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L'effort associé à la reconnaissance de la parole chez les adultes et les personnes aînées

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Cette thèse intitulée :

L'effort associé à la reconnaissance de la parole chez les adultes et les personnes aînées

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Résumé

L'objectif principal de cette thèse était de quantifier et comparer l'effort requis pour reconnaître la parole dans le bruit chez les jeunes adultes et les personnes aînées ayant une audition normale et une acuité visuelle normale (avec ou sans lentille de correction de la vue). L'effort associé à la perception de la parole est lié aux ressources attentionnelles et cognitives requises pour comprendre la parole. La première étude (Expérience 1) avait pour but d'évaluer l'effort associé à la reconnaissance auditive de la parole (entendre un locuteur), tandis que la deuxième étude (Expérience 2) avait comme but d'évaluer l'effort associé à la reconnaissance auditivo-visuelle de la parole (entendre et voir le visage d'un locuteur). L'effort fut mesuré de deux façons différentes. D'abord par une approche comportementale faisant appel à un paradigme expérimental nommé double tâche. Il s'agissait d'une tâche de reconnaissance de mot jumelée à une tâche de reconnaissance de patrons vibro-tactiles. De plus, l'effort fut quantifié à l'aide d'un questionnaire demandant aux participants de coter l'effort associé aux tâches comportementales. Les deux mesures d'effort furent utilisées dans deux conditions expérimentales différentes : 1) niveau équivalent – c'est-à-dire lorsque le niveau du bruit masquant la parole était le même pour tous les participants et, 2) performance équivalente – c'est-à-dire lorsque le niveau du bruit fut ajusté afin que les performances à la tâche de reconnaissance de mots soient identiques pour les deux groupes de participant. Les niveaux de performance obtenus pour la tâche vibro-tactile ont révélé que les personnes aînées fournissent plus d'effort que les jeunes adultes pour les deux conditions expérimentales, et ce, quelle que soit la modalité perceptuelle dans laquelle les stimuli de la parole sont présentés (c.-à.-d., auditive seulement ou auditivo-visuelle). Globalement, le 'coût' associé aux performances de la tâche vibro-tactile était au plus élevé pour les personnes aînées lorsque la parole était présentée en modalité auditivo-visuelle. Alors que les indices visuels peuvent améliorer la reconnaissance auditivo-visuelle de la parole, nos résultats suggèrent qu'ils peuvent aussi créer une charge additionnelle sur les ressources utilisées pour traiter l'information. Cette charge additionnelle a des conséquences néfastes sur les performances aux tâches de reconnaissance de mots et de patrons vibro-tactiles lorsque celles-ci sont effectuées sous des conditions de double tâche. Conformément aux études antérieures, les coefficients de corrélations effectuées à partir des données de l'Expérience 1 et de l'Expérience 2 soutiennent la notion que les mesures comportementales de double tâche et les réponses aux questionnaires évaluent différentes dimensions de l'effort associé à la reconnaissance de la parole. Comme l'effort associé à la perception de la parole repose sur des facteurs auditifs et cognitifs, une troisième étude fut complétée afin d'explorer si la mémoire auditive de travail contribue à expliquer la variance dans les données portant sur l'effort associé à la perception de la parole. De plus, ces analyses ont permis de comparer les patrons de réponses obtenues pour ces deux facteurs après des jeunes adultes et des personnes aînées. Pour les jeunes adultes, les résultats d'une analyse de régression séquentielle ont démontré qu'une mesure de la capacité auditive (taille de l'empan) était reliée à l'effort, tandis qu'une mesure du traitement auditif (rappel alphabétique) était reliée à la précision avec laquelle les mots étaient reconnus lorsqu'ils étaient présentés sous les conditions de double tâche. Cependant, ces mêmes relations n'étaient pas présentes dans les données obtenues pour le groupe de personnes aînées ni dans les données obtenues lorsque les tâches de reconnaissance de la parole étaient effectuées en modalité auditivo-visuelle. D'autres études sont nécessaires pour identifier les facteurs cognitifs qui sous-tendent l'effort associé à la perception de la parole, et ce, particulièrement chez les personnes aînées.

Mots-clés : effort associé à la perception de la parole, paradigme de double tâche, vieillissement, audition, cognition, reconnaissance de la parole, reconnaissance auditivo-visuelle de la parole, mémoire de travail

Abstract

The primary objective of the current thesis was to quantify and compare the amount of listening effort that young and older, normal-hearing adults with normal (or corrected normal) vision expend when speech is presented in background noise. Listening effort refers to the attentional and cognitive resources required to understand speech. Study 1 was designed to determine the listening effort associated with auditory speech recognition (hearing a speaker) whereas Study 2 examined the listening effort involved with audiovisual speech recognition (hearing and seeing the face of a speaker). Listening effort was assessed behaviourally, using a dual task paradigm where a word recognition task was paired with a tactile pattern recognition task and, with self-reported ratings. Both measures of listening effort were assessed under two experimental conditions: 1) equated level - where the level of background noise was the same for all participants and, 2) equated performance - where single task word recognition performance did not differ between groups. The tactile task costs revealed that older adults expended more listening effort than young adults for both experimental conditions regardless of the perceptual modality in which the speech stimuli were presented (i.e., audio-only and audiovisual). Overall, the cost involved with tactile task performance was highest for older adults when speech was presented audiovisually. While visual cues can improve audiovisual speech recognition our results suggest they can also place an extra demand on processing resources with performance consequences for the word and tactile tasks under dual task conditions. Consistent with the literature, the correlation findings of Study 1 and Study 2 support the idea that dual task measures and self-reported ratings each assess different aspects of listening effort. As listening effort draws upon auditory and cognitive factors, the purpose of Study 3 was to determine to what extent the separate components of auditory working memory (capacity and processing) contribute towards the variance observed in listening effort and to determine if the pattern of working memory predictor variables changes with age. Results of a sequential regression analysis for young adults indicated that a measure of auditory capacity (span size) was related to listening effort whereas a measure of auditory processing (alphabetical recall) was related to the cost associated with word recognition accuracy performance under dual task conditions. However, these relationships did not extend to older adults or to the data obtained when the speech recognition tasks were performed audiovisually. Further research is required to determine what cognitive factors underlie listening effort – especially for older adults.

Key Words: Listening effort, dual task paradigm, aging, audition, cognition, speech recognition, audiovisual speech recognition, working memory

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List of Acronyms and Abbreviations

A: Auditory
ANL: Acceptable Noise Level Test
AV: Audio-visual
BKB-SIN: Bamford-Kowal-Bench Speech in Noise Test
BNL: Background noise level
CHABA: Committee on Hearing and Bioacoustics and Biomechanics
CID: Central Institute for the Deaf
DNR: Digital Noise Reduction
ELU: Ease of Language Understanding
HHIA: Hearing Handicap Inventory for Adults
HHIE: Hearing Handicap Inventory for the Elderly
HINT: Hearing in Noise Test
ICF: International Classification of Functioning, Disability and Health
IOI-HA: International Outcome Inventory for Hearing Aids
LNS: Letter Number Sequencing
MCL: Most comfortable level
MoCA: Montreal Cognitive Assessment
OA: Older Adult
pDTC: Proportional dual task cost
QuickSIN: Quick Speech in Noise Test
RAMBPHO: Rapid Automatic Multimodal Binding of Phonological Information
SNR: Signal-to-noise ratio
SSQ: Speech, Spatial and Qualities of Hearing Scale
SVIPS: Speech and Visual Information Processing System
WHO: World Health Organization
WIN: Words in Noise Test
YA: Younger Adult

To Kellen, Daniel and my parents

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encouragement, love and understanding of my son Kellen and my husband Daniel day after day after day ….

Introduction

The current thesis consists of four articles which explore the influence of age on listening effort when speech is presented in background noise. Listening effort refers to the attentional and cognitive resources required to understand speech. The following introduction explains the effect of aging on audition and cognition as well as the comorbidity and interaction amongst auditory and cognitive factors. The introduction culminates with a description of how listening effort can be measured under different experimental conditions and discusses what cognitive measures could be linked to listening effort. Finally, the introduction concludes with an outline to describe how all of the articles and chapters of the dissertation are organized.

Aging and effects on audition

In the clinical domain, it is well known that many older adults report that listening in noise is a challenging and exhausting experience that requires a great deal of effort. In general, the speech understanding difficulties experienced by older adults can be related to any one or combination of the following factors: peripheral auditory factors, central auditory factors, or cognitive factors (CHABA, 1988; L Humes, 1996; Pichora-Fuller, 1997, 2006).

Peripheral and central auditory factors

Among the elderly, age-related hearing loss or presbycusis ranks among the most prevalent chronic conditions following arthritis and high blood pressure (Davis & Davis, 2009). According to Statistics Canada, 40% of adults just entering their retirement years (i.e., 65-74 years old) have a hearing loss significant enough to restrict their participation or limit their activities of daily living (Statistics Canada, 1992). When older adults between 75-84 years of age are considered, the prevalence of hearing impairment increases to 85% and it is expected that at least 55% of this age group would benefit from hearing aid amplification (Davis & Davis, 2009).

Although a variety of different audiometric patterns can occur, the typical pattern observed with presbycusis involves a bilateral symmetrical mild to moderate sensorineural hearing loss that is worse in the high frequencies (Worrall & Hickson, 2003). Irrespective of the sensory contribution of presbycusis - damage to the outer hair cells of the cochlea due to the cumulative effects of a lifetime of noise exposure - metabolic, mechanical and neural aspects of presbycusis can also contribute to hearing loss (Schuknecht, 1974). For a more recent review of the predominant physiological factors that influence age-related hearing loss, see Mills, Schmiedt, Shulte and Dubno, 2006. In terms of the metabolic contribution of presbycusis, it is now recognized that a lowering of the endocochlear potential can reduce the influence of the cochlear amplifier and the gating of the inner hair cells. Taken together, either of these actions can degrade the timing of the neural response (Mills & Schmiedt, 2004; Schmiedt, Lang, Okamura, & Shchulte, 2002). The resulting neural degeneration can account for age-related deficits in temporal auditory processing which can further exacerbate the difficulties older adults experience when trying to understand speech spoken in a noisy background (Frisina et al., 2001; Gordon-Salant & Fitzgibbons, 2001; Schneider, Pichora-Fuller, & Daneman, 2010).

Expanded definition of audition

Even when older adults have “normal hearing ability”, young adults still outperform older adults on word recognition tasks when performed in noise (CHABA, 1988). This suggests that beyond perceptual factors like the ability “to hear”, other age-related changes may be involved in speech understanding. Using the World Health Organization’s International Classification of Functioning, Disability and Health (ICF; (WHO, 2001)) as a guide, an international panel of experts expanded upon the definition of “audition” to include: hearing, listening, comprehending and communicating (Kiessling et al., 2003). Using this broader definition, it’s clear that a substantial amount of cognitive processes are involved in auditory function (Kiessling et al., 2003; Worrall & Hickson, 2003). Hearing is a sense whereas the listening effort involved in listening comprehension, the focus of the current dissertation, is a skill that requires attention and intention to access and use the information that is heard. Comprehension involves the reception and interpretation of the meaning and intent of the information and communicating involves the effective use and transfer of information (Kiessling et al., 2003; Pichora-Fuller & Singh, 2006).

Aging and effects on cognition

Like presbycusis, dementia is also an age-related disorder which is diagnosed when cognitive deficits are considered to be sufficient enough to impair social or occupational functioning (American Psychiatric Association, 1994). The prevalence of dementia begins at roughly 2% for people under 65 years, but doubles every 5 years such that at age 90 the prevalence of dementia is estimated to be 50% (Lemke, 2009; Raina et al., 2009).

With or without dementia, the active process involved with listening, comprehending and communicating engages both auditory and cognitive processes. On the positive side, static or "crystallized" linguistic and world knowledge are well preserved in healthy aging adults which accounts for the ability of many older adults to benefit from and use supportive context in challenging listening conditions (Craik, 1986; Schneider et al., 2010; Wingfield & Tun, 2007). However, age-related declines in the dynamic or "fluid" aspects of information processing involving working memory (Salthouse, 1994, 2004), attentional resources (Craik & Byrd, 1982), speed of processing (Salthouse, 1996) and inhibition from distraction (Stoltzfus, Hasher, & Zacks, 1996) are well documented. For a comprehensive review see Pichora-Fuller & Singh (2006) and Schneider et al. (2010).

Comorbidity of auditory and cognitive impairment

As adults age, the number of chronic conditions and co-morbidities increases. In terms of audition and cognition, research has shown that hearing loss is more prevalent in those with dementia than in the general population without dementia (Uhlmann, Larson, Rees, Koepsell, & Duckert, 1989; Uhlmann, Teri, Rees, Mozlowski, & Larson, 1989). One study in particular reported 9 out of 10 participants with dementia also had a hearing loss (Gold, Lightfoot, & Hnath-Chisolm, 1996). Despite the high prevalence of hearing impairment and/or cognitive impairment, as a starting point, to examine the effect of age on auditory and cognitive factors, only healthy aging older adults ranging from 65-80 years were studied for the current dissertation. All participants had normal hearing sensitivity (≤ 25 dB HL at octave frequencies between 0.25 and 2.0 kHz, as well as at 3 kHz, re: ANSI, 1996), in both ears and normal (or corrected normal) binocular visual acuity (i.e., 6/12 or better) as measured with Sloan Letters at a distance of 3 metres (NAS-NRC, 1980; Sloan, Rowland, & Altman, 1952). In addition, all older adults had clinically normal cognitive function as determined by the Montreal Cognitive Assessment [MoCA (Nasreddine et al., 2005)].

Interaction of auditory and cognitive factors

To better understand and address the rehabilitative needs of older adults, there has been an increasing interest to learn how these various auditory and cognitive factors inter-relate (Pichora-Fuller, 2009a; Pichora-Fuller & Singh, 2006). Much of this interest has been sparked by the growing number of studies published within the last decade that have linked various cognitive measures (e.g., visual letter or digit monitoring, reading span and IQ) with hearing aid outcome (Cox & Xu, 2010; Gatehouse, Naylor, & Elberling, 2003, 2006; Humes, 2007; Lunner, 2003; Lunner & Sundewall-Thoren, 2007).

Findings from hearing aid research

In unaided listening conditions, Humes showed that auditory factors are the primary contributor to the speech-understanding difficulties of older adults with hearing impairment (Humes, 2007). However, when an experimental approach is taken to restore audibility (i.e., spectrally shaping speech so that the long-term speech spectrum is 15 dB above conversational levels), age and cognitive factors (i.e., IQ and memory) emerge to account for half of the variance associated with word identification performance in noise (Amos & Humes, 2007; Humes, 2007; Humes, Burk, Coughlin, Busey, & Stauser, 2007).

In other research involving hearing aid processing, several studies demonstrated that in simple listening conditions (i.e., hearing aid processing involving slow time constants with unmodulated competing noise), auditory factors as measured by pure tone average, explained most of the variance in aided word recognition. However, in more complex or difficult listening conditions (i.e., fast time constants and modulated competing noise) cognitive factors as measured by the Visual Letter Monitoring Test explained the majority of variance (Gatehouse et al., 2003, 2006; Lunner & Sundewall-Thoren, 2007). More recently, studies have shown that listeners with low cognitive abilities tend to benefit from a hearing aid programmed with slow time constants for listening situations reliant on audibility - word identification where semantic context is unavailable (Foo, Rudner, Ronnberg, & Lunner, 2007; Gatehouse et al., 2006; Lunner & Sundewall-Thoren, 2007)). However, with more naturally and ecologically produced speech that is rich in contextual cues, these same listeners with low cognitive abilities can benefit from a hearing aid programmed with fast time constants. Under these conditions, the new cues made available by "listening in the dips" of modulated competing noise can supplement the benefits provided from context (Cox & Xu, 2010; Foo et al., 2007).

Bottom-up and top-down processing

In agreement with the findings reported by Gatehouse (2003, 2006), Humes (2007) and Lunner & Sundewall-Thoren (2007) is the schematic illustrated in Figure 1. In general, under ideal listening conditions when speech is not degraded by hearing loss or background noise, the four levels of auditory functioning (hearing, listening, comprehending and communicating/reacting) proceed predominantly with a bottom-up or "signal based processing" (Edwards, 2007; Stenfelt & Ronnberg, 2009; Sweetow & Henderson-Sabes, 2004). However, under difficult listening situations, a listener may have to rely to a greater extent on top-down or "knowledge based processing" as a compensation strategy to disambiguate an unclear message (Ronnberg et al., 1998; Wingfield & Tun, 2007).

