensation, la diminution de l'asymétrie fonctionnelle s'expliquerait par un recrutement accru des régions controlatérales dans le but de pallier la diminution d'efficacité de la région spécialisée et de soutenir ainsi la réalisation de la tâche. En revanche, l'hypothèse de la dédifférenciation propose que la réduction de l'asymétrie reflète une réduction dans la qualité du signal qui réduit la capacité à recruter des régions cérébrales spécialisées et n'a donc pas d'action compensatoire (Li & Lindenberger, 1999). Cabeza et al., (1997) favorisent l'hypothèse de la compensation pour expliquer la diminution de l'asymétrie fonctionnelle parce qu'ils ont observé que les âgés les plus performants sur le plan de la mémoire sont aussi ceux chez qui la réduction de l'asymétrie est la plus importante.

Le modèle de CRUNCH (Compensation Related Utilization of Neural Circuits Hypothesis) proposé par Reuter-Lorenz & Lustig (2005) propose quant à lui que les personnes âgées auraient besoin de plus de ressources neuronales que les jeunes pour la réalisation d'une même tâche. Cela se manifesterait par des niveaux d'activation plus importants chez les âgés que chez les jeunes. De plus, les âgés disposant de moins de ressources, leur niveau maximal de ressources serait plus rapidement atteint, ce qui se manifesterait par des activations moins grandes pour les tâches plus complexes ou plus difficiles. Reuter-Lorenz & Lustig (2005) proposent donc deux formes de compensation. La première forme consiste à employer davantage les aires spécifiques à l'exécution d'une tâche et surviendrait quand les tâches n'ont pas atteint le seuil maximal de ressource. La deuxième forme consiste à employer des stratégies alternatives pour pallier les déficits en recrutant des régions cérébrales qui ne sont pas habituellement recrutées par la tâche, ce qui surviendrait lorsque le fonctionnement des régions spécialisées dans la réalisation de la tâche est compromis ou diminué (Reuter-Lorenz & Cappell, 2008).

En revanche, Mahncke et ses collègues proposent que le déclin cognitif relié à l'âge est causé par des processus de plasticité négative et que l'utilisation d'un entraînement favorisant la plasticité permettrait de renverser les effets de la plasticité négative (Mahncke, Bronstone & Merzenich, 2006a; Mahncke et al., 2006b). Mahncke et al., (2006b) ont testé l'hypothèse voulant que les déficits reliés à l'âge pouvaient être partiellement renversés à l'aide d'un programme d'entraînement ciblé. Ce programme visait à engager les structures neuromodulatoires du cerveau en entraînant de façon intensive certaines fonctions associées à la réception du langage. Le programme incluait 182 participants âgés sains (62 qui prenaient part à l'entraînement, 61 qui prenaient part à une activité « contrôle » sur le même programme informatisé et 59 qui ne suivaient aucun entraînement et aucune activité). Les participants réalisaient des exercices sensoriels et cognitifs nécessitant l'identification et la discrimination de stimuli auditifs (i.e., des sons de différentes fréquences, des pseudo-syllabes [e.g., ba], des mots [bad, dad], etc.). Les résultats de l'étude suggèrent une amélioration du fonctionnement aux tâches entraînées et sa généralisation à une mesure (un score de mémoire auditif global) chez le groupe ayant suivi l'entraînement. Cependant, la taille d'effet (d = 0,25) est modeste et les effets ne se maintiennent que sur une tâche de mémoire à court-terme (empan de chiffre). De plus, l'étude postule que le programme favorise la plasticité cérébrale, mais elle ne la mesure pas directement avec de l'imagerie structurelle ou fonctionnelle. L'utilisation de la neuro-imagerie en association avec les entraînements cognitifs pourrait permettre de vérifier la nature des effets induits par ces entraînements et contribuer aux modèles de plasticité cérébrale du vieillissement. Les quelques rares études ayant combiné les entraînements à des marqueurs cérébraux sont présentées dans la prochaine section.