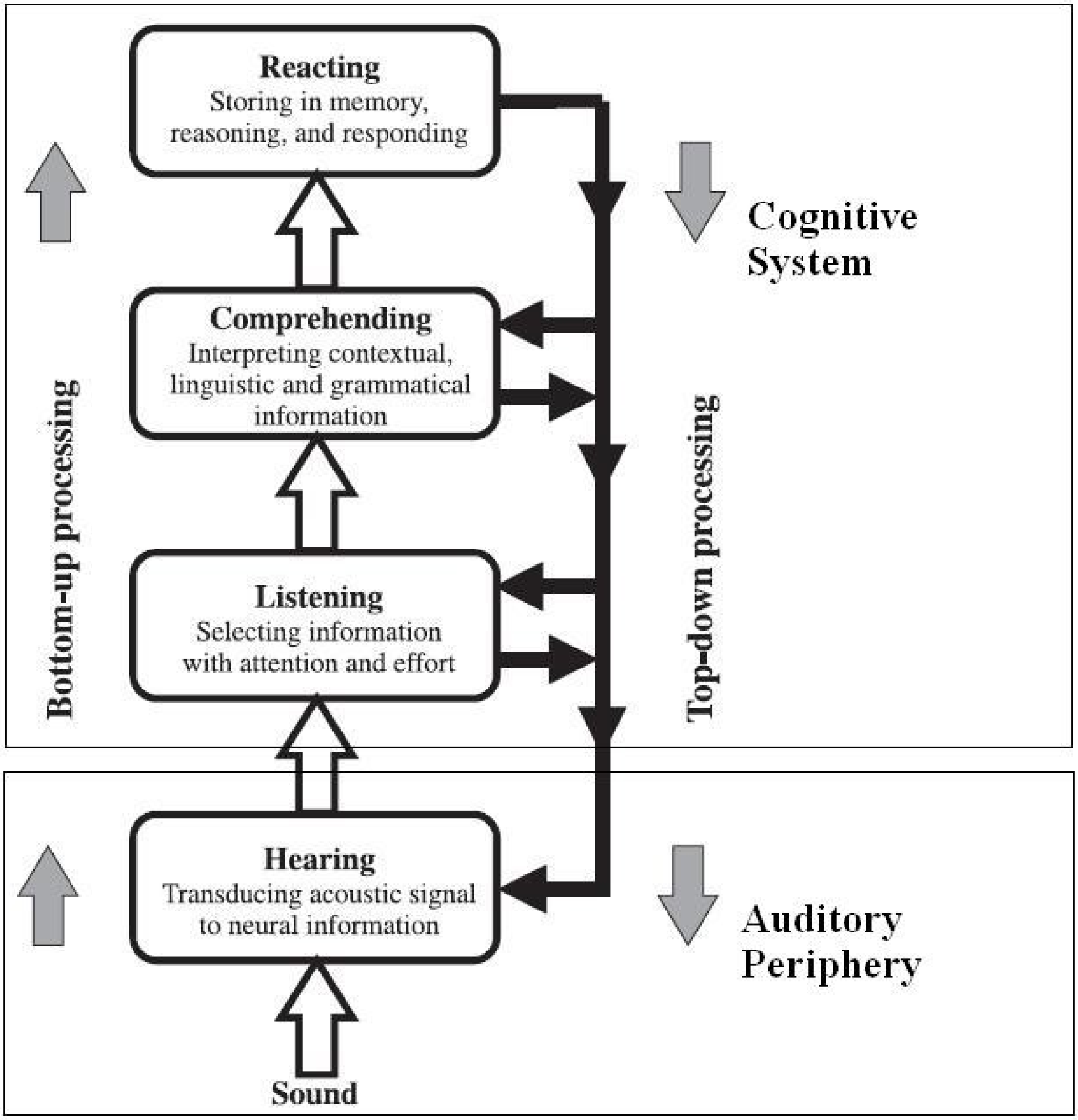

Figure 1. A generalized model for bottom-up and top-down processing of auditory input (adapted from Edwards, 2007).

In challenging listening situations, while top-down processing can be engaged as a compensation strategy, it is also possible that hearing difficulties can exacerbate cognitive difficulties (Baltes & Baltes, 1990; Lindenberger & Baltes, 1994). As described by the information degradation hypothesis, if the quality of the sensory input is reduced, less efficient cognitive functioning can result. As a consequence, if hearing impairment is not taken into account, it can masquerade as a cognitive impairment with clinical implications for both assessment and intervention. For example, Weinstein & Amsel (1986) showed that when cognitive tests were conducted without vs. with hearing aids, dementia was over-estimated in 1/3 cases.

Based on information processing theory (Kahneman, 1973), one of the important implications of difficult listening situations is that if more resources need to be allocated to auditory perception to determine what is being said, fewer resources are available for higher-level cognitive tasks such that poorer comprehension and memory for what was heard can result (Arlinger, Lunner, Lyxell, & Pichora-Fuller, 2009; McCoy et al., 2005; Pichora-Fuller, 2007; Rabbitt, 1966, 1990; Rakerd, Seitz, & Whearty, 1996). For the studies listed above where memory was specifically used in a recall paradigm, the changes observed in memory performance were used to gauge the "effort" involved with a difficult listening situation (Rabbitt, 1966, 1990; Rakerd et al., 1996).

Measurement of listening effort

Throughout the current dissertation, "listening effort" has been broadly defined as the attentional and cognitive resources required for speech understanding (Bourland-Hicks & Tharpe, 2002; Downs, 1982; Feuerstein, 1992; Fraser, Gagné, Alepins, & Dubois, 2010). Over the years, listening effort has been assessed with a variety of techniques including: self-report rating scales, physiological measures and behavioural measures.

Self-report rating scales

In clinical practice, very few questionnaires exist that tap the construct of listening effort directly. Of the 80 items included in the Speech, Spatial and Qualities of Hearing

Scale (SSQ), 3 items on the Qualities scale are designed to target listening effort (Gatehouse & Noble, 2004). More recently, the Device Oriented Subjective Outcome (DOSO) Scale was developed which includes an entire subscale with two equivalent forms that are devoted to the assessment of listening effort (Cox, Alexander, & Xu, 2009). As the studies of the current dissertation were not targeted toward a specific device (i.e., hearing aid or cochlear implant), using the suggestion of Kricos (2006) estimates of listening effort were obtained by asking participants to rate the effort involved in the experimental tasks on a scale ranging from 0 to 100 where 0 signified a negligible amount of effort and 100 signified a high degree of effort.

Physiological measures

To investigate listening effort, physiological measures have included: cortisol measurements obtained from saliva samples (Bourland-Hicks & Tharpe, 2002), the P300 response taken from evoked response potentials (Pichora-Fuller, 2009b) and more recently with the use of an eye tracker, pupil dilatation (Kramer, Kapteyn, Festen, & Kuik, 1997; Kuchinsky, Eckert, & Dubno, 2011; Zekveld, Kramer, & Festen, 2010). Since the late 1800s, researchers have known that the diameter of one's pupil can provide a sensitive index of mental effort such that the harder a task is, the larger one's pupil will become (Hess & Polt, 1964).

Behavioural measures

Borrowing from psychology, the dual task paradigm provides a behavioural means to quantify the degree of listening effort. Dual tasking has the added benefit of ecological validity as it is rare that all we do is listen in isolation. More often than not, when engaged in activities of daily living, we are doing many things as we are listening (i.e., note-taking, walking, driving). Unlike the recall paradigm where the memory test is presented sequentially, with a dual task paradigm participants perform two tasks (a primary and a secondary task) separately and concurrently. For the studies of the current dissertation a dual-task paradigm was used to quantify the degree of listening effort young and older adults expend when listening to speech presented in noise. The primary task involved closed-set word recognition and the secondary task involved tactile pattern recognition. Similar to information processing theory, one of the underlying assumptions of dual task paradigms is that the cognitive system has a limited capacity of resources to process information (Kahneman, 1973). As a result, when the processing capacity for the primary task becomes excessive (e.g., when a speech recognition task is performed with background noise), decreases in secondary task performance will be observed when the tasks are performed together (Kahneman, 1973; Lavie, 1995; Pashler, 1994). Traditionally, listening effort has been operationally defined as the decline of secondary task performance under dual task conditions (Bourland-Hicks & Tharpe, 2002; Broadbent, 1958; Fraser et al., 2010).

Influence of age on listening condition: equated level vs. equated performance

In general, at a fixed signal to noise ratio (SNR) where the levels of speech and background noise are presented at the same level to both young and older participants, the differences observed on cognitive measures typically reflect differences based on age and/or hearing loss (Larsby, Hallgren, & Lyxell, 2005). In contrast, when the presentation levels of speech and noise are individually adjusted to equate word recognition performance, many studies have reported that age-related differences on cognitive measures can be minimized (Murphy, Craik, Li, & Schneider, 2000; Pichora-Fuller, 2003, 2006; Schneider & Pichora-Fuller, 2000). Given this observation, the studies of the current dissertation tested the listening effort of young and older adults under two experimental conditions: 1) equated level – when the noise level of the speech task was the same for all participants and, 2) equated performance – when the noise level was individually attenuated for older adults to ensure that baseline word recognition ability did not differ between young and older adults.

Linking listening effort with cognitive measures

Cognitive tests used to predict speech recognition ability

Rather than focusing on the construct “listening effort” most research has examined the relationship between a performance based measure – word recognition ability in noise – and cognitive abilities (Akeroyd, 2008). Similar to the work of Humes (2007), the results from a comprehensive review of 20 experimental studies indicated that word recognition ability in noise was determined primarily by hearing ability followed by cognitive abilities (Akeroyd, 2008). Given the limited number of cognitive tests included in the meta-analysis conducted, Akeroyd (2008) concluded that tests of working memory such as the reading or listening working memory span tests emerged as the best predictors of speech recognition ability in noise.

In other research involving time-compressed word identification, a principal component analysis revealed three major cognitive components for the battery of neurocognitive tests under study: sequential working memory, non-sequential working memory, and processing speed (Vaughan, Storzbach, & Furukawa, 2008). Using an analysis of covariance, after adjusting for age and hearing loss, sequential working memory was the only component to emerge as being significantly related to performance on a time-compressed speech task (Vaughan, Storzbach, & Furukawa, 2006; Vaughan et al., 2008). Further analysis by Vaughan et al. (2008) revealed that of all the sequential working memory tests under study, Letter-Number Sequencing (LNS) was the most strongly associated with rapid speech understanding. The LNS is a test of auditory working memory taken from the WAIS-III (Wechsler, 1997). As the title suggests, letters and numbers are presented in a random order and participants report the numbers first in ascending order followed by the letters in alphabetical order.

Taken together, tests of working memory have been shown to be related to word recognition ability in noise (Akeroyd, 2008) and word recognition ability using time compressed speech (Vaughan et al., 2006, 2008).

The relationship between working memory and language understanding

Working memory is a limited capacity system that allows for the temporary storage and manipulation of information until it is either forgotten or consolidated into long-term memory according to the theoretical framework originally proposed by Baddeley & Hitch (1974). Similarly, language understanding is a process that occurs over time where often early parts of a message need to be temporarily stored while the remainder of the message is perceived (Pichora-Fuller, 2006).

Given the similarity between the two processes, the Ease of Language Understanding (ELU) model (see Figure 2) was proposed to describe the role of working memory in language understanding (Ronnberg, Rudner, Foo, & Lunner, 2008). In the first step, incoming multimodal language input is processed as streams of phonological information by a mechanism which involves the ‘rapid automatic multimodal binding of phonological information’ or RAMBPHO (Ronnberg et al., 2008). Under “easy” listening conditions, the information contained in the RAMBPHO can be matched rapidly and implicitly with the phonological representation stored in long-term memory. However, under “difficult” listening conditions, the ELU model predicts that more explicit processing involving both processing and storage capacity will be required in the event that a mismatch between RAMBPHO and long-term memory occurs. The mismatch condition is very similar to the difficult listening situation described in Figure 1 wherein a listener would be more reliant on top-down processing as a compensation strategy.

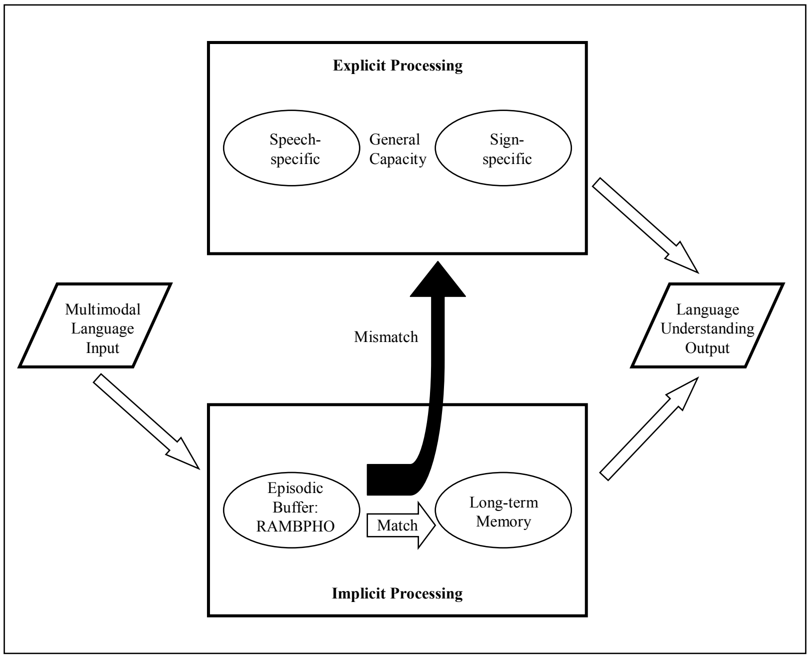

Figure 2. The Ease of Language Understanding (ELU) Model (adapted from Rönnberg et al., 2008).

Processing and storage components of working memory

As shown in both the mismatch condition of the ELU model and the description of working memory, the idea involving processing and storage capacity figure prominently. In general, measures which tap the combined processing and storage resources of working memory (i.e., reading or listening working memory span tests) are better predictors of language comprehension ability than are measures of storage alone (Daneman & Carpenter, 1980; Daneman & Merickle, 1996). In a typical working memory span task participants read or listen to a sentence and complete a task related to that sentence (i.e., read the sentence aloud, repeat the sentence they heard or verify the logical accuracy or semantic sensibility of the sentence). Following the presentation of a set of sentences which can range in size from two to six, participants are prompted to recall a target word (i.e. first word or last word) from each sentence in the same order that they were presented in the set. With correct recall performance, the number of sentences per set is increased. The working memory span score represents the maximum number of target words recalled (Conway et al., 2005; Pichora-Fuller, 2006).

One of the common features of many working memory span tasks (i.e., reading span, operation span and counting span) is that a demanding secondary processing task is required to compete with information storage (Conway et al., 2005). However, the processing component of the test is rarely scored (Conway et al., 2005). Despite the volume of research in this area (Daneman & Merickle, 1996) very few investigators have examined each of the constituent processes of working memory (Baddeley, 2002). A notable exception involves work by Belleville et al (1998) involving the Alpha Span test (Craik, 1986). The Alpha Span test is a measure of auditory working memory in which the processing component involves a mental transformation of the target memory items. Participants repeat words initially presented in a random order in alphabetical order (Craik, 1986). Using the Alpha Span test, Belleville et. al (1998) examined the influence of storage capacity on the processing ability of young and older adults. To control for varying storage capacity, the authors assessed recall at each participants word span (i.e., the longest sequence correctly recalled on 50% of the trials). Using this technique, in a series of experiments Belleville et al. (1998) found that there were no significant differences between young and older adults on the alphabetical recall component of the Alpha Span. To examine how the separate contributions of processing and storage may in turn relate to word recognition in noise under dual task conditions and the effort involved with listening, the studies of the current dissertation used a French version of the Alpha Span test and followed the same experimental procedure as outlined by Belleville et al. (1998).

Outline of current thesis

As the dual task paradigm is used in each of the studies of the current dissertation, Chapter 1 includes a Methods paper (Article 1) which describes how a dual task paradigm has been used to measure listening effort and provides a review of the literature. Chapter 2 includes the three principal studies conducted to investigate the influence of age on listening effort and the relationship between listening effort and auditory working memory.

The primary purpose of Study 1 and Study 2 was to quantify and compare the amount of listening effort that young and older normal hearing adults expend when speech is presented in background noise. The focus of Study 1 (Article 2) was to determine the listening effort associated with auditory speech recognition (hearing a speaker), whereas for ecological validity Study 2 (Article 3) examined the listening effort involved with audiovisual speech recognition (hearing and seeing the face of a speaker). By incorporating two different modalities for speech presentation, the influence of adding visual cues on listening effort was examined for both young and older adults. It is well known that when a person can hear and see the face of their communication partner (i.e. adding visual speech cues), speech-recognition is facilitated (Grant & Braida, 1991; Macleod & Summerfield, 1987; Macleod & Summerfield, 1990; Sommers, Tye-Murray, & Spehar, 2005; Sumby & Pollack, 1954). However, it is unknown whether normal hearing older adults with normal (or corrected normal) vision process audiovisual speech as proficiently as young adults and in so doing – display a reduction in listening effort compared to speech processed in an audio-only modality.

Listening effort was quantified behaviourally using a dual task paradigm, in which a speech recognition task was paired with a tactile pattern recognition task. For both tasks accuracy performance and response times were measured. In addition, listening effort was also assessed using a self-report rating scale. As a result, the secondary purpose of Study 1 and Study 2 was to determine if there was a correlation between self-reported estimates of accuracy and effort with dual task measures of performance and effort. Based on studies completed with young normal hearing adults from our own lab (Fraser et al., 2010) and discrepancies between self-report results and behavioural measures with older adults (Ford et al., 1988; Saunders & Echt, 2007; Shulman, Pretzer-Aboff, & Anderson, 2006; Uchida, Nakashima, Ando, Nino, & Shimokata, 2003), we expected that estimates of listening effort would not correlate with any dual task measure for both young and older adults (Feuerstein, 1992).

For both Study 1 and Study 2, speech recognition was investigated under two experimental conditions: 1) when the noise level of the speech task was the same for all participants (i.e., the equated level condition) and, 2) when baseline single task word recognition ability did not differ between groups (i.e., the equated performance condition). Based on studies that have investigated capacity theory and age-related cognitive and sensory decline (Chisolm, Willot, & Lister, 2003; Kricos, 2006; McCoy et al., 2005; Tun, Benichov, & Wingfield, 2008; Wingfield & Tun, 2001, 2007), we expected that older adults would expend greater listening effort for the equated level condition. For the equated performance condition, we expected age-related differences in listening effort to be minimized relative to the equated level condition (Murphy et al., 2000; Pichora-Fuller, 2003, 2006; Schneider & Pichora-Fuller, 2000). However, for the equated performance condition we still anticipated that the capacity for the primary task would be exceeded to a greater extent by older adults relative to young adults leaving less processing resources available for the secondary task (Salthouse, 1988). As a result, for both the equated level and equated performance conditions, we expected older adults to have greater costs associated with secondary task processing compared to young adults (Salthouse, 1988).

The goals of Study 3 (Article 4) were twofold: 1) to determine to what extent the separate components of auditory working memory (i.e., capacity and processing) contribute to the variance observed in listening effort from word recognition in noise under dual task conditions and, 2) to determine if different patterns of the working memory predictor variables would emerge across the age groups. Based on working memory span research (Pichora-Fuller, 2007), we expected that those with long span sizes as measured with the Alpha Span test would expend less listening effort as measured by low costs on secondary task performance (i.e., tactile task accuracy and response time measures). In terms of processing, we expected that participants with high alphabetical recall ability would have high accuracy scores on word recognition in noise given the strong relationship observed between the LNS and rapid speech understanding. However, how alphabetical recall relates to word recognition under dual task conditions is unknown. For the second goal, we expected a similar pattern of results for young and older adults such that age-related declines in working memory (Salthouse, 1994, 2004) would be associated with age-related increases in listening effort.

Chapter 3 includes a general discussion and outlines the limitations and future directions that can be explored from this research. The final section presents the conclusions as well as clinical implications that can be drawn from this body of work.

Chapter 1

Article 1 - Use of a dual task paradigm to measure listening effort

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Abstract

Listening effort is an important dimension of speech understanding. Despite the fact that a significant amount of speech understanding involves cognitive processes, much of clinical audiology remains focused on assessing the auditory periphery. As speakers age, their sensory, perceptual and cognitive functions decline. It has been speculated that older adults exert increased listening effort compared to younger adults but this effect is still poorly understood. Listening effort refers to the attention and cognitive resources required to understand speech. Listening effort can be evaluated indirectly in clinical practice through self-report, or it can be quantified more objectively using a dual-task paradigm. This paper emphasizes the importance of measuring listening effort and reviews the literature. The review focuses on dual task paradigms which have been used to investigate the effort related to understanding speech. The paper concludes with a discussion of the clinical importance of measuring listening effort.

Key Words: Listening effort, dual task paradigm, cognition, aging, speech perception, hearing loss, hearing aids, rehabilitation

Hearing and listening are different

Audiologists routinely measure hearing ability. However, there is more to communication then simply hearing. The process of communication involves not only perceptual factors like the ability to hear but also cognitive factors (Kiessling et al., 2003; Worrall & Hickson, 2003). In 2001, the hearing aid company Oticon assembled an international panel of experts to discuss the delivery of audiological services to older adults. Taking inspiration from the World Health Organization's International Classification of Functioning, Disability and Health (ICF; (WHO, 2001), the group found that the traditional term "hearing" must be understood to involve hearing, listening, comprehending, and communicating (Kiessling et al., 2003). This expanded definition of "hearing" recognizes the contributions of peripheral and central factors and acknowledges the fundamental difference between hearing and listening. Hearing is a sense whereas listening is a skill that requires attention and intention to access and use the information that is heard. Comprehension involves the reception and interpretation of the meaning and intent of the information. Communicating involves the effective use and transfer of information.

This paper focuses on the distinction between hearing and listening with an emphasis on the listening effort involved with listening comprehension. The importance of measuring listening effort and the influence that age and hearing impairment have on listening effort is explained. Subjective and objective measures of listening effort are detailed, including the mechanics of dual task-paradigms that can be used as an objective means to assess listening effort behaviourally. Next, a review of the literature related to the dual task paradigm as a measure for the effort related to speech understanding is presented. The paper concludes with a discussion of the clinical importance of measuring listening effort.

The importance of measuring listening effort

To illustrate the importance of distinguishing hearing from listening, let us consider two hypothetical (but realistic) case studies with similar hearing ability but varying degrees of difficulty in day-to-day listening and communication situations. Client A has a moderate sensorineural hearing loss bilaterally and wears two hearing aids. Masked word discrimination ability was measured at 68% and 72% for the right and left ears respectively. Even with amplification, Client A has marked difficulties understanding speech in noisy situations and hearing the television clearly at a normal volume level. Over the years, Client A has slowly started to withdraw from social situations as he feels tired and stressed at the end of the day, when he has had to concentrate hard on listening. In contrast, a second Client B has a moderate to severe sensorineural hearing loss bilaterally and uses a combination of hearing aids and assistive listening devices. Her word discrimination ability is equivalent to Client A. Client B has minimal difficulties hearing in noise because she uses an FM system. Client B continues to have some difficulties hearing telephone conversations clearly, even when using her telecoil settings and volume control. She continues to work full time and has a very active family and social life.

If we use the ICF model (WHO, 2001) to interpret these hypothetical cases, we find that Client A has more activity limitations and participation restrictions than Client B. However, these important differences would be invisible to an audiologist who only relied on traditional measures such as the audiogram or standardized speech tests.

In clinical practice, speech understanding is evaluated using a standardized word recognition test (e.g., CID W-22 lists; (Hirsh et al., 1952)) in which the percentage of words repeated correctly constitutes the score. More recently, standardized speech-in-noise protocols have emerged, such as the Bamford-Kowal-Bench Speech in Noise Test- BKB-SIN; (Bench, Kowal, & Bamford, 1979), the Quick Speech in Noise Test- QuickSIN; (Killion, Niquette, Gudmundsen, Revit, & Banerjee, 2004), the Hearing in Noise Test-HINT; (Nilsson, Soli, & Sullivan, 1994) and the Words in Noise Test-WIN; (Wilson &

Burks, 2005). In these tests, the score is the signal-to-noise ratio where a listener recognizes the speech materials correctly for a fixed percentage of the presentations (e.g., 50%).

As shown in our hypothetical example, it is often possible that two listeners could receive an identical score even though one of the listeners may find that listening in typical day to day situations is extremely challenging and requires great effort. Researchers involved with telephone engineering have long recognized that intelligibility testing (i.e., observing how many words are correctly reported by a listener at the other end of the line) does not differentiate in a situation where a listener may score within a region of high intelligibility but report that the voice was unintelligible and required considerable 'mental effort' to discriminate (Broadbent, 1958; Fletcher, 1953).

The challenge faced by clinicians is that on the basis of the audiogram and speech test results, listeners with equal scores may be provided with similar audiological rehabilitative services such as amplification despite the fact that there could be large differences in the amount of listening effort. We therefore argue that listening effort is an important variable to consider. Listening effort is an important dimension of speech understanding, yet much of clinical audiology remains focused on assessing hearing impairment even though a significant amount of listening, comprehending and responding involves the cognitive system (Baltes & Lindenberger, 1997; Edwards, 2007; Pichora-Fuller & Singh, 2006; Sweetow & Henderson-Sabes, 2004). Listening effort refers to the attention and cognitive resources required to understand speech (Bourland-Hicks & Tharpe, 2002; Downs, 1982). In contrast, 'ease of listening' refers to the listener's perceived difficulty of the listening situation (Bourland-Hicks & Tharpe, 2002; Feuerstein, 1992).

The influence of age on listening effort

Age is an important factor to consider in terms of an individual's ability to listen and communicate because as adults age, their sensory, perceptual and cognitive functions decline (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994; Pichora-Fuller &

Singh, 2006; Scialfa, 2002). These declines affect the ability to understand speech, especially in noisy situations. Most normal hearing older adults perform more poorly than younger adults on speech comprehension tasks, especially in noise (CHABA, 1988). In terms of day-to-day listening, many older adults indicate that listening in noisy situations is a challenging and often exhausting experience. Although it has been speculated that older adults exert increased listening effort compared to younger adults, very few studies have actually evaluated listening effort experimentally (Larsby, Hallgren, & Lyxell, 2005; Tun, Benichov, & Wingfield, 2008).

Larsby et al. (2005) examined how different speech or speech-like background noises may interact with cognitive processes important for speech understanding in young and elderly listeners with and without hearing loss. The cognitive processes evaluated included tests from the Speech and Visual Information Processing System (SVIPS) test battery (Hallgren, Larsby, Lyxell, & Arlinger, 2001). In general, Larsby et al. (2005) found that relative to younger adults, the elderly subjects were more distracted by noise with temporal variations and were especially affected by noise with meaningful content. The components of the test battery that were most affected by these noise variations involved the non-word category of the lexical decision making test. For this test, participants were asked to judge whether a combination of three letters represented a real word or a non-word. However, despite the performance differences for the lexical test in terms of accuracy and reaction time scores, interestingly, the elderly listeners did not report a higher degree of perceived effort than younger subjects in these situations. Larsby et al. (2005) interpreted this finding as being due to the fact that the elderly are less prone to complain.

In terms of response time findings, research by Tun et al. (2008) demonstrated similar results. Using a sentence comprehension task, Tun et al. (2008) showed that older adults were slower than younger adults when processing speech at low sound intensities or when processing speech with difficult syntax. The increased response time results were then used to infer increased processing effort and difficulties for older adults though effort was never explicitly measured.

The influence of hearing impairment on listening effort

In addition to the influence of age on listening effort, hearing impairment can exacerbate difficulties with listening, particularly in noise (Hallgren et al., 2001; Hallgren, Larsby, Lyxell, & Arlinger, 2005; Larsby et al., 2005; Tun et al., 2008; Worrall & Hickson, 2003). A common complaint among people with hearing loss is the effort required to understand speech in noisy situations. Since the CHABA (1988) report, a comprehensive review of twenty experimental studies involving both normal hearing listeners and those with hearing loss was undertaken to examine the relationship between speech understanding in noise and cognitive abilities (Akeroyd, 2008). Akeroyd (2008) concluded that while hearing loss emerged as the primary factor in determining one's speech recognition ability in noise, cognition was secondary. Further, while no single cognitive test emerged across all the studies reviewed, Akeroyd found that measures of working memory were significantly correlated to speech understanding ability in noise (Akeroyd, 2008). For a further review of the effects of age on cognitive ability and hearing loss, readers are directed to Pichora-Fuller & Singh (2006).

The debilitating effects of hearing loss can be manifested as both fatigue and as extra effort which is needed to listen to understand speech and to concentrate (Bourland-Hicks & Tharpe, 2002; Hétu, Riverin, Lalande, Getty, & St-Cyr, 1988; Kramer, Kapteyn, Festen, & Kuik, 1997). Hearing loss can dramatically alter one's social interactions and quality of life due to the increases in effort, stress, and the fatigue of coping (Demorest & Erdman, 1986). Stephens and Hétu (1991) have suggested that the World Health Organization's classification of auditory handicap (WHO, 1980) be extended to include the effects of effort and fatigue.

Humes (1999) examined the multidimensional nature of hearing aid outcome. In this study, principal component analyses were used to evaluate functional associations between different outcome parameters. Interestingly, the notion of "effort" emerged as a separate aspect of hearing aid outcome that was distinct from aided speech recognition performance.

Compared to normal hearing listeners, Larsby et al. (2005) found that listeners with hearing loss had more problems completing the SVIPS test battery in noises with a high degree of temporal variations (i.e., a single or multi-talker babble noise compared to a steady state noise). Collapsing the data across younger and older adults, the perceived effort ratings of listeners with hearing loss were significantly higher than the perceived effort ratings of normal hearing listeners (Larsby et al., 2005). The highest effort ratings for listeners with hearing loss were obtained for tasks that were administered in an auditory only modality, followed by audiovisual conditions. Text based tests required the least effort (Larsby et al., 2005).

Tun et al. (2008) used response latency data to demonstrate that older adults with hearing loss were slower than older adults with normal hearing and even younger adults with hearing loss. Subjects were asked to verify the accuracy of sentences presented at either low levels or with complex syntactic structure. While effort was not explicitly measured these findings were used to conclude that older adults with poor hearing are slower processing sentences under challenging conditions (e.g., low sound intensity, difficult syntax) due to increased processing effort (Tun et al., 2008).

Subjective measures of listening effort

Questionnaires

Given the importance of measuring listening effort, the question for practicing clinicians is how to obtain a reliable measure of listening effort? Currently, if listening effort is evaluated in audiological practice, it is done with self-reports or rating scales designed to measure handicap reduction, acceptance, benefit, and satisfaction with hearing-aid amplification (Humes & Humes, 2004). Two examples of questionnaires that quantify handicap due to hearing loss and measure change in perceived handicap after the fitting of hearing aids include the Hearing Handicap Inventory for Adults (HHIA; (Newman, Weinstein, Jacobson, & Hug, 1991)) and the Hearing Handicap Inventory for the Elderly (HHIE (Weinstein, Spitzer, & Ventry, 1986)). One promising new questionnaire which can be administered in an interview format is the Speech, Spatial and Qualities of Hearing Scale (SSQ; (Gatehouse & Noble, 2004)). The 80 questions of the SSQ are designed to measure both dynamic and static aspects of hearing function. The questionnaire includes items to assess hearing disabilities and handicap as they relate to auditory attention, perceptions of distance and movement, sound-source segregation, prosody, sound quality and listening effort. The items that specifically target listening effort include questions 14, 18 and 19 from the Qualities scale (Gatehouse & Akeroyd, 2006):

> Qualities 14: Do you have to concentrate very much when listening to someone or something?
>
> Qualities 18: Do you have to put in a lot of effort to hear what is being said in conversation with others?
>
> Qualities 19: Can you easily ignore other sounds when trying to listen to something?

In a recent study designed to determine the benefits of binaural amplification, the SSQ was used (Gatehouse & Akeroyd, 2006). In addition to the expected dynamic benefits of binaural amplification relative to monaural amplification, the SSQ was able to show a significant reduction in the effort needed to communicate effectively (Gatehouse & Akeroyd, 2006).

According to Kricos (2006), it is essential that clinicians document how successful a program of audiologic rehabilitation has been in reducing listening effort as this represents a unique aspect of hearing aid outcome which is separate from aided speech recognition. In the absence of a formalized questionnaire, Kricos suggests that an estimate of listening effort could be obtained by asking clients to rate their ease of listening on a scale from 0 to 100 with 100 representing very easy listening (Kricos, 2006).

As evidence-based practice paradigms require clinicians to demonstrate that their hearing aid fittings are providing real-world benefit, self-reports of outcome are now becoming a new standard measure for reporting treatment effectiveness, in addition to clinic-based measures of hearing aid benefit and aided speech recognition (Cox, 2003; Humes, 1999; Humes & Humes, 2004).

Acceptable Noise Level Test (ANL)

The Acceptable Noise Level Test (ANL) adds an interesting nuance to the notion of listening effort as an essential component of the test is to measure the maximum level of background noise that a listener is willing to "put up with" without becoming tired or tense while listening to a story (Nabelek, Freyaldenhoven, Tampas, Burchfield, & Muenchen, 2006; Nabelek, Tampas, & Burchfield, 2004). To obtain an ANL, a recorded story is adjusted to a listener's most comfortable listening level (MCL). Next, background noise is increased to the maximum level that the listener will tolerate while listening to the story (i.e., the background noise level, BNL). The ANL is calculated as the difference between the two subjective measures (i.e., ANL = MCL – BNL).

The literature has reported that one's willingness to tolerate background noise is a predictor for successful hearing aid use (Nabelek et al., 2006; Nabelek et al., 2004; Plyler, 2009). According to investigators, the ANL test can identify with 85% accuracy those individuals who will wear and use their hearing aids (Nabelek et al., 2006) . Individuals that are able to "put up with" high levels of background noise (i.e., have low ANL scores) are more likely to be successful hearing aid users compared to individuals who cannot deal with background noise (i.e., have high ANL scores). ANL scores have received attention in the literature because they have been shown to be reliable and consistent over time for both people with normal hearing as well as those with hearing loss (Nabelek et al., 2006; Nabelek et al., 2004; Plyler, 2009). Since ANL scores do not change with hearing aid use, it is possible that they can be measured before hearing aids are fitted and used as a predictor of hearing aid use (Nabelek et al., 2006; Nabelek et al., 2004). The unaided ANL has also been shown to be significantly related to outcome as measured by the International Outcome Inventory for Hearing Aids (IOI-HA; (Taylor, 2008). However, it must be noted that the starting point of the ANL is based on two subjective level-setting measures (i.e., MCL and BNL).

Limitations of subjective measures

While self-report through questionnaires may be effective for many adult clients, several studies have shown that in the case of older adults, discrepancies exist between self-report and objective measures (Saunders & Forsline, 2006; Shulman, Pretzer-Aboff, & Anderson, 2006). Older adults tend to overestimate their capabilities and underestimate their degree of impairment (Ford et al., 1988; Uchida, Nakashima, Ando, Nino, & Shimokata, 2003).

In a similar way, the ANL test could also be underestimated by many people. Elderly people in particular may indicate a greater tolerance for speech in noise even though it may result in poorer speech comprehension. Larsby (2005) observed that the elderly are less likely to report a high degree of perceived effort than younger adults despite measurable performance differences (i.e., accuracy and response time measures). This was interpreted as evidence that the elderly are less prone to complain. This finding could also apply to the ANL. On a final note, while the ANL asks listeners to indicate when the noise is too loud, listeners are never asked any questions regarding the passage they heard. In other words, there is no actual measure of comprehension. For these reasons, an objective measure of the listening effort involved with listening comprehension would be beneficial.

The dual task paradigm – A means to quantify listening effort

We argue that a dual task paradigm provides a quantitative measure to assess listening effort during a specific listening condition (Bourland-Hicks & Tharpe, 2002; Broadbent, 1958). In a dual-task paradigm, participants are asked to perform two tasks (a primary and a secondary task) separately and then concurrently. To assess listening effort, the primary task typically involves a listening activity such as word recognition in quiet or in noise at a predetermined signal-to-noise (SNR) ratio. Participants are told that recognizing speech is the primary task and that any additional task is secondary. The secondary task may involve a memory task, a probe reaction time task, or a tactile pattern recognition task (Bourland-Hicks & Tharpe, 2002; Downs, 1982; Downs & Crum, 1978;

Feuerstein, 1992; Fraser, Gagné, Alepins, & Dubois, 2007, 2009; Rabbitt, 1966; Rakerd, Seitz, & Whearty, 1996). Research has shown that individuals are able to prioritize one task over another based on verbal instruction (Bourland-Hicks & Tharpe, 2002; Crossley & Hiscock, 1992; Pashler, 1994; Somberg & Salthouse, 1982).

Dual task paradigms make the implicit assumption that the cognitive system has a limited capacity of resources available at any given point in time (Kahneman, 1973). When individuals are required to divide their attention between two tasks, it is this limited processing capacity that is being tested. For the last century, psychologists have been interested in people's ability to perform two or more activities concurrently. By overloading a system, it can be determined what the parts of a system are and how they function together (Pashler, 1994). The principles from Lavie's cognitive load theory can be applied to dual task research paradigms (Lavie, 1995, 2005). Under conditions of low load, spare capacity from the primary task spills over to the secondary task, with no performance decrements to either task when they are performed in combination. However, under conditions of high load, where processing capacity is exceeded, decrements to secondary task performance will be observed when the tasks are performed together (Lavie, 1995).

With the dual task paradigm, it is assumed that performance on the primary listening task utilizes the required mental capacity, and performance on any secondary task utilizes any spare or left-over mental capacity (Kahneman, 1973). Accordingly, any increase in effort or load associated with performing the primary task (e.g., adding noise to a listening task) leads to decreases in performance on the concurrent secondary task (Broadbent, 1958). As a result, declines in secondary task performance are interpreted as increases in listening effort (Downs, 1982).