L'étude de Nyberg et al., (2003) est l'une des premières à avoir examiné chez les âgés les changements dans l'activité cérébrale reliés à un bref entraînement de la mémoire. À l'intérieur d'une même séance de TEP scan, les participants (jeunes et âgés) devaient effectuer un rappel sériel de quatre listes randomisées de 18 mots. Entre les deux rappels, les participants apprenaient à mettre en pratique la méthode des lieux, un procédé mnémotechnique qui fait appel à l'imagerie mentale. Les résultats de l'étude montrent que les participants jeunes et âgés ayant amélioré leur performance au post-test présentaient une augmentation significative de l'activation au niveau du cortex pariéto-occipital. Selon les auteurs, ce résultat indique que l'apprentissage réussi de la méthode des lieux est associé à une augmentation de l'activation dans cette région. Les activations observées sont cohérentes avec le moyen mnémotechnique appris, puisqu'elles sont présentes dans des régions jouant un rôle dans l'imagerie mentale. Ainsi, ces données suggèrent que l'utilisation de stratégies nouvelles pourrait dépendre du recrutement de régions cérébrales alternatives. Les auteurs montrent aussi que l'entraînement amène de nouvelles activations dans les régions préfrontales chez les jeunes mais pas chez les âgés (Nyberg et al., 2003). L'absence de changement dans les régions préfrontales pourrait s'expliquer par une diminution dans les capacités de traitement ou par une incapacité à recruter des régions qui sont plus sensibles au vieillissement.

Une étude IRMf récente (Braver, Paxton, Locke, & Barch, 2009) a utilisé un bref entraînement de la mémoire de travail chez des jeunes et des âgés. L'étude montre qu'une seule session d'entraînement sur une tâche de mémoire de travail AX-CPT (Continuous Performance Test) modifie les processus utilisés par les âgés en les rendant plus proactifs lors de la réalisation de la tâche. L'intervention prenait la forme d'une brève (30 min) période d'apprentissage de stratégies proactives (i.e., utiliser les indices afin de guider la stratégie à employer lors de la présentation subséquente de la cible). Les participants étaient évalués selon une tâche qui consistait à détecter une cible avec ou sans indice contextuel préalable. Braver et al., (2009) montrent qu'avant l'entraînement, l'activation des âgés au niveau préfrontal était moins élevée lors de la présentation des indices contextuels que lors de la présentation de la cible. Le patron inverse était observé chez les jeunes, puisqu'ils montraient plus d'activation associée aux indices qu'aux cibles. Après l'entraînement, cependant, les âgés montraient un patron similaire à celui des jeunes, soit une activation préfrontale plus importante lors de la présentation des indices que des cibles. Selon les auteurs, l'entraînement aurait amené les âgés à adopter un comportement plus proactif, ce qui se traduirait par des changements d'activation dans les régions préfrontales (Braver et al., 2009).

Erickson et al., (2007) ont étudié l'effet d'un entraînement attentionnel soutenu sur l'activité cérébrale en IRMf. Ils ont évalué l'effet d'un entraînement en attention divisée chez des âgés et des jeunes. Chez les participants âgés, les auteurs rapportent une amélioration des performances après l'entraînement, qui est corrélée à une augmentation des activations au niveau du cortex préfrontal ventral (CPFV) gauche. Les jeunes ne présentent pas de modification de l'activation dans ces régions après l'entraînement. Les auteurs montrent également une diminution de l'activation dans le CPFV droit après l'entraînement tant chez les jeunes que chez les âgés. Cette combinaison particulière d'augmentation d'activation à gauche et de diminution d'activation à droite fait en sorte qu'on retrouve une plus grande asymétrie hémisphérique pour le CPFV avant qu'après l'intervention. Selon Erickson et al., (2007), l'augmentation de l'asymétrie dans ces régions après l'intervention est en contradiction avec le modèle HAROLD (Cabeza, 2002) puisque ce modèle propose au contraire que la réduction de l'asymétrie hémisphérique a un rôle compensatoire et permet une meilleure performance.

Le potentiel de plasticité cérébrale chez les âgés sains a aussi été montré dans l'étude de de Boysson et al. (en préparation) et dans celle de Belleville et al., (2010) qui évaluent l'effet d'un entraînement à priorité variable, à priorité fixe et en attention focalisée sur les potentiels évoqués cognitifs et sur les activations fonctionnelles mesurées par l'IRM. Celles-ci rapportent un effet positif de l'entraînement attentionnel sur les capacités d'attention divisée et de contrôle de l'attention. Ainsi, de Boysson et al., (en préparation) rapportent une augmentation de l'amplitude de la N200, une onde qui a été suggérée comme marqueur électrophysiologique de plasticité cérébrale (Rueda, Rothbart, McCandliss, Saccomanno, & Posner, 2005). En IRMf, Belleville et al. (2010) ont rapporté des augmentations d'activation cérébrale dans les régions préfrontales qui sont typiquement associées à l'attention. La nature des changements d'activation était toutefois grandement modulée par le type d'intervention.