Other assumptions of the capacity theory include: 1) a more difficult task requires more resources or mental capacity for execution, 2) dual task performance assumes that the two tasks compete for resources from a unique general-purpose structure and, 3) as one system is taxed more (e.g., the bottom-up perceptual systems), other systems (e.g., the top-down cognitive systems) have their capabilities negatively impacted (Edwards, 2007;

Kahneman, 1973). For a complete review of the nature of dual task interference, the processing resources involved in attention, and the impact of load on dual task performance, interested readers are referred to the following additional references: (Lavie, 1995, 2005; Pashler, 1994; Wickens, 1984).

Studies in which a dual task paradigm has been used to investigate aspects of speech understanding are summarized in Table 1. Broadbent (1958) was one of the first to advocate for more than just intelligibility scores to assess communication ability. His pioneering work demonstrated that while it was possible for listeners to maintain equal percent correct scores across various distorted listening conditions, it came at the expense of unequal amounts of effort exerted by the listener. The effort involved in listening was reflected by a reduction in efficiency for the simultaneously performed secondary task involving visual tracking (Broadbent, 1958).

In three studies, a memory test was used as the secondary task. In each case, the memory test was presented sequentially (i.e., after the primary task) rather than concurrently, as is usually the case with dual task studies. Rabbit (1966), showed that while the addition of white noise did not affect the number of words correctly shadowed in the primary task, it did have a significant impact on the number of words that could be recalled in the secondary task. Later, Rakerd (1996) demonstrated that listeners with hearing loss were more adversely affected by noise than normal hearing listeners on a secondary task which involved digit memorization. Also, when the memory retention interval was filled with a speech passage (which required participants to listen for understanding) rather than noise, listeners with hearing loss had more difficulty with digit memorization than normal hearing listeners. In a more recent study, Choi et al. used a secondary task that involved serial digit recall (Choi, Lotto, Lewis, Hoover, & Stelmachowicz, 2008). Participants were instructed to remember sets of three or five numbers in the exact order of presentation. Primary and secondary task assignment was manipulated by instruction to investigate how young children could allocate their attention. Interestingly, regardless of which task was given priority, dual task decrements in performance were only associated with serial digit recall and not with word recognition.

Table 1. Literature Review

Author	**Participants**	**Primary Task Description**	**Secondary Task Description**	**Significant Finding**
Broadbent, 1958	6 NH adults	Word recognition using List 3 of the W-22 at 0, -200 Hz and -300 Hz downward transposed conditions each at 0 and 660 Hz high-pass filtering.	High speed visual tracking in which participants were required to keep a pointer on a line of contacts.	Under various conditions of distorted speech: 1) speech intelligibility scores were maintained for the primary task, and, 2) visual tracking accuracy performance decreased (especially with frequency transposition).
Rabbitt, 1966	Exp 1: 29 NH adults (19-53, M=39) Exp 2: 14 NH adults (17-25, M=23)	Word recognition in quiet and noise (i.e., +10 dB SNR)	Memory for primary task words	When noise was added, intelligibility remained high for the primary task but errors on the memory task increased.
Downs & Crum, 1978	49 NH adults (18-25)	Word recognition at 20, 35, 50 dB SL reference to each participant's PTA in quiet and at +6 dB SNR	Reaction time to respond to light probe	Reaction times to the light probe were significantly longer in the noise condition compared to the quiet condition irrespective of the sensation level.

Author	**Participants**	**Primary Task Description**	**Secondary Task Description**	**Significant Finding**
Downs, 1982	23 adults with hearing loss (29-68, M=51) – with and without hearing aids	Speech recognition at 45 dB HL and 0 dB SNR, with and without hearing aids	Reaction time to respond to light probe	When adults with hearing loss wore their hearing aids, speech recognition was better and response time for the secondary task was significantly shorter, compared to the unaided condition.
Feuerstein, 1992	48 NH young adults (M=19) who simulated a hearing loss with an earplug	Speech recognition at 65 dB SPL and +5 SNR	Reaction time to respond to light probe	Binaural listening produced better word recognition and better ease of listening ratings. Response times to the light probe were shorter with binaural listening compared to monaural indirect listening (when noise was directed to the ear that was not plugged). Binaural and direct listening (when noise was directed to the ear with earplug) were equivalent.

Author	Participants	Primary Task Description	Secondary Task Description	Significant Finding
Rakerd et al., 1996	Exp 1: 8 NH young adults and 9 young adults with hearing loss Exp 2: 11 NH young adults (21-29, M=24) and 11 adults with hearing loss (52-73, M=62)	Noise listening task for 60 seconds and speech listening task for 60 seconds followed by 5 comprehension test questions, at 65 dB SPL for NH adults and at MCL for adults with hearing loss	Visually presented serial digit recall	Participants with hearing loss had more difficulty with digit memorization than NH listeners. More digits were forgotten when the memory retention interval was filled with speech compared to noise for those with NH and with hearing loss but those with hearing loss had more difficulty.
Bourland-Hicks & Tharpe, 2002	14 NH children (5-11) and 14 children with hearing loss (6-11)	Speech recognition of PBK word lists presented at 70 dBA at +20, +15, +10 SNR and quiet conditions	Reaction time to respond to light probe	Primary task performance remained over 80% for both listener groups but the response times for the secondary task were significantly longer for children with hearing loss compared to NH children.

Author	Participants	Primary Task Description	Secondary Task Description	Significant Finding
Fraser et al., 2007	Exp 1: 30 NH young adults (18-41, M=25) Exp 2: 30 NH young adults (18-45, M=25)	Speech recognition in auditory (A) and auditory-visual (AV) modalities with speech at 57 dB SPL and noise at 68 and 76 dB SPL	Accuracy and response time to tactile pattern recognition task	Exp 1: When noise was presented at the same level in the AV condition relative to the A condition, speech accuracy improved and tactile response times decreased. Exp 2: When 10 dB more noise was added to the AV condition relative to the A condition, tactile response times slowed.
Choi et al., 2008	64 NH children (7-14)	Word recognition with PBK word lists presented at 65 root mean square (RMS) and +8 dB SNR	Visually presented serial digit recall	Regardless of instruction for which task should receive priority, significant dual-task decrements were seen for serial recall but not for word recognition. 7-8 year old children showed the greatest improvement in word recognition with the greatest decrease in serial recall.

Choi found that children aged 7-8 years old showed the greatest improvement in word recognition but at the expense of the greatest decrease in digit recall during dual task trials (Choi et al., 2008).

Most of the remaining studies summarized in Table 1 used a probe reaction-time test for the secondary task. This technique commonly involves the visual modality as a light signal is presented at random intervals during the primary task and the participant is required to press a button as quickly as they can to indicate that they are aware of the probe signal. Longer reaction times to the probe are associated with greater processing demands on the primary task (Downs & Crum, 1978). On the basis of this observation, Downs and Crum (1978) concluded that normal listeners required extra effort to listen in noise. Studies using this technique with people who had hearing loss found that hearing aid use can improve speech recognition and speech understanding as well as reduce listening effort (Downs, 1982). In a study by Feuerstein (1992), listeners simulated a unilateral hearing loss by inserting an earplug in one ear. The probe reaction time results indicated that binaural listening and the direct listening condition (in which noise was directed to the plugged ear) produced equivalent results. These conditions were judged to require less effort relative to the indirect listening condition (in which noise was directed to the unplugged ear). More recently, Bourland-Hicks (2002) demonstrated that even when children with mild to moderate or high frequency sensorineural hearing loss wore their hearing aids, they expended more effort than normal hearing children when listening in noise.

Many probe reaction time studies of listening effort also included a subjective measure of this construct. Downs and Crum (1978) incorporated a seven-point scale to indicate learning task difficulty. They found that although participants were good judges of learning accuracy, they were poor judges of how much effort was involved in the learning task. Feuerstein (1992) used a rating scale ranging from difficult (e.g., 0) to easy (e.g., 100) to indicate the perceived difficulty of the listening situation by the listener. Like Downs and Crum (1978), Feuerstein (1992) found that while ease of listening and performance accuracy on the primary speech recognition task were positively correlated, performance on the secondary response time task (i.e., listening effort) was not correlated with the subjective ease of listening measures. In a similar study, Bourland-Hicks and Tharpe (2002) asked children to rate the word-repetition task from 1 ("not hard at all") to 5 ("very hard"). Even though the secondary task reaction time data indicated that children with hearing loss expended more effort than children with normal hearing, the two groups' ratings of perceived effort did not differ significantly. Taken together, these studies suggest that objective and subjective measures of listening effort are not correlated in adults or children (Bourland-Hicks & Tharpe, 2002; Downs & Crum, 1978; Feuerstein, 1992). Therefore, caution is needed when measuring listening effort by subjective measures only (Bourland-Hicks & Tharpe, 2002). This further supports the case for developing an objective clinical measure of listening effort.

Of all of the studies summarized in Table 1, only one involved a non-visual and non-auditory secondary task (Fraser et al., 2010). The purpose of the study was to compare the listening effort associated with auditory vs. audiovisual speech perception in young adults. While the primary task involved closed-set sentence-recognition, the secondary task consisted of tactile or somatosensory pattern recognition. By using a secondary task unrelated to the primary tasks' sensory modalities, Fraser et al. (2009) excluded the possibility of structural interference (i.e., overlapping demands on the same perceptual system) (Kahneman, 1973).

In the first experiment, where the same signal-to-noise (SNR) was used for both the auditory (A) and the auditory-visual (AV) modalities, adding visual speech cues improved AV speech recognition performance, and listeners rated their performance as requiring less effort. In the second experiment, the level of performance to complete the speech recognition task in isolation was equated across the A and AV modalities. This was accomplished by adding 10 dB more noise to the AV vs. the A condition. With the increased noise level in the AV modality, reaction times for both tasks were slower and tactile task accuracy was poorer. Despite these performance differences, participants ratings of perceived effort did not differ between the two modalities, which again emphasizes need for an objective test of listening effort (Fraser et al., 2007, 2009).

Clinical implications

With the current trends of population aging, it is estimated that by 2050 approximately 59% of the overall audiology caseload will consist of older adults (Worrall & Hickson, 2003). Systematic testing of dual task paradigm performance would give clinicians an additional performance index over and beyond traditional word recognition scores. In addition, the dual task paradigm provides a more ecological approach to test speech recognition performance as it is often the case that we have to process speech and perform other tasks at the same time (e.g., listen to a lecture and take notes simultaneously). An objective measure of listening effort that takes into account a listener's cognitive capacity can provide a sensitive means to differentiate listener outcomes – especially for older adults who may demonstrate equivalent hearing sensitivity and word recognition performance.

More than 50 years ago, Broadbent (1958) concluded that there was a need for multiple criteria in assessing communication channels and that more than the speech recognition scores should be used to assess communication ability. However, it has only been recently that investigators have begun to explore the relationships between cognitive ability, listening conditions and hearing aid settings. Research has demonstrated that the results from a reading span test can be used to optimize the compression settings of hearing aids (Foo, Rudner, Ronnberg, & Lunner, 2007; Gatehouse, Naylor, & Elberling, 2003, 2006; Lunner, 2003; Lunner & Sundewall-Thoren, 2007; Rudner, Foo, Ronnberg, & Lunner, 2007). Other researchers have used dual task paradigms to evaluate the effectiveness of different noise reduction algorithms incorporated in hearing aids (Edwards, 2007; Sarampalis, Kalluri, Edwards, & Hafer, 2006, 2009). In these studies, the primary task involved either word or sentence recognition at various signal-to-noise ratios. The secondary tasks involved either holding words in short term memory or responding to a complex visual reaction-time task in which a driving game was used to gauge the mental effort involved with speech understanding. The results of these studies suggest that noise reduction algorithms reduce listening effort and free cognitive resources for other tasks (Sarampalis et al., 2006, 2009).

To our knowledge, use of a dual-task paradigm has never been used to quantify the listening effort related to understanding speech by older adults. Clinically, the use of this approach could be beneficial because the current means of assessing listening effort involves self-report scales. Research findings have revealed discrepancies between self-report ratings by seniors and related objective or behavioural measures (Saunders & Forsline, 2006; Shulman et al., 2006). Specifically, older adults tend to overestimate their capabilities and underestimate their degree of impairment (Ford et al., 1988; Uchida et al., 2003). Taken together, this underscores the importance of developing an objective test that can be implemented clinically to evaluate listening effort.

In addition to aided speech recognition scores and measures of subjective benefit, in the future, an objective measure of listening effort or cognitive benefit could be used by clinicians 1) as an assessment tool, 2) as an outcome measure to differentiate listeners, 3) to target clients that would benefit from aural rehabilitation and 4) to optimize an individual's hearing aid settings to improve speech understanding (Humes, 1999; Humes & Humes, 2004; Sarampalis et al., 2009).

Acknowledgements

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Chapter 2

Article 2 – Older adults expend more listening effort than young adults recognizing speech in noise

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Abstract

Purpose: Listening in noisy situations is a challenging experience for many older adults. We hypothesize that older adults exert more listening effort compared to young adults. Listening effort involves the attention and cognitive resources required to understand speech. The purpose was 1) to quantify the amount of listening effort young and older adults expend when they listen to speech in noise and, 2) to examine the relationship between self-reported listening effort and objective measures.

Method: A dual task paradigm was used to objectively evaluate the listening effort of 25 young and 25 older adults. The primary task involved a closed-set sentence-recognition test and the secondary task involved a vibro-tactile pattern recognition test. Participants performed each task separately and concurrently under two experimental conditions: 1) when the level of noise was the same, and 2) when baseline word recognition performance did not differ between groups.

Results: Older adults expended more listening effort than young adults under both experimental conditions. Subjective estimates of listening effort did not correlate with any of the objective dual task measures.

Conclusions: Older adults require more processing resources to understand speech in noise. Dual task measures and subjective ratings tap different aspects of listening effort.

Key Words: Listening effort, dual task paradigm, audition, cognition, aging, speech recognition.

Introduction

Many older adults indicate that listening in noisy situations is a challenging and often exhausting experience (CHABA, 1988). Age is an important factor to consider in terms of an individual's ability to listen and communicate because as adults age, their sensory, perceptual and cognitive functions decline (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994; Pichora-Fuller & Singh, 2006; Scialfa, 2002). Even when older adults have normal hearing ability, they still perform more poorly than young adults on speech recognition tasks presented with background noise (CHABA, 1988). This suggests that beyond perceptual factors like the ability to hear, cognitive factors are essential for communication.

To better understand and address the rehabilitative needs of older adults, there has been an increasing interest to learn how auditory and cognitive processes inter-relate (Baltes & Baltes, 1990; Baltes & Lindenberger, 1997; Pichora-Fuller, 2006, 2009; Pichora-Fuller & Singh, 2006). Since the CHABA (1988) report, a comprehensive review of twenty experimental studies involving normal hearing listeners and those with hearing loss examined the relationship between speech recognition in noise and cognitive abilities (Akeroyd, 2008). Akeroyd (2008) concluded that while hearing was the primary factor in determining one's speech understanding ability in noise, cognition was secondary.

It is common practice in both the clinical and research domains of audiology to include a performance measurement like speech recognition. Speech recognition tests can be used to assess the accuracy with which phonemes, syllables, words or sentences are reported. However, unlike the field of human factors engineering or cognitive psychology, within audiology it is less common to examine the construct "effort". Listening effort, the focus of the current study, refers to the attention and cognitive resources required to understand speech (Bourland-Hicks & Tharpe, 2002; Downs, 1982; Feuerstein, 1992; Fraser, Gagné, Alepins, & Dubois, 2010). Currently, if listening effort is evaluated clinically, questionnaires or self-reports are used to gain insight into one's ease of listening.

Alternatively, the questionnaire could be geared towards the effort or difficulty involved in listening. Regardless of which end of the continuum is used, ultimately it is one's perception of the ease or effort involved with listening in a particular situation that is evaluated (Bourland-Hicks & Tharpe, 2002; Feuerstein, 1992). Although it has been speculated that older adults exert increased listening effort relative to young adults, very few studies have been conducted to lend support to this idea (Larsby, Hallgren, & Lyxell, 2005; Tun, Benichov, & Wingfield, 2008).

Along with cognitive performance related measures, Larsby et al. (2005) included a rating scale to examine how different speech or speech-like background noises interact with cognitive processes important for speech understanding in young and elderly listeners. The cognitive processes evaluated included tests from the Speech and Visual Information Processing System (SVIPS) test battery (Hallgren, Larsby, Lyxell, & Arlinger, 2001). Relative to young adults, Larsby et al. (2005) found that the elderly participants were more distracted by noise with temporal variations and noise with meaningful content such as speech. The test most affected by these noise variations was the non-word category of the lexical decision making test which required participants to judge whether a combination of three letters represented a real word or a non-word.

Older adults had lower accuracy scores and longer response times than young adults for this test however, despite these performance differences, the elderly listeners did not report a higher degree of perceived effort than young participants.

For another study, using a sentence comprehension task, Tun et al. (2008) showed that when the sentences were presented at low intensity or included difficult syntax, older adults took longer than young adults to recognize what they heard. The longer response time results were then used to infer that older adults expended more processing effort than young adults.

One way to objectively evaluate listening effort is to use a dual task paradigm (Bourland-Hicks & Tharpe, 2002; Broadbent, 1958; Choi, Lotto, Lewis, Hoover, &

Stelmachowicz, 2008; Downs, 1982; Downs & Crum, 1978; Feuerstein, 1992; Fraser et al., 2010; Rabbitt, 1966; Rakerd, Seitz, & Whearty, 1996; Sarampalis, Kalluri, Edwards, & Hafer, 2009). For example, Sarampalis et al. (2009) used a dual task paradigm to determine if digital noise reduction (DNR) used in modern hearing aids reduces the listening effort needed when processing speech in background noise. Within such a paradigm, participants are asked to perform two tasks (a primary and a secondary task) separately and then concurrently. Dual task paradigms make the implicit assumption that the cognitive system has a limited capacity of resources to process information (Kahneman, 1973). Performance on the primary task (when given priority) utilizes mental capacity, and performance on the secondary task utilizes any spare or left-over mental capacity (Kahneman, 1973). For the current study, the primary task involved a closed-set word recognition task and the secondary task involved tactile pattern recognition. Under conditions of low load or “easy” listening (e.g., listening to the primary word recognition task in quiet), spare capacity from the primary task becomes available for the secondary task, without performance decrements to either of the tasks when they are performed in combination. However, under conditions of high load or “difficult” listening (e.g., adding background noise to the primary word recognition task), when the processing capacity for the primary task is exceeded, decrements to secondary task performance will be observed when the tasks are performed together (Kahneman, 1973; Lavie, 1995; Pashler, 1994). These declines in secondary task performance are interpreted as increases in listening effort (Bourland-Hicks & Tharpe, 2002; Broadbent, 1958; Fraser et al., 2010). For a comprehensive review of studies that have used a dual task paradigm to investigate aspects of listening effort and speech recognition refer to Anderson Gosselin & Gagné (2010).

As Feuerstein (1992) noted, performance (as measured with the primary task), effort (as measured with the secondary task) and ease (as measured with a rating scale to capture the subjective percept of ease or effort involved with listening) each measure a different aspect of listening effort yet they are all interrelated. For example, two individuals may have equal performance but one individual may have expended more effort than the other. The individual who expended less effort is more likely to indicate that they could complete the performance task with more ease. For the remainder of this paper, Feuerstein's concept of 'ease' will be referred to as a 'self-reported estimate of effort'. These subtle distinctions are important if we are to gain a better understanding of the hearing and listening difficulties experienced by older adults.

Using a dual task paradigm, the objectives of the current study were a) to determine if older adults expend more listening effort than young adults when a speech recognition task is performed in noise at a fixed signal-to-noise ratio - the equated level condition; b) to determine if older adults expend more listening effort than young adults at a level where baseline word recognition performance in noise did not differ between the two groups - the equated performance condition; and, c) to determine if there is a correlation between self-reported estimates of accuracy and effort with dual task measures of performance and effort. On the basis of studies that have investigated capacity theory and age-related cognitive and sensory decline (Chisolm, Willot, & Lister, 2003; Kricos, 2006; McCoy et al., 2005; Tun et al., 2008; Wingfield & Tun, 2001, 2007), we expected that older adults would expend greater listening effort for the equated level and equated performance conditions. In other words, under conditions of high load or "difficult" listening due to background noise, we argue that capacity for the primary task will be exceeded for older adults leaving less processing resources available for the secondary task relative to the processing resources available to younger adults (Salthouse, 1988). As a result, we expected older adults to have greater costs associated with secondary task performance as measured by accuracy or response time (Salthouse, 1988). Based on studies from our own lab (Fraser et al., 2010) and the discrepancies between subjective and objective measures reported in other domains (Ford et al., 1988; Saunders & Echt, 2007; Shulman, Pretzer-Aboff, & Anderson, 2006; Uchida, Nakashima, Ando, Nino, & Shimokata, 2003), we expected that accuracy estimates would correlate with the related dual task performance measures but that estimates of listening effort would not correlate with any dual task measure.

Method

Participants

Participants included 25 young adults ranging from 18 to 33 years of age (M = 23.5, SD = 3.6) and 25 older adults ranging from 64 to 76 years of age (M = 69, SD = 4.0). All participants had normal hearing sensitivity (≤ 25 dB HL at octave frequencies between 0.25 and 2.0 kHz, as well as at 3 kHz, re: ANSI, 1996), in both ears and binocular visual acuity of 20/40 or better as measured with Sloan Letters at a distance of 3 metres (NAS-NRC, 1980; Sloan, Rowland, & Altman, 1952). The older adults all had clinically normal cognitive function as determined by the Montreal Cognitive Assessment [MoCA (Nasreddine et al., 2005)]. In addition, all participants reported that: 1) French was the language they regularly used to perform activities of daily living and, 2) they had good self-reported health and, 3) they were able to transport themselves independently to and from the laboratory. All participants voluntarily signed a consent form prior to taking part in the investigation and upon completion all of them were offered a small monetary compensation.

Dual task description

Primary task

The primary task involved a closed set sentence recognition test presented orally (i.e., auditory-only). All sentences were spoken by a female adult whose native language was Québec-French. Each sentence had the same syntactic structure and contained three critical elements (subject, verb, and adjective). For each critical element there were seven interchangeable alternatives which generated a total of 343 different sentences. As a result, multiple lists of similar sentences could be used for each of the various test conditions. Within each critical element, the words were chosen to have the same number of syllables but they were distinct from each other visually and acoustically. The stimuli used for the sentence recognition test and a sample sentence are shown in Figure 1.

A customized computer program (Leclab) was used to conduct the experiment. Separate audio files, one with the speech stimuli and one with the masking noise (a steady-state speech shaped noise) were routed to an 8 channel stereo mixer (Inkel, MX880E). The output from the mixer was amplified (InterM, PA-935) and presented via a loudspeaker (Realistic, Minimus-77) positioned directly 1 metre in front of the participant. Because the primary task consisted of a closed set sentence recognition task, after the presentation of each sentence, participants were asked to indicate the three key words they heard. Specifically, the participant was required to touch each of the three key words that appeared on a 17 inch touch screen monitor (ELO TouchSystems, ET1725L). The target words appeared with a horizontal degree of visual angle (dva) ranging from 1.18 to 2.53 and a vertical dva ranging from 0.25 to 0.38 (see Figure 1). The software program recorded both the accuracy and the response time for each of the three key words of the sentence. Once completed, the participant touched the word "prochain" (i.e., next) to advance to the following trial.

Prior to each testing session a free-field acoustic calibration was conducted with calibration tones to ensure that the speech stimuli were consistently presented at 60 dBA and broadband background noise was presented at 72 dBA. The masking signal consisted of a speech shaped noise (i.e., pink noise). Pink noise was used as it has been found to be more efficient than white noise in that a lower overall level of noise is required to mask speech stimuli (Saeki, Takahiro, Yamaguchi, & Sunada, 2004).

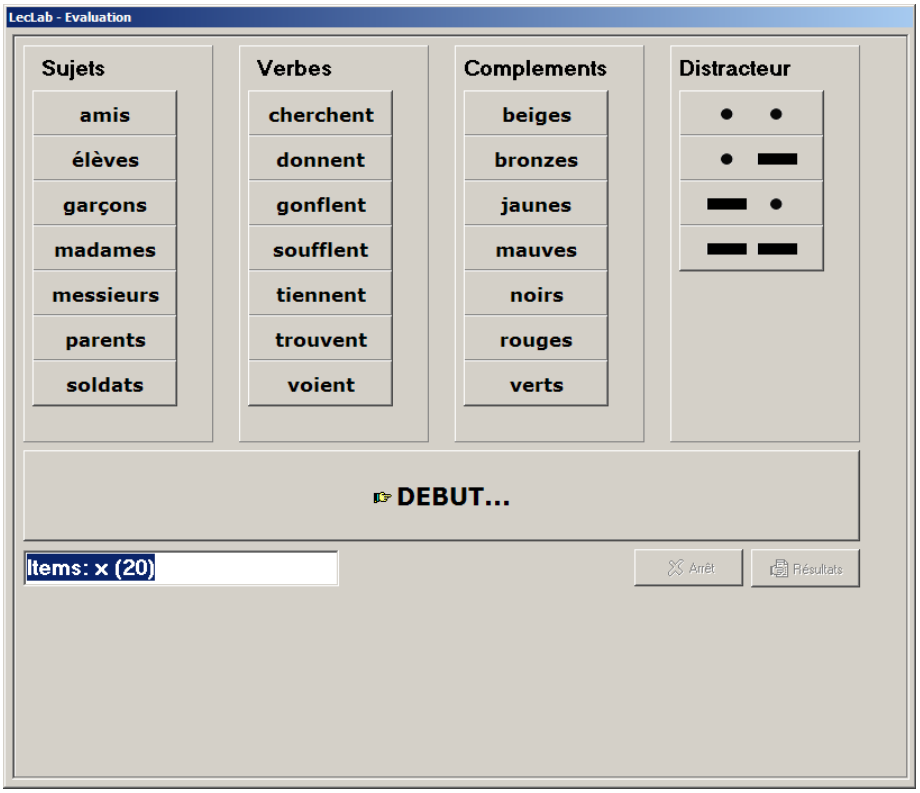

Figure 1. Dual task response screen including the response options for the speech recognition task and the tactile pattern recognition task. An example of a possible sentence used for the speech recognition task: "Les parents[a] trouvent[b] des ballons rouges[c]." Where a = sujets/subjects; b = verbes/verbs; c = complements/adjectives, and these are the critical elements for each sentence. Each of these critical elements can be replaced by any one of the alternatives listed in the column. An English translation of the current sentence would be "The parents found the red balloons". An alternative sentence using the third row of critical elements would read: "The boys inflate the yellow balloons." "Distracteur" is the French heading used to indicate the four response alternatives of the tactile pattern recognition task shown here as short-short, short-long, long-short and long-long. 'Short' stimuli are denoted by circles and 'Long' stimuli are denoted by bars.

Secondary task

The secondary task involved a tactile pattern-recognition task in which participants had to identify one of four pulse combinations (i.e. short-short, long-long, short-long or long-short). By incorporating a secondary task which does not involve the same perceptual modality as the one used for the primary task, we excluded the possibility of structural interference (i.e., overlapping demands due to the same perceptual system) to analyze capacity interference (Kahneman, 1973). The pulses emanated from a small oscillator (Radioear B-71) which is used in clinical audiometry for bone-conduction testing. 'Short' was 250 msec and 'long' was 500 msec in duration. The interstimulus interval was 500 msec. To complete this task, participants held the vibrating device in their non-dominant hand and placed their hand in a box which contained sound attenuating padding on the inside. The purpose of the box was twofold: 1) to prevent the participant from being able to hear the vibrations and, 2) to prevent the participant from being able to view their hand. Recent studies have shown that being able to see part of one's body can influence the tactile perception of that area of the body (Igarashi, Kimura, Spence, & Ichihara, 2007).

During dual-task trials, the software program would initiate tactile trials with a random variable time delay relative to the onset of the sentence stimuli. The delay ranged from 0 msec to 1000 msec in 250 msec steps. This was done so that the onset of the tactile stimuli would not be predictable, relative to the onset of the sentences. After each trial the participants would indicate which of the four tactile patterns they perceived by touching the corresponding iconic symbol that appeared on the touch screen monitor. The software program recorded the accuracy and response times of participants' answers.

Experimental procedure

The complete test protocol was administered in a single test session. For younger participants the total amount of time required to complete the experiment was approximately 1 hour. In contrast, older adults required a maximum of 1 hour and 45 minutes. Participants performed the primary and secondary task separately and concurrently in up to two conditions: 1) Equated level condition (speech at 60 dBA and noise at 72 dBA) and, 2) Equated performance condition (speech at 60 dBA and noise at a reduced level as required for older adults only). All participants performed the equated level condition however, only 13 older adults participated in the equated performance condition. Single and dual task performance was evaluated with 40 test-trials under each experimental condition. In addition, at the beginning of each session, all the participants took part in a practice session. Rest periods were encouraged throughout the practice and test sessions.

Practice session

The goal of the practice session was to ensure that the participants were familiar with the tasks and that they understood the type of responses they were expected to provide. To continue on to the experimental conditions, participants had to reach a criterion level of performance (i.e., 80% correct) on 20 trials of both the primary and secondary tasks when performed under the single task test condition without the masking noise.

An additional 20 practice trials of the dual-task condition were also administered in quiet. For these trials, the verbal instructions were similar to those used in previous experiments where a dual-task paradigm had been used to evaluate listening effort (Bourland-Hicks & Tharpe, 2002; Downs, 1982; Fraser et al., 2010). Specifically, under dual-task conditions participants were instructed as follows: "the listening task is the more important of the two, pick the corresponding subject/verb/adjective for the sentence that you hear as quickly as possible and, identify the pulse pattern that you feel as quickly and as accurately as you can." Note the same verbal instructions were used for each of the experimental conditions.

Equated level condition

When the speech recognition task was performed at a fixed listening level the stimuli were presented at a signal-to-noise ratio (SNR) of -12 dB (i.e., speech at 60 dBA and noise presented at 72 dBA). This signal-to-noise ratio was specifically chosen based on the results of previous experiments (Fraser et al., 2010) and additional pilot work. Pilot testing conducted with the same test equipment and stimuli used in the current investigation, demonstrated that at this signal-to-noise ratio (-12 dB), the primary task (when performed singly) resulted in a mean accuracy rate of approximately 80% by normal hearing young adults. These results were obtained from a sample of 10 normal hearing young adults who did not take part in the current study. The secondary task, tactile pattern recognition, was administered in quiet, with the same equipment and presentation levels used by Fraser et al. (2010). Under the equated level condition, all the participants completed three experimental tasks: 1) the primary task – closed-set sentence recognition in noise, 2) the secondary task – tactile pattern recognition in quiet, and 3) the dual task – sentence recognition in noise and the tactile pattern recognition task concurrently (1 & 2). The order in which the three tasks were administered was counterbalanced across participants to reduce the possibility of confounds due to presentation order.

Equated performance condition

The purpose of the equated performance condition was to control for age-related variance in single task word recognition performance by investigating the effect of an individualized level of testing. For young adults, performance at the fixed level met the 80% performance criterion for the equated performance condition. That is, at the fixed level, the young adults performed the speech task in isolation at an average level of approximately 80% correct. As a result, young adults did not perform any further testing.

Similarly, older adults, who met the 80% performance criterion or better on single task word recognition, were also exempt from any further testing. The exemption of older adults was extended to include the 80% performance criterion minus 1 standard deviation based on the single task word recognition data obtained from the first 15 young adults of the current investigation (i.e., SD=3.79). Hence, for older adults whose performance on single task word recognition at the fixed level was 76% or lower, three additional experimental tasks were performed.

For each older adult who did not meet the equated performance criterion, the first task involved a brief level setting procedure to determine the noise level required in order for the participant to obtain the criterion level of 80% correct on single task word recognition. Specifically, using an adaptive level setting procedure, the noise level was reduced by 2 dB and 10 practice sentences were given. If the total target word score was less than the criterion, the noise level was reduced by an additional 2 dB and 10 more practice sentences were given. If however, the average score was more than the criterion, the noise level was increased by 1 dB and an additional 10 practice sentences were given. The bracketing technique of decreasing by 2 dB (for scores below the pre-established criterion) and increasing by 1 dB (for scores above the pre-established criterion) continued until the level of noise that provided the smallest deviation from the criterion was established. At this individualized noise attenuation level, older adults received the primary sentence recognition task and the dual task (i.e., sentence recognition and the tactile pattern recognition task concurrently). The primary word task and dual task were administered in a counterbalanced order. Specifically, half of the participants performed the dual task trials first followed by the single task word trials. The remaining participants received the single task word trials first followed by the dual task trials.

Subjective rating

At the conclusion of each block of dual task trials, the participants were asked to rate: 1) their perceived level of accuracy for the speech recognition task, 2) their perceived level of accuracy for the tactile pattern recognition task, 3) the level of effort expended to perform the speech recognition task, and 4) the level of effort expended to perform the tactile pattern recognition task. The same written version of the rating scales as those used by Fraser et al. (2010) were employed for each of the rating tasks. The specific questions given for the accuracy ratings were: "What percentage of sentences do you think you identified correctly?" and "What percentage of the vibrations in your hand do you think you identified correctly?" Participants were required to place a mark on a print version of a continuous scale which ranged from 0% to 100%. The questions for the effort ratings were: "How much effort was required for you to identify the components of the sentence?" and "How much effort was required for you to identify the vibrations in your hand?" Again, participants were required to place a mark on the printed continuous scale which ranged from 0-100 where 0 signified a negligible amount of effort and 100 signified a high degree of effort.

Results

Analysis overview

One of the central issues involved with the interpretation of age-related changes in dual-task performance is the construct validity of the dual-task paradigm itself. Specifically, researchers have questioned whether the age-related differences observed from divided attention tasks are due to "attentional differences" or if age-related generalized slowing (e.g., mental operations take longer to perform with increased age) could account for the observed changes between younger and older adults (McDowd & Shaw, 2000).

One Method proposed by Somberg and Salthouse (1982) to control for age-related variation involves computing the relative or proportional dual task cost (i.e., pDTC = (single task – dual task)/single task). This Method ensures that all participants are compared against their own single task baseline performance. For example, if a participant's single task tactile accuracy performance was 80% and their dual task performance declined to 40%, the pDTC or the "cost" of performing the two tasks together would be 50%. However, if their dual task performance declined to only 60%, the pDTC would decrease to 25%. To compare across age groups, proportional dual task costs (pDTC) were calculated for each of the dependent variables (i.e., primary word task percent correct and response time, secondary tactile task percent correct and response time) under study. For the response time data, the mean correct response time for both the word and tactile task was calculated for each participant under single and dual task conditions and used in the pDTC measure. Thus, in the present investigation, the dependent variables were relative pDTC scores rather than absolute scores. To explore the effect of age (younger vs. older adults) on the dual task performance of each experimental condition (i.e., equated level and equated performance), using the GLM, a one-way ANOVA was conducted for each of the pDTC measures. For each analysis 'age' was the between subject variable. The alpha criterion level for each of the analysis of variance was set to 0.05. Effect sizes were calculated as partial eta squared (η_{p2}) values. Changes in secondary task, tactile pattern recognition accuracy and/or response times reflected objective changes in listening effort. For the older adults, to compare the effect of experimental condition (i.e. equated level vs. equated performance); paired t-tests for each pDTC dependent measure were conducted.

Spearman rho correlations using a two-tailed alpha criterion were performed to determine if the participants' measured performance matched their perception of accuracy and effort. For the equated performance level, the four subjective ratings (i.e., accuracy and effort estimates for the primary word task and secondary tactile task) were correlated with each of the absolute dependent measures obtained under dual task conditions (i.e., dual task word accuracy, dual task word response time, dual task tactile accuracy, dual task tactile response time). Separate correlation matrices were produced for the young adults and older adults. This procedure was repeated for the equated level condition, producing separate correlation matrices for the two subgroups of older adults. For the resulting 28 comparisons of each correlation analysis, the conservative Bonferroni significance criterion was adopted to control for Type I error (i.e., 0.05/28=.0018). The subjective estimates of accuracy and effort were further analyzed using the Mann Whitney Rank Sum test, to examine the effect of age and with the Wilcoxon test to examine the effect of experimental condition (i.e. equated level vs. equated performance) across older adults only.

Dual task results

Equated level findings

This section reports the dual task results of the experimental condition where the level of noise for the speech-related task was the same for young and older adults.