Belleville et al., (en préparation) ont aussi utilisé l'IRMf afin de mesurer l'effet d'un entraînement de la mémoire chez une population à risque de maladie d'Alzheimer. Le programme d'intervention (MEMO, Gilbert, Fontaine, Belleville, Gagnon & Ménard, 2008) était axé sur l'apprentissage de stratégies basées sur l'imagerie mentale et l'encodage sémantique. L'étude évaluait si un tel entraînement pouvait renverser les changements cérébraux associés au MCI. Cette étude comprenait 30 participants : 15 personnes avec MCI et 15 personnes saines prenaient part à une séance d'IRMf six semaines avant l'entraînement (Préentraînement1), une semaine avant l'entraînement (Pré-entraînement 2) et une semaine après l'entraînement (Postentraînement). Les résultats chez les personnes MCI indiquent une augmentation de l'activation dans plusieurs régions cérébrales à la suite de l'intervention. Les auteurs notent que certaines zones déjà activées avant l'intervention le sont davantage après l'intervention (p. ex., lobe pariétal gauche). Toutefois, certaines zones non activées au préalable sont activées après l'intervention (p. ex., le lobule pariétal inférieur droit lors de l'encodage et le gyrus temporal supérieur lors de la récupération). Ainsi, les auteurs proposent que chez les personnes avec MCI, l'entraînement a pour effet d'augmenter l'activation tant de régions spécialisées pour la tâche que de régions alternatives, c'est-à-dire qui n'étaient pas recrutées lors de la tâche de mémoire effectuée en pré-entraînement. Belleville et al., (en préparation) montrent également que l'activation dans le lobule pariétal inférieur droit, une région impliquée dans la mémoire visuo-spatiale, corrèle avec la performance après l'intervention et pourrait donc soutenir la compensation cognitive. Les auteurs concluent qu'un entraînement de la mémoire peut produire des changements cérébraux significatifs qui sont mesurables à l'aide de l'IRMf et que le cerveau des individus présentant un MCI demeure hautement plastique.

Conclusion

L'objectif de cet article était de présenter les données appuyant la présence de réserve et de plasticité cérébrale dans le vieillissement et d'apporter ainsi des arguments remettant en cause une vision strictement déficitaire du vieillissement cognitif. Bien que certaines études suggèrent une vision strictement négative du vieillissement, nous voulions montrer que le vieillissement cognitif était modifiable et hautement plastique.

Nous avons vu que la notion de réserve cognitive fait référence à la capacité qu'ont certains individus à résister aux dommages cérébraux. Ainsi, l'effet protecteur de l'éducation, du type d'emploi et du style de vie sur le vieillissement cognitif a été appuyé par de nombreuses études, et ces facteurs ont été souvent utilisés comme reflétant ou mesurant la réserve. Bien que la notion de réserve soit fort intéressante et heuristiquement forte, elle suscite toujours de nombreuses questions (Villeneuve & Belleville, 2010). D'une part, on connaît encore mal les mécanismes neurobiologiques sous-tendant la réserve et il est probable que tant la réserve « dite » passive que la réserve « dite » active sous-tendent la résistance aux lésions et les phénomènes de compensation. De plus, des caractéristiques personnelles comme l'éducation et le style de vie ont été associées à la réserve, mais on connaît mal leur relation de causalité avec la réserve. Ainsi, on ne sait pas si ces caractéristiques causent la réserve, si elles en sont la conséquence ou si elles sont reliées à une même variable causale encore inconnue. Par exemple, une activité intellectuelle variée tout au long de la vie pourrait favoriser la création et la consolidation de réseaux cérébraux alternatifs qui permettront ensuite une plus grande résistance aux lésions cérébrales. On pourrait toutefois à l'inverse dire que les individus qui sont dotés de réseaux cérébraux riches et flexibles, soit de par leur bagage génétique, soit pour des raisons reliées à l'environnement physique précoce (par exemple, leur nutrition), seront plus à même de poursuivre une scolarité plus élevée. Il est également possible que des facteurs physiques ou génétiques facilitent tout à la fois la réalisation d'activités complexes et un recrutement flexible de circuits alternatifs sans qu'il n'existe de lien direct entre les deux derniers facteurs. Les études d'intervention pourraient être utiles à cet égard puisqu'elles permettent de reproduire les conditions enrichies censées soustendre les facteurs environnementaux, comme l'éducation ou l'activité professionnelle, en faisant appel à la méthode expérimentale plutôt qu'à l'analyse corrélationnelle. La réserve cognitive est une notion complexe et ses mécanismes tant dans le vieillissement normal que dans les maladies neurodégénératives se doivent d'être davantage explorés.