Accuracy results

For the equated level condition, the average single and dual task word recognition and tactile pattern recognition scores for young and older adults are summarized in Table 1. Comparing the average single task word accuracy scores of the young adults (83%) with the expected 80% performance average obtained from pilot testing, a one sample t test revealed no significant difference between the means [t(24)=1.689, p=.104]. Overall, the average single task accuracy results of older adults' were significantly lower than those of the young adults for both the word recognition task [t(48)=4.686, p<.0001] and the tactile pattern recognition task [t(48)=2.984, p=.005]. A similar pattern of results was observed for the dual task accuracy results as well.

In contrast, in comparing the relative data, the main effect of age was not significant for the word task pDTC accuracy scores [F(1,48)=.206, p=.652, η_{p2}=.004]. However, the pDTC accuracy data from the tactile task revealed a significant age effect whereby older adults had larger pDTCs than the young adults [F(1,48)=10.961, p=.002, η_{p2}=.186]. This result indicates a greater difference between single and dual task performance on the tactile task by older adults compared to young adults. This result suggests that older adults exerted more listening effort. Mean accuracy results plotted by age and task for the equated level condition, are displayed in Figure 2.

Table 1. Mean single and dual task results and standard deviations for 25 young adults and 25 older adults obtained during the equated level condition (speech at 60 dBA, noise at 72 dBA). Accuracy reported as percent correct. Response time reported in seconds.

		Young Adults (n=25)		**Older Adults (n=25)**	
		Mean	SD	Mean	SD
Single Task	Word - Accuracy	83.00	6.90	71.30	10.41
	Tactile - Accuracy	95.80	3.80	90.10	8.76
	Word - Response Time	3.08	0.44	4.38	0.82
	Tactile - Response Time	2.23	0.21	2.65	0.38
Dual Task	Word - Accuracy	80.30	7.85	67.83	9.23
	Tactile - Accuracy	78.40	14.01	60.60	13.27
	Word - Response Time	3.71	0.83	5.03	1.01
	Tactile - Response Time	3.21	1.06	5.11	2.15

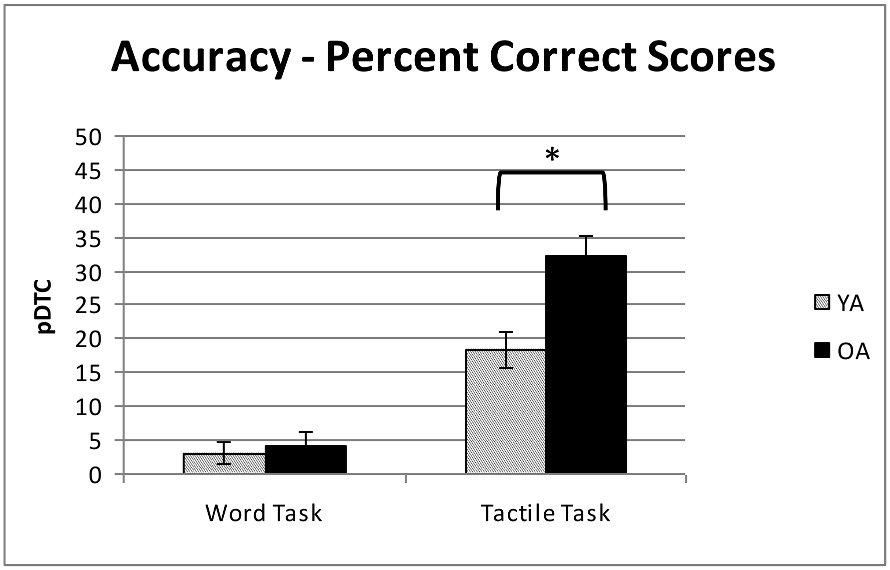

Figure 2. Mean accuracy scores and standard errors plotted as proportional dual task costs (pDTC) by task (word task and tactile task) and age (YA=young adults, depicted by striped bars and OA= older adults, depicted by solid bars) for the equated level condition. Brackets and asterisks denote comparisons that were significant (* p=.002).

Response time results

The average single and dual task response time results for young and older adults are summarized in Table 1. In general, the average response time results of older adults were significantly longer than those of young adults for both the word recognition task [t(48)=-6.956, p<.0001] and the tactile task [t(48)=-4.819, p<.0001]. Similar findings were observed for the dual task response time results as well.

Similar to the accuracy results, comparing the relative data, the main effect of age was not significant for the word task pDTC response times [F(1,48)=.934, p=.338, η_{p2}=.019]. However, the pDTC response time data for the tactile task revealed a significant age effect whereby the older adults had larger pDTCs than the young adults [F(1,48)=7.029, p=.011, η_{p2}=.128]. Again, the larger cost on secondary task response time performance for older adults relative to young adults suggests that older adults exerted more listening effort. Mean response time results plotted by age and task for the equated level condition, are displayed in Figure 3.

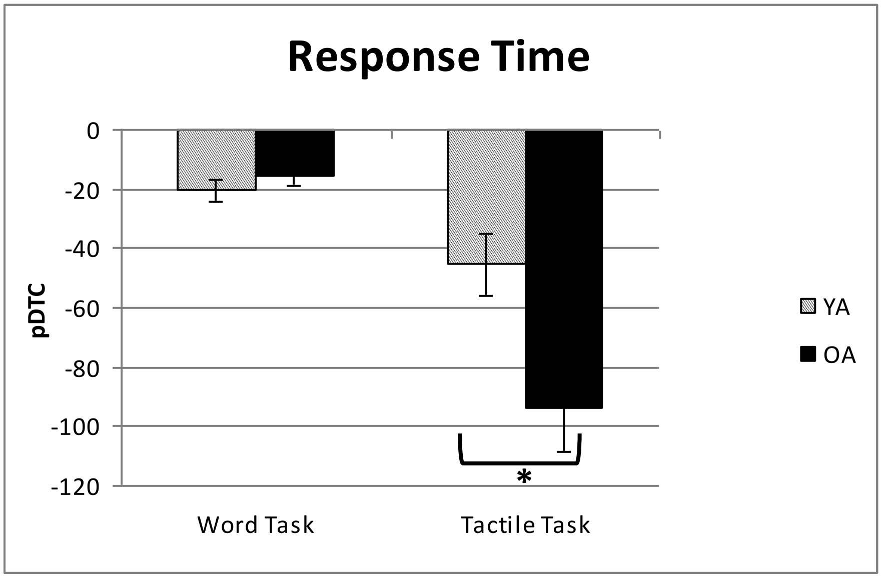

Figure 3. Mean response times and standard errors plotted as proportional dual task costs (pDTC) by task (word task and tactile task) and age (YA=young adults, depicted by striped bars and OA= older adults, depicted by solid bars) for the equated level condition. Brackets and asterisks denote comparisons that were significant (* p=.011).

Equated performance findings

This section reports the dual task results of the experimental condition where the level of noise was individually adjusted for older adults to provide the same performance level as young adults on the speech recognition task when performed in isolation.

Accuracy results

For the equated level condition, the single task word recognition results obtained from the young adults achieved the 80% criterion set for the equated performance condition (i.e., Mean 83%, SD 6.89). As a result, the data initially obtained from young adults for the equated level condition was used in the data analyses to compare with the performance of older adults under the equated performance condition. Similarly, 12 of the 25 older adults also met the pre-established word recognition performance criterion under the equated level condition (i.e., OA Group 1). For the remaining 13 of the 25 older adults (i.e., OA Group 2), the experimental tasks were performed a second time at a reduced noise level which was individually set for each older adult. The noise level ranged from 66-71 dBA (i.e., Mean 69.31 dBA, SD 1.65). The average single and dual task results for all older adults and the two subgroups of older adults (i.e., OA Group 1 & 2) are summarized in Table 2.

Further analysis revealed that the two subgroups of older adults differed significantly by age [t(23)=-3.845, p=.001]. The 12 participants who met the performance criterion at the equated level were younger in age (range from 65-73 years; M=66 years; SD 2.19) than the 13 participants who required an individualized noise adjustment (range from 64-76, M=71; SD 3.96). Aside from the significant age difference between OA Groups 1 and 2, it must be noted that there was no significant difference on the cognitive screening results from the MoCA [t(23)=-1.983, p=.059]. Furthermore, after the level setting procedure OA Group 2, there was no significant difference on single task word recognition ability between the two OA subgroups [t(23)=.137, p=.892].

While the single task word recognition scores were comparable between the two OA subgroups, it did come at a cost for OA Group 1 as the pDTC for word task accuracy was significantly larger than the pDTC obtained for OA Group 2 who performed the task with 3 dBA less noise on average [t(23)=-2.943, p=.007]. However, all of the remaining pDTC’s were not significantly different between the two OA subgroups. As a result, we collapsed the two subgroups of older adults together for all further analysis to compare with younger adults.

Table 2. Mean single and dual task results and standard deviations for all older adults (OA), and OA Groups 1 and 2 during the equated performance condition. Accuracy reported as percent correct. Response time reported in seconds.

		OA (n=25)		**OA Group 1 (n=12)**		**OA Group 2 (n=13)**	
		Mean	SD	Mean	SD	Mean	SD
Single Task	Word - Accuracy	80.00	4.78	80.14	5.10	79.87	4.68
	Tactile - Accuracy	90.10	8.76	92.08	8.58	88.27	8.86
	Word - Response Time	4.08	0.61	3.93	0.56	4.21	0.64
	Tactile - Response Time	2.65	0.38	2.49	0.35	2.81	0.36
Dual Task	Word - Accuracy	76.27	5.93	73.26	4.53	79.04	5.84
	Tactile - Accuracy	64.70	14.18	65.42	14.05	64.04	14.84
	Word - Response Time	4.72	0.73	4.68	0.89	4.76	0.58
	Tactile - Response Time	4.60	1.87	4.28	1.62	4.90	2.09

The mean word recognition performance data for all 25 older adults resulted in a group average of 80% (SD 4.78). An independent samples t-test revealed that there were no significant differences between the younger and older adults on their performance of the word recognition task performed in isolation [t(48)=1.787, p=.080]. Hence, performance for single task word recognition ability was equated.

The pattern of results for the relative data obtained for the equated performance condition was similar to the results obtained for the equated level condition. The main effect of age was not significant for the pDTC word task accuracy scores [F(1,48)=.450, p=.506, η_{p2}=.009]. However, the pDTCs of the tactile task revealed a significant age effect in which older adults had larger pDTCs compared to younger adults [F(1,48)=6.387, p=.015, η_{p2}=.117]. This result suggests that older adults exerted more listening effort. Mean accuracy results plotted by age and task for the equated performance condition, are displayed in Figure 4.

Response time results

The response time data shown in Table 2, demonstrate that in general, the average response time results of older adults` were significantly longer than young adults for single task word recognition [t(48)=-6.677, p<.0001] and dual task word recognition [t(48)=-4.552, p<.0001].

In contrast, the relative data revealed that the main effect of age was not significant for the word task pDTC response time data [F(1,48)=.741, p=.393, η_{p2}=.015], nor for the tactile task pDTC response time data [F(1,48)=3.063, p=.086, η_{p2}=.06]. Mean response time results plotted by age and task for the equated performance condition, are displayed in Figure 5.

Comparison of equated level and equated performance findings

Examining the data from OA Group 2 across the two experimental conditions, we found that when the noise level was reduced as was the case for the equated performance condition relative to the equated level condition, there was a significant reduction in pDTC

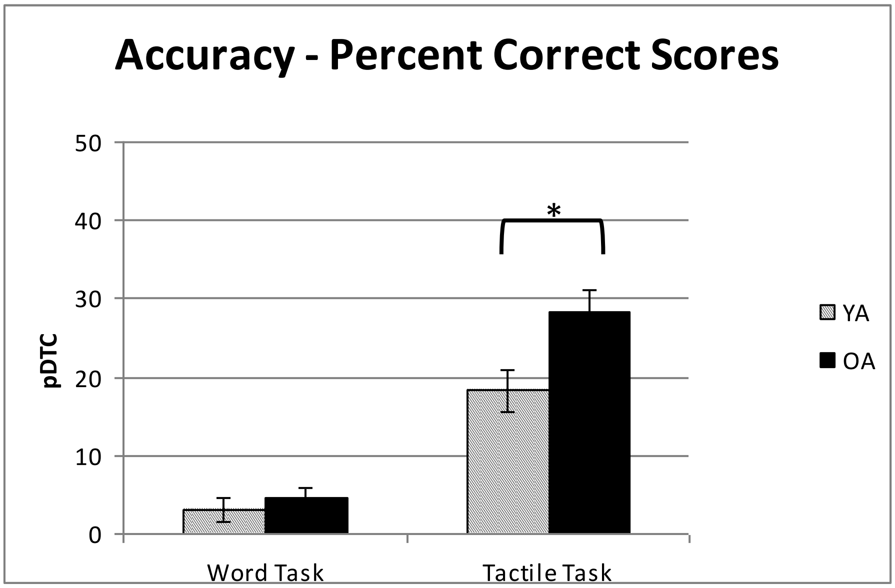

Figure 4. Mean accuracy scores and standard errors plotted as proportional dual task costs (pDTC) by task (word task and tactile task) and age (YA=young adults, depicted by striped bars and OA= older adults, depicted by solid bars) for the equated performance condition. Brackets and asterisks denote comparisons that were significant (* p=.015).

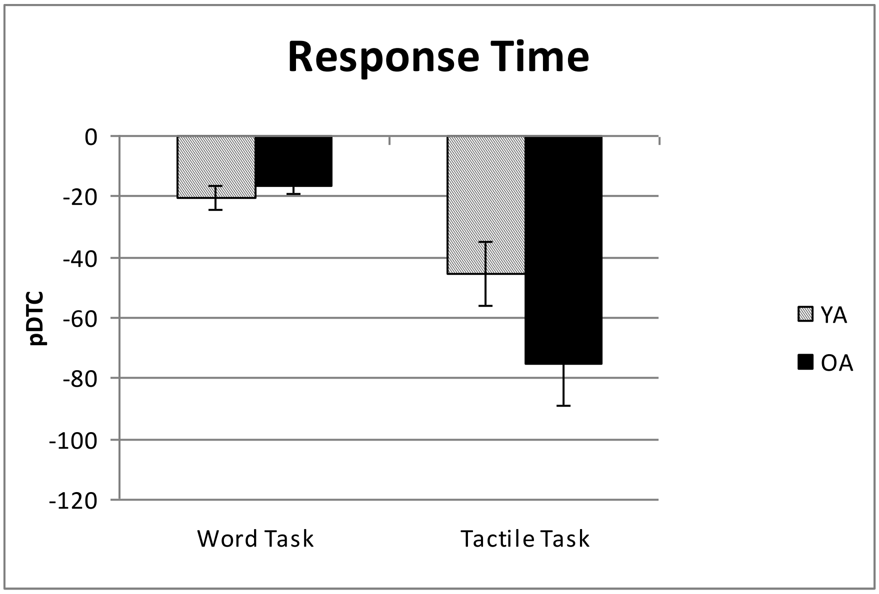

Figure 5. Mean response times and standard errors plotted as proportional dual task costs (pDTC) by task (word task and tactile task) and age (YA=young adults, depicted by striped bars and OA= older adults, depicted by solid bars) for the equated performance condition.

for the tactile task response time [t(12)=-2.289, p=.041]. This reduction in cost for the tactile task response time suggests that as the noise level was reduced, the effort involved with listening was also reduced. Comparing across conditions, there were no significant changes in pDTCs for the remaining measures: Tactile task percent correct [t(12)=1.357, p=.200], Word task percent correct [t(12)=-.159, p=.876], Word task response time [t(12)=.296, p=.772].

Comparison between dual task results and subjective ratings

In general, subjective ratings of effort did not correlate with any of the dual-task measures. Correlation matrices summarizing the relationship between dual task measures and one's perception of accuracy and effort are displayed in Tables 3 and 4 for the equated level and equated performance conditions respectively.

Equated level findings

At the equated level, we found that the subjective word accuracy rating correlated with the dual task word recognition accuracy performance (e.g., older adults (n=25), r=.602, p=.001 and young adults (n=25), r=.518, p=.008). With the Bonferonni correction applied, only the correlation obtained for older adults was significant (see Table 3). Both correlations suggest that higher accuracy ratings are associated with higher dual task percent correct scores. In contrast, the subjective estimates of effort did not correlate with any of the dual task measures (see Table 3).

Equated performance findings

At the equated performance level, none of the correlations achieved significance once corrections were applied for multiple comparisons whether examined with the entire older adult cohort or with either older adult subgroup in isolation (see Table 4).

Table 3. Spearman rho correlations between objective and subjective measures obtained during the equated level condition for younger adults (YA) and older adults (OA). Asterisks denote significant correlations corrected for multiple comparisons.

				Subjective Ratings			
				Word Accuracy	Word Effort	Tactile Accuracy	Tactile Effort
Dual Task Measures	Word Accuracy	YA	r	0.518	0.016	0.490	0.329
			p	0.008	0.939	0.013	0.108
		OA	r	.602*	0.001	0.111	0.122
			p	0.001*	0.996	0.599	0.562
	Tactile Accuracy	YA	r	0.118	0.018	0.464	0.207
			p	0.573	0.931	0.020	0.320
		OA	r	0.128	-0.265	0.239	0.220
			p	0.543	0.200	0.250	0.290
	Word Response Time	YA	r	-0.130	-0.094	-0.137	0.061
			p	0.535	0.654	0.512	0.770
		OA	r	-0.139	-0.028	-0.097	-0.215
			p	0.509	0.893	0.646	0.301
	Tactile Response Time	YA	r	-0.187	0.203	0.097	-0.133
			p	0.371	0.330	0.646	0.527
		OA	r	-0.283	0.028	-0.258	-0.343
			p	0.170	0.896	0.213	0.093

Table 4. Spearman rho correlations between objective and subjective measures obtained during the equated performance condition for all older adults (OA) and OA Group 1 and OA Group 2.

				Subjective Ratings			
				Word Accuracy	Word Effort	Tactile Accuracy	Tactile Effort
Dual Task Measures	Word Accuracy	OA	r	0.011	0.073	-0.057	0.434
			p	0.960	0.729	0.785	0.030
		OA Group 1	r	0.529	0.401	-0.050	0.174
			p	0.077	0.196	0.878	0.588
		OA Group 2	r	0.430	-0.156	-0.106	-0.249
			p	0.143	0.610	0.730	0.411
	Tactile Accuracy	OA	r	-0.122	0.406	-0.524	0.008
			p	0.563	0.044	0.007	0.970
		OA Group 1	r	0.042	-0.568	0.262	0.050
			p	0.898	0.054	0.411	0.876
		OA Group 2	r	0.279	-0.133	0.686	0.011
			p	0.356	0.664	0.010	0.971
	Word Response Time	OA	r	-0.113	-0.024	-0.221	-0.102
			p	0.592	0.911	0.289	0.628
		OA Group 1	r	-0.245	-0.482	0.035	-0.379
			p	0.444	0.112	0.914	0.225
		OA Group 2	r	0.090	0.418	-0.122	0.372
			p	0.770	0.156	0.691	0.211
	Tactile Response Time	OA	r	0.278	-0.124	0.202	0.177
			p	0.178	0.556	0.333	0.397
		OA Group 1	r	0.038	0.268	-0.074	0.196
			p	0.908	0.400	0.820	0.541
		OA Group 2	r	-0.471	-0.023	-0.619	-0.185
			p	0.105	0.942	0.024	0.546

Between-group and within-group comparisons of subjective ratings

Equated level findings

With the noise level fixed for both young adults (n=25) and older adults (n=25) interestingly, there was no significant group difference on word task accuracy ratings [U=221, p=.072]. In contrast, for the tactile task, older adults rated their accuracy as significantly lower than young adults [U=114, p<.0001]. For the effort ratings, neither the word task [U=286.5, p=.609] nor the tactile task [U=270, p=.406] revealed a significant difference between age groups. In fact, for the word task, the mean effort ratings on a scale from 0-100 for both groups were identical (i.e., M=78.8) (see Table 5).

Equated performance findings

With performance equated, comparing OA Group 2 ratings (n=13) with those obtained from the young adults (n=25), there was no significant group difference on word task accuracy ratings [U=132, p=.361]. Similar to the equated level condition, the older adults from Group 2 still rated their tactile accuracy significantly lower than young adults [U=67.5, p=.003]. In terms of effort, for the word task relative to young adults, Group 2 older adults rated the word task as significantly less effortful [U=85.5, p=.016] however, there was no significant group difference in tactile task effort ratings [U=132, p=.345] (see Tables 5 and 6).

Comparison of equated level and equated performance findings

Comparing the results of OA Group 2 participants (n=13) across the two experimental conditions, the analysis revealed that when noise was reduced as was the case for the equated performance condition, word accuracy ratings increased significantly [Z=-2.406, p=.016] but there was no significant difference in tactile task accuracy ratings [Z=-1.137, p=.256]. Similarly, for the effort ratings, when the noise was reduced under the equated performance condition (M=68.1, SD=13.3) relative to the equated level (M=79.6, SD=15.5), the word task was rated as requiring significantly less effort [Z=-2.494, p=.013]

Table 5. Mean subjective ratings and standard deviations by experimental condition and age.

Equated Level Condition

	Young Adults (n=25)		Older Adults (n=25)	
	Mean	SD	Mean	SD
Word Accuracy	70.20	14.75	62.60	16.96
Word Effort	78.80	20.12	78.80	15.63
Tactile Accuracy	70.40	19.25	47.00	18.82
Tactile Effort	67.40	25.74	74.00	21.16

Equated Performance Condition

	Young Adults (n=25)		Older Adults (n=25)	
	Mean	SD	Mean	SD
Word Accuracy	70.20	14.75	70.20	10.56
Word Effort	78.80	20.12	72.80	15.42
Tactile Accuracy	70.40	19.25	51.20	19.27
Tactile Effort	67.40	25.74	72.20	18.03

Table 6. Mean subjective ratings and standard deviations for OA Group 2 (n=13) by experimental condition.

	Equated Level		Equated Performance	
	Mean	SD	Mean	SD
Word Accuracy	53.08	16.53	67.69	10.53
Word Effort	79.62	15.47	68.08	13.31
Tactile Accuracy	41.54	15.46	49.62	18.31
Tactile Effort	67.69	24.12	64.23	16.81

but there was no significant difference for the tactile effort rating [Z=-.908, p=.364] (see Table 6).

Discussion

Dual task findings – objective measures of performance and listening effort

The most important result of this study is that the dual task measures clearly demonstrated that older adults expend more listening effort than young adults. In other words, the dual task measures were sensitive to between group age-related differences. For the equated level condition, the absolute data shown in Table 1 demonstrated that older adults did not perform as well as young adults (i.e., older adults had lower percent correct scores and longer response times for both tasks). However, using relative data to compare across the age groups, the results revealed that older adults exerted increased listening effort compared to young adults as shown by significantly larger pDTC's for the concurrent tactile task percent correct scores and response time measures shown in Figure 2 and Figure 3. These results suggest that older adults require more resources to recognize speech, leaving less resources available for the tactile secondary task (Kahneman, 1973). However, it was not clear whether these findings were due to an age effect or if they were due to the fact that single task word recognition ability was not equivalent for young and older adults. This led us to consider how listening effort would be affected if we equated the baseline word recognition ability. To ensure that older adults performed the word task at the same average accuracy level as younger adults (i.e. approximately 80%), the noise level was individually attenuated as required. Even when performance was equated, using relative data to compare across the age groups, the results revealed that older adults still exerted increased listening effort compared to younger adults as shown by the significantly larger pDTC's for the tactile task accuracy measure, illustrated in Figure 4.

Many studies investigating aspects of listening effort and speech understanding abilities of young adults have demonstrated similar decrements in secondary task performance under different experimental conditions (Bourland-Hicks & Tharpe, 2002;

Broadbent, 1958; Downs, 1982; Downs & Crum, 1978; Feuerstein, 1992; Fraser et al., 2010; Rabbitt, 1966; Rakerd et al., 1996). The current study extends these findings to include older adults. Using a stringent measure of cost (i.e., the pDTC), the older adults displayed larger decrements in secondary task performance relative to young adults. As expected, the significant age effect observed for both experimental conditions is consistent with studies that have investigated capacity theory and age-related cognitive and sensory decline (Kahneman, 1973; Kricos, 2006; McCoy et al., 2005; Tun et al., 2008; Wingfield & Tun, 2001). While the current study was designed to investigate the impact of age on listening effort, it remains possible that a combination of perceptual and cognitive factors mediated by age could have accounted for the increased listening effort observed among older adults (Humes, 2007).

From an acoustical perspective, all of our participants had what would be considered "normal hearing." That is, hearing was screened only at 25 dB HL at octave frequencies between 0.25 and 2.0 kHz, as well as at 3 kHz. When the data from the equated performance condition of the two OA subgroups were collapsed together and compared with younger adults, there were no significant differences in either the word task pDTC accuracy scores or word task pDTC response time results. However, OA Group 2 had significantly larger word task pDTC accuracy scores than OA Group 1. This suggests that varying degrees of peripheral hearing loss at 4 kHz and beyond due to presbycusis may have influenced the auditory speech recognition performance (Amos & Humes, 2007; Hull, 1995; Weinstein, 2002) and listening effort results. For example, it's possible that in both experimental conditions the sensation level used for speech presentation may have been less for older adults than young adults. To determine the magnitude of this effect, the hearing thresholds of all participants should be measured rather than screened, in future studies. However, with the screening approach used in the current study, our results can be generalized to healthy aging older adults, whom most clinical audiologists would regard as having "normal hearing".

While single task word recognition ability was equated across the groups for the equated performance condition, it must be noted that this was the only factor that was equated. Differences in single task vibro-tactile abilities may have accounted for the significant age-effect observed even though all participants had to pass the 80% minimum criterion during the single task practice session. To explore this possibility further, a separate analysis comparing young adults with OA Group 1 was conducted as the 3.72 percentage point difference on single task vibro-tactile ability was not statistically significant (p=.36). Comparing the accuracy data from the tactile task, OA Group 1 had larger pDTCs than the young adults [F(1,35)=4.187, p=.048, ηp2=.107]. Again, these results suggest that older adults expend more listening effort than young adults to recognize speech presented in noise. Notwithstanding these results, one factor that was not accounted for in the current study was the threshold of vibratory sensitivity. The older adults may have had a poorer absolute sensitivity to the tactile pattern recognition task. However, recent research designed to investigate tactile temporal processing found that whether an older adult had good or poor vibratory sensitivity, it did not appear to have an effect on their temporal order judgements (Craig, Rhodes, Busey, Kewley-Port, & Humes, 2010). Specifically, the participants of this study identified the tactile pattern and order of presentation for three tasks: 1) two patterns presented to the same finger, 2) four patterns presented to the same finger and, 3) two patterns presented to different hands (i.e., one pattern to the right index finger and another pattern to the left index finger) (Craig et al., 2010). Despite these findings, future research should consider evaluating and equating the vibrotactile sensitivity of all participants to rule out the possibility of this confounding effect.

Beyond the perceptual variables (acoustic and tactile), an alternative view, is that when listening is no longer perceived as “easy”, cognitive variables may explain differences in the degree of effort associated with an individual’s listening experience (Hallgren, Larsby, Lyxell, & Arlinger, 2005; Humes, 2007). Cognitive abilities such as attention, speed of processing and especially working memory, have been shown to affect the effort involved with listening comprehension, written comprehension and communication (Akeroyd, 2008; Daneman & Merickle, 1996; Pichora-Fuller, 2007, 2009; Vaughan, Storzbach, & Furukawa, 2008). While all of our older adults were screened for cognitive function as measured with the MoCA, any of the above mentioned cognitive variables may have influenced the age differences observed. Future research is required to provide more insight into the relationship between listening effort and these cognitive variables.

Correlation findings - objective and subjective measures of listening effort

The correlation analyses between dual task performance and effort measures and subjective ratings revealed that overall subjective ratings of effort did not correlate with any of the dual-task measures irrespective of experimental condition or participant group. These findings are consistent with other studies that have included subjective measures of "effort" in their evaluation of young adults (Downs & Crum, 1978; Feuerstein, 1992; Fraser et al., 2010) and older adults (Larsby et al., 2005). Downs and Crum (1978) used a seven-point scale to characterize learning task difficulty. Although participants were good judges of learning accuracy, they found they were poor judges of how much effort was involved in the learning task. Similarly, Feuerstein (1992) included a rating scale ranging from difficult (e.g., 0) to easy (e.g., 100) to indicate the perceived difficulty of the listening situation by the listener. Feuerstein (1992) found that while the relative effort and ease of listening ratings were positively correlated with performance accuracy on the primary speech recognition task, the secondary response time task (i.e., listening effort) was not correlated with the subjective ratings. More recently, Fraser (2010) found that despite differences in dual task performance between an auditory vs. an audiovisual presentation condition, there were no differences in ratings of perceived effort between the two modalities. In terms of older adults, Larsby (2005) found that the elderly were less likely to report a higher degree of perceived effort than young adults despite measurable performance differences (i.e., accuracy and response time measures). Overall, these results corroborate Feuerstein's findings (1992) and suggest that objective measures of effort and subjective ratings of effort reflect different aspects of listening effort. While subjective measures provide an indication of one's perception of effort or ease in a listening situation, given the degree of individual variability, they do not appear to reflect the availability of, or demand on processing resources (Wickens, 1992: (Zekveld, Kramer, & Festen, 2010). In other words, expending more resources to recognize speech under noisy conditions (i.e., high load) may not be perceived as more effortful for some listeners. Even though a statistically significant correlation between dual task measures and subjective ratings of listening effort was not observed, using the average data for the entire group, differences are seen between the two age groups and within OA Group 2 across the two experimental conditions.

Rating findings – subjective perception of the relative effort involved with listening

The dual task measures provided a sensitive means to compare listening effort between groups on the basis of age. However, using subjective data to draw between-group comparisons is complicated by the fact that the criteria by which people assess their own listening effort are unknown (Edwards, 2009; Yeh & Wickens, 1988). For the equated level condition, even though there was a significant difference between young and older adults on single task word recognition ability, interestingly there was no significant difference between young and older adults in their accuracy ratings for the word task. Furthermore, the effort ratings of both groups were identical for the word task. Research by Larsby (2005) demonstrated similar findings. Specifically, the elderly were less likely to report a higher degree of perceived effort than young adults despite objectively measured performance differences (i.e., accuracy and response time measures). Larsby accounted for this finding as being due to the fact that the elderly are less prone to complain. For the equated performance condition, with the baseline word recognition ability equated, as expected young and older adults had equivalent word accuracy ratings. In addition, the word task effort ratings between young and older adults were not significantly different. However, for the tactile task, older adults indicated that the tactile task required significantly less effort than younger adults. This finding is consistent with research in other domains which has shown that older adults tend to under-estimate their degree of difficulties (Ford et al., 1988; Uchida et al., 2003). However, it remains to be determined whether young and older adults use the same or different criteria to make their subjective judgments.

While the subjective rating results conflicted with the dual task measures when making between-group comparisons, our results suggest that subjective ratings can be used effectively to make within-group comparisons across different listening conditions. Comparing the subjective ratings of OA Group 2 across both experimental conditions, when the noise level was reduced, the accuracy ratings for the word task increased and the word task was rated as requiring significantly less effort (see Figure 4). Similarly, considering the OA Group 2 response time data for the tactile task, as the noise level was reduced, the magnitude of the pDTC decreased for the equated performance condition relative to the equated level condition. Taken together, our results suggest that during the equated performance condition, on average, word recognition was subjectively rated as less effortful. Similarly, the dual task measures suggest that fewer resources were required to perform the primary task, leaving more resources available and hence smaller pDTC's for the secondary task response time results. While the response time results may have been influenced by a practice effect, these findings demonstrate that the response time measure of the secondary tactile task can provide a sensitive index to changes in listening effort across different experimental conditions. Research by Tun et al. (2008) corroborates this finding. The longer response time results on a sentence comprehension task were used to infer increased processing effort. In general, they found that older adults were slower than young adults when processing speech at low sound intensities or when processing syntactically complex sentences. Taken together, this underscores the value of including response time in addition to accuracy as an outcome measure (Fraser et al., 2010; Tun et al., 2008).

Conclusion

In conclusion, our results indicate that dual task measures are sensitive to between-group age differences. Older adults expend more effort than young adults to recognize speech in noise at a fixed signal-to-noise ratio - the equated level condition, and at a level where the noise level was individually adjusted for older adults - the equated performance condition. Even when the level of noise was reduced on an individual basis for older adults, to ensure a similar level of performance on the speech recognition task (performed singly), older adults still exerted more listening effort than young adults. These results suggest that older adults require more processing resources to understand speech in noise (Chisolm et al., 2003; Kricos, 2006; McCoy et al., 2005; Salthouse, 1988; Tun et al., 2008; Wingfield & Tun, 2001, 2007). One of the clinical implications of these findings is that hearing healthcare professionals need to be careful when making inter-individual comparisons on the basis of word recognition results alone. Two individuals with equal performance as measured by word recognition accuracy may not necessarily have expended an equivalent degree of listening effort. Beyond age, a combination of sensory and cognitive factors mediated by age can influence listening effort results. In contrast, both the objective and the subjective measures of listening effort were sensitive to changes across experimental conditions within-groups. This suggests that objective dual task measures can help validate subjective measures of listening effort. Relative to the equated level condition, when the noise level was reduced for the equated performance condition, older adults indicated that the word task required significantly less effort. These results suggest that on average older adults can in fact rate a task that is perceptually easier (i.e., a listening task with less noise) as requiring less effort. Further research in the clinical domain is required to determine if these within-group differences hold on an individual basis. If so, the clinical use of subjective rating scales by older adults for the purpose of making intra-individual comparisons of listening effort is supported. However, for those who are unable to make reliable subjective ratings, the objective dual task measures may provide a valid alternative to assess listening effort behaviourally on an individual basis. To the extent that a dual task paradigm can quantify that listening in noise is more effortful and more variable for older adults than young adults, hearing health care professionals gain an alternative performance index sensitive to cognitive changes (Beck & Clark, 2009).

Acknowledgments

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Article 3 – Older adults expend more listening effort than young adults recognizing audiovisual speech in noise

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Abstract

Purpose: Listening in noise is challenging for many older adults. We hypothesized that even with the addition of visual cues that older adults would exert more listening effort compared to young adults. Listening effort involves attentional and cognitive resources required to understand speech. The purpose was 1) to quantify the amount of listening effort young and older adults expend when they listen to audiovisual speech in noise and, 2) to examine the relationship between self-reported listening effort and dual task measures.

Method: A dual task paradigm was used to assess the listening effort of 25 young and 25 older adults. The primary task involved a closed-set sentence-recognition test and the secondary task involved a vibro-tactile pattern recognition test. Participants performed each task separately and concurrently under two experimental conditions.

Results: Older adults expended more listening effort than young adults when the level of background noise was the same and when baseline word recognition performance did not differ between groups. Self-reported ratings of listening effort did not correlate with dual task measures.

Conclusions: Older adults required more processing resources than young adults to recognize audiovisual speech. Equal audiovisual speech recognition performance does not guarantee an equivalent degree of listening effort.

Key Words: Listening effort, dual task paradigm, audition, aging, audiovisual speech recognition

Introduction

Many older adults report that it is extremely challenging to listen in situations with background noise. One common communication strategy used to overcome the exhaustion and fatigue experienced in difficult listening conditions is to look at a speaker's face while listening. When a person can see and hear (i.e. adding visual speech cues) their communication partner, speech-recognition is facilitated (Grant & Braida, 1991; Macleod & Summerfield, 1987; Macleod & Summerfield, 1990; Sumby & Pollack, 1954). In general, the benefit gained from adding visual speech cues increases as the amount of auditory speech information decreases (Macleod & Summerfield, 1987; Macleod & Summerfield, 1990; Sumby & Pollack, 1954). Adding visual speech cues can have the same effect on speech recognition as reducing background noise by approximately 7-10 dB (Macleod & Summerfield, 1987; Macleod & Summerfield, 1990).

Age has an influence on both components of audiovisual speech recognition. In terms of audio-only speech recognition in noise, older adults perform more poorly than young adults even when they have normal hearing ability (CHABA, 1988). Older adults also perform speechreading tasks (i.e. speech recognition under visual-alone conditions) more poorly than young adults (Campbell, Preminger, & Ziegler, 2007; Shoop & Binnie, 1979). Even though sensory, perceptual and cognitive functions decline with age (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994; Pichora-Fuller & Singh, 2006; Scialfa, 2002), the addition of visual speech cues have been shown to improve speech recognition for both young and older adults alike (Grant & Braida, 1991; Macleod & Summerfield, 1990; Sommers, Tye-Murray, & Spehar, 2005).