Aussi, nous avons vu qu'il est possible d'améliorer les capacités cognitives chez une population vieillissante à la suite de la participation à des programmes d'intervention cognitive. Cette amélioration se traduit par des modifications cérébrales, un phénomène reflétant des processus de neuroplasticité chez les âgés. Un nombre grandissant d'études rapporte que les programmes d'intervention cognitive peuvent aussi contribuer à optimiser le fonctionnement cognitif chez une population MCI. Bien que ces résultats soient prometteurs, certaines incertitudes demeurent en raison du manque d'essais randomisés contrôlés et du faible nombre de participants, particulièrement pour les études chez les MCI. La généralisation des effets observés à des mesures subjectives, rapportée dans certaines études, rend compte d'une certaine validité écologique. Cependant, l'évaluation de la généralisation des effets dans le quotidien n'est pas fréquente et doit donc être mieux documentée. Le maintien des effets des interventions a été largement documenté par les études impliquant des âgés sains. Toutefois, cet effet n'a pas été mesuré chez une population MCI et il devient nécessaire de montrer que ces interventions ont un effet durable et d'examiner s'ils ont un impact sur la conversion des MCI vers la démence. Il est possible, comme le proposent Belleville (2008), que des séances de rappel (booster) soient nécessaires pour favoriser le maintien de l'effet positif de l'entraînement, particulièrement chez les personnes souffrant de troubles cognitifs.

Enfin, nous avons décrit les modèles de plasticité cérébrale qui font appel aux résultats produits par les techniques de neuro-imagerie et avons examiné les données empiriques qui pourraient appuyer de tels modèles. À ce jour, très peu d'études ont évalué les substrats neuronaux des entraînements cognitifs à l'aide de la neuro-imagerie. Toutefois, les quelques études sur ce sujet indiquent que le cerveau des personnes âgées saines peut recruter de nouveaux réseaux neuronaux après un entraînement cognitif, ce qui indique qu'il conserve un important potentiel de plasticité. À notre connaissance, une seule étude a tenté de vérifier si des effets similaires pouvaient être observés chez des individus répondant aux critères de MCI en utilisant une technique d'IRMf (Belleville et al., en révision). Il s'agit d'une avancée importante dans le domaine puisque l'étude montre qu'un entraînement de la mémoire peut produire des changements cérébraux significatifs et mesurables chez ces personnes qui sont à un stade très précoce de la maladie d'Alzheimer et que leur cerveau demeure donc hautement plastique.

Somme toute, l'ensemble de ces observations permet de montrer que le vieillissement n'est pas homogène et qu'il ne peut être décrit comme caractérisé par un déclin global et inexorable des fonctions cognitives. Au contraire, nous avons montré que certaines caractéristiques personnelles peuvent retarder le déclin cognitif et compenser pour les modifications cérébrales accompagnant le vieillissement normal ou pathologique. Nous avons aussi montré que le cerveau âgé peut apprendre et demeurer plastique. Les recherches futures réalisées dans ce domaine devront tenter de mieux comprendre les mécanismes qui sous-tendent ces phénomènes de réserve et de plasticité afin d'identifier des méthodes efficaces – qu'elles soient pharmacologiques ou non pharmacologiques – qui pourraient en accroître les effets et afin de prédire qui sont les individus les plus susceptibles de répondre à des interventions qui ciblent ces phénomènes.

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