In addition, the perceptual and cognitive processes underlying audiovisual speech recognition for young and older adults appears to be the same (Musacchia, Arum, Nicol, Garstecki, & Krause, 2009; Walden, Busacco, & Montgomery, 1993). Specifically, Walden et al. (1993) found that the pattern of nonsense syllable confusions presented in a visual-only condition were similar for middle aged and elderly men with comparable hearing ability. More recently, Musacchia et al. (2009) investigated the neural mechanisms of audiovisual integration. Specifically, cortical evoked potentials of older adults with and without hearing loss were recorded in three conditions: audio, visual and audiovisual speech presentation. Musacchia et al. (2009) found that older adults had the same qualitative pattern of audiovisual integration (i.e., earlier latencies and lower amplitudes in AV compared to the linear summation of A + V) as had been observed in younger adults (Besle, Fort, & Delpuech, 2004).

While aging does not appear to change the mechanisms involved in audiovisual integration it is not clear whether older adults are as proficient in processing audiovisual speech as young adults. Some studies have shown that when visual cues are provided, older adults receive the same degree of benefit as young adults (Sommers et al., 2005) while other studies have shown that age influences audiovisual integration, especially in difficult listening situations (Campbell et al., 2007). Taken together, these results suggest that the proficiency of integration is influenced by the level of background noise used for the speech recognition tasks.

Rather than approaching the concept of proficiency via traditional means of assessing audiovisual integration (which relies on examining the relationship between audiovisual as well as audio-only and/or visual-only speech recognition performance), the current study considers whether there are differences in the qualitative and quantitative amount of “listening effort” expended by young and older adults during audiovisual speech recognition. Listening effort, the focus of the current study, refers to the attentional and cognitive resources required to understand speech (Bourland-Hicks & Tharpe, 2002; Downs, 1982; Feuerstein, 1992; Fraser, Gagné, Alepins, & Dubois, 2010).

In the clinical domain, if listening effort is evaluated questionnaires or self-reports are used to gain insight into one’s perception of the ease or effort involved with listening in a particular situation (Bourland-Hicks & Tharpe, 2002; Feuerstein, 1992). In contrast, a dual task paradigm can be used to evaluate listening effort quantitatively (Alsius, Navarra, Campbell, & Soto-Faraco, 2005; Alsius, Navarra, & Soto-Faraco, 2007; Anderson Gosselin & Gagné, 2011; Bourland-Hicks & Tharpe, 2002; Broadbent, 1958; Choi, Lotto, Lewis, Hoover, & Stelmachowicz, 2008; Downs, 1982; Downs & Crum, 1978; Feuerstein, 1992; Fraser et al., 2010; Rabbitt, 1966; Rakerd, Seitz, & Whearty, 1996; Tun, McCoy, & Wingfield, 2009). Within such a paradigm, participants perform two tasks (a primary and a secondary task) separately and then concurrently. For the current study, the primary task involved closed-set audiovisual word recognition and the secondary task involved tactile pattern recognition. Dual task paradigms assume that the cognitive system has a limited capacity of resources to process information (Kahneman, 1973). In general, when the processing capacity for the primary task is exceeded due to increases in effort or load (e.g., adding noise to a listening task), decreases in secondary task performance will be observed when the tasks are performed together (Kahneman, 1973; Lavie, 1995; Pashler, 1994). The declines in secondary task performance are interpreted as increases in listening effort (Bourland-Hicks & Tharpe, 2002; Broadbent, 1958; Fraser et al., 2010).

Two recent studies that investigated the influence of age on listening effort using a dual task paradigm, both reported larger secondary task costs for older adults relative to young adults (Anderson Gosselin & Gagné, 2011; Tun et al., 2009). One study used an audio-only version of a word recognition task (Anderson Gosselin & Gagné, 2011) and the other used an audio-version of a word recall task (Tun et al., 2009). Very few studies have used audiovisual speech stimuli with a dual task paradigm (Alsius et al., 2005; Alsius et al., 2007; Fraser et al., 2010). Fraser et al. (2010) found that while visual cues can improve audiovisual speech recognition, they may also place an extra demand on processing resources depending on the level of background noise. Researchers have also found that audiovisual speech integration decreases when visual or auditory attentional resources are depleted (Alsius et al., 2005), and with a difficult tactile task (Alsius et al., 2007). The studies by Fraser et al. (2010) and Alsius et al. (2005, 2007) were all conducted using normal hearing and normally sighted young adults. Whether normal hearing older adults with normal vision would process audiovisual speech as proficiently as young adults remains an open question.

The objectives of the current study were to quantify and compare the amount of listening effort young and older adults expend when they perform an audiovisual speech recognition task under two conditions: i) at a fixed level of background noise – the equated level condition and, ii) when the level of background noise is individually adjusted for older adults to a fixed level of audiovisual word recognition performance - the equated performance condition. A second objective was to determine if there is a correlation between self-reported estimates of accuracy and effort with quantitative measures assessed using a dual task paradigm. On the basis of studies that have investigated capacity theory and the availability of attentional resources, age differences are probable (Chisolm, Willot, & Lister, 2003; Kricos, 2006; McCoy et al., 2005; Tun, Benichov, & Wingfield, 2008; Wingfield & Tun, 2001, 2007). Under dual task conditions, we expected to see larger secondary task costs for older adults relative to younger adults. And, we expected that self-reported ratings of listening effort would not correlate with the dual task measures (Anderson Gosselin & Gagné, 2011; Ford et al., 1988; Fraser et al., 2010; Saunders & Echt, 2007; Shulman, Pretzer-Aboff, & Anderson, 2006; Uchida, Nakashima, Ando, Nino, & Shimokata, 2003), as research suggests they each tap a different aspect of listening effort (Feuerstein, 1992).

Method

Participants

Participants included 25 young adults ranging from 20 to 43 years of age (M = 24.9, SD = 5.6) and 25 older adults ranging from 65 to 77 years of age (M = 69.4, SD = 3.5). All participants had normal hearing sensitivity (≤ 25 dB HL at octave frequencies between 0.25 and 2.0 kHz, as well as at 3 kHz, re: ANSI, 1996), in both ears and normal (or corrected normal) binocular visual acuity (i.e., 6/12 or better) as measured with Sloan Letters at a distance of 3 metres (NAS-NRC, 1980; Sloan, Rowland, & Altman, 1952). The older adults all had clinically normal cognitive function (M=27.5, SD=0.92) as determined by the Montreal Cognitive Assessment [MoCA (Nasreddine et al., 2005)]. In addition, all participants reported that: 1) French was the language they regularly used to perform activities of daily living 2) they had good self-reported health and, 3) they were able to transport themselves independently to and from the laboratory. All participants voluntarily signed a consent form prior to taking part in the investigation and upon completion all of them were offered a small monetary compensation.

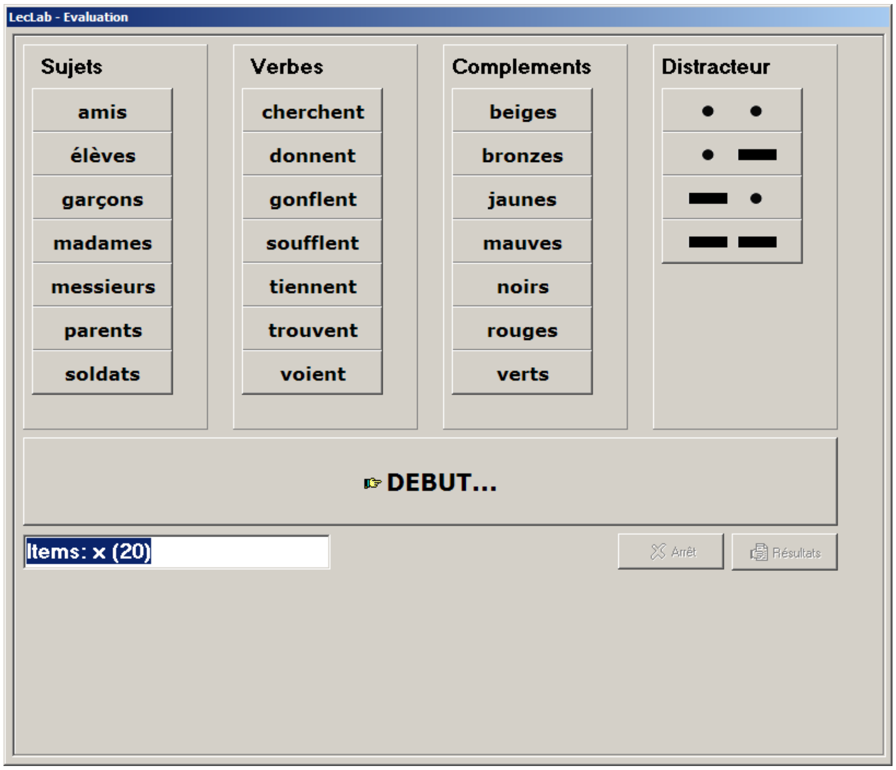
Dual task description

The tasks used for the dual task paradigm implemented in the current study are briefly described here as they are similar to those used in Anderson Gosselin & Gagné (2011) and Fraser et al. (2010).

Primary task

The primary task involved a closed set sentence recognition test presented audiovisually. All sentences were spoken by a female native speaker of Québec-French. Each sentence had the same syntactic structure and contained three critical elements (subject, verb, and adjective). For each critical element there were seven interchangeable alternatives. Each of the alternatives had the same number of syllables but they were distinct from each other both acoustically and visually. The stimuli used for the sentence recognition test are shown in Figure 1.

A customized computer program (Leclab) was used to conduct the experiment. Acoustically, separate audio files, one with the speech stimuli and one with the masking noise (a steady-state speech shaped noise) were routed to an 8 channel stereo mixer (Inkel, MX880E). The output from the mixer was amplified (InterM, PA-935) and presented via a loudspeaker (Realistic, Minimus-77) positioned directly 1 metre in front of the participant. Visually, the female speakers' head and shoulders were visible with her face appearing in



Sujets	Verbes	Complements	Distracteur
amis	cherchent	beiges	● ●
élèves	donnent	bronzes	● ▬
garçons	gonflent	jaunes	▬ ●
madames	soufflent	mauves	▬ ▬
messieurs	tiennent	noirs	
parents	trouvent	rouges	
soldats	voient	verts	

Figure 1. Dual task response screen showing the response options for the speech recognition task and the tactile pattern recognition task. For each sentence, participants report three critical elements. Each critical element can be replaced by any of the alternatives listed in the same column. An example of the syntactic structure of a possible sentence used for the speech recognition task includes: "Les amis^{a} trouvent^{b} des ballons verts^{c}", where a = sujets/subjects; b = verbes/verbs; c = complements/adjectives. An English translation of the current sentence would be "The friends found the green balloons". An alternative sentence using the third row of critical elements would read: "The boys inflate the yellow balloons." "Distracteur" is the French heading used to indicate the four response alternatives of the tactile pattern recognition task shown here as short-short, short-long, long-short and long-long. 'Short' stimuli are denoted by circles and 'Long' stimuli are denoted by bars.

the centre of a 17 inch touch screen monitor (ELO Touch Systems, ET1725L) placed at eye-level approximately 70 cm in front of the participant.

After each audiovisually presented sentence, participants indicated the three key words they heard. Specifically, the participant was required to touch each of the three key words that appeared on the touch screen monitor. The target words appeared with a horizontal degree of visual angle (dva) ranging from 1.18 to 2.53 and a vertical dva ranging from 0.25 to 0.38. The software program recorded both the accuracy and the response time for each of the three key words of the sentence. Once completed, the participant touched the word "prochain" (i.e., next) to advance to the following trial.

Prior to each testing session a free-field acoustic calibration was conducted with calibration tones to ensure that the audiovisual speech stimuli were consistently presented at 52 dBA. The masking signal consisted of a broadband speech shaped noise (i.e., pink noise) was presented at 72 dBA.

Secondary task

The secondary task involved a tactile pattern-recognition task in which participants had to identify one of four pulse combinations (i.e. short-short, long-long, short-long or long-short). The pulses emanated from a small oscillator (Radioear B-71) commonly used in clinical audiometry for bone-conduction testing. 'Short' was 250 msec and 'long' was 500 msec in duration. The interstimulus interval was 500 msec. Participants held the vibrating device in their non-dominant hand and placed their hand in a box which contained sound attenuating foam material.

To ensure that the onset of the tactile stimuli would not be predictable, the software program would initiate tactile trials with a random variable time delay. The delay ranged from 0 msec to 1000 msec in 250 msec steps. After each trial the participants would indicate which of the four tactile patterns they perceived by touching the corresponding iconic symbol that appeared on the touch screen monitor (see Figure 1). The software program recorded the accuracy and response times of participants' answers.

Experimental procedure

Participants completed the experiment in a single test session. On average, young adults required 1 hour to complete the experiment while older adults typically needed 1 hour and 45 minutes. Participants performed the primary and secondary task separately and concurrently in up to two conditions (an equated level condition and, an equated performance condition) described below. While all participants performed the equated level condition, only 13 older adults completed the equated performance condition. Single and dual task performance was evaluated with blocks of 40 test-trials under each experimental condition. Prior to the experimental conditions, all participants completed a practice session. Rest periods were encouraged throughout the session.

Practice session

The goal of the practice session was to ensure that the participants were familiar with the tasks. To continue on to the experimental conditions, participants had to reach a criterion level of performance (i.e., 80% correct) on 20 trials of both the primary and secondary tasks performed singly without masking noise.

In addition, 20 practice trials of the dual-task condition were also administered in quiet. Under dual-task conditions participants received the following instruction: "the listening task is the more important of the two, pick the corresponding subject/verb/adjective for the sentence that you hear as quickly as possible and, identify the pulse pattern that you feel as quickly and as accurately as you can." These same verbal instructions were used for each of the experimental conditions as they are similar to other studies where a dual-task paradigm was used to evaluate listening effort (Anderson Gosselin & Gagné, 2011; Bourland-Hicks & Tharpe, 2002; Downs, 1982; Fraser et al., 2010).

Equated level condition

A signal-to-noise ratio (SNR) of -20 dB (i.e., speech at 52 dBA and noise presented at 72 dBA) was chosen for the equated level condition, based on the results of previous experiments (Fraser et al., 2010) and additional pilot work. Pilot testing using the same test equipment and stimuli as the current investigation, demonstrated that at this SNR (-20 dB), the primary task (when performed singly) resulted in a mean accuracy score of approximately 80% by normal hearing young adults. The pilot results were obtained from a sample of 12 normal hearing young adults who did not take part in the current study. The secondary task, tactile pattern recognition, was administered in quiet, with the same equipment and presentation levels as had been used in previous studies conducted in our lab (Anderson Gosselin & Gagné, 2011; Fraser et al., 2010). Under the equated level condition, all the participants completed one block of 40 trials for each of the three experimental tasks: 1) the primary task – closed-set sentence recognition in noise, 2) the secondary task – tactile pattern recognition in quiet, and 3) the dual task – sentence recognition in noise and the tactile pattern recognition task concurrently (1 & 2). The order in which the three tasks were administered was counterbalanced across participants.

Equated performance condition

The purpose of the equated performance condition was to compare the results obtained when the group of young and older adults performed at the same performance criterion (80% correct) on single task audiovisual word recognition. The SNR chosen for the equated level condition was specifically chosen such that the group of young adults met the performance criterion on this task. As a result, young adults did not perform any further testing. Similarly, older adults, who met the 80% performance criterion or better on single task audiovisual word recognition, were also exempt from further testing. The exemption of older adults was extended to include the 80% performance criterion minus 1 standard deviation based on the single task word recognition data obtained from the first 15 young adults of the current investigation (i.e., SD=9.72). Hence, older adults whose performance on single task word recognition during the equated level condition was 70% or lower performed three additional experimental tasks.

For each older adult who did not meet the equated performance criterion, an adaptive level setting procedure was employed to determine the noise level required for the participant to obtain 80% correct on single task audiovisual word recognition using blocks of 10 test sentences that were not employed in any experimental condition. Specifically, the noise level was reduced by 2 dB and a block of 10 test sentences were given. If the total target word score was less than the 80% criterion, the noise level was reduced by an additional 2 dB and another block of 10 test sentences were given. If however the total target word score exceeded the 80% criterion, the noise level was increased by 1 dB and another block of 10 test sentences were given. The bracketing technique of decreasing by 2 dB (for scores below the 80% criterion) and increasing by 1 dB (for scores above the 80% criterion) continued until the level of noise that provided the smallest deviation from the 80% criterion was established. At this individualized noise attenuation level, older adults then completed one block (40 test sentences) of the primary audiovisual word recognition task and one block (40 trials) of the dual task (i.e., audiovisual word recognition and the tactile pattern recognition task concurrently) in a counterbalanced order.

Self-reported rating

At the conclusion of each block of dual task trials, participants were asked to rate: 1) their perceived level of accuracy for both primary and secondary tasks and, 2) the level of effort expended to perform both primary and secondary tasks. The specific questions for the accuracy ratings were: "What percentage of sentences do you think you identified correctly?" and "What percentage of the vibrations in your hand do you think you identified correctly?" To indicate their response, participants placed a mark on a printed version of a continuous scale which ranged from 0% to 100%. The questions for the effort ratings were: "How much effort was required for you to identify the components of the sentence?" and "How much effort was required for you to identify the vibrations in your hand?" Again, participants indicated their response by placing a mark on a printed continuous scale which ranged from 0-100 where 0 signified a negligible amount of effort and 100 signified a high degree of effort.

Results

Analysis overview

To compare across age groups, proportional dual task costs (i.e., pDTC = (dual task – single task)/single task*100) were calculated for each dependent variable (i.e., primary word task percent correct and response time, secondary tactile task percent correct and response time). For the response time data, the mean correct response time for both the word and tactile task was calculated for each participant under single and dual task conditions and used in the pDTC measure. The pDTC statistically controls for individual differences in single task performance (Anderson Gosselin & Gagné, 2011; Somberg & Salthouse, 1982). For example, if a participant's single task tactile accuracy performance was 80% and their dual task performance declined to 40%, the pDTC or the cost of performing the two tasks together would be 50%. To explore the effect of age (younger vs. older adults) on the dual task performance of each experimental condition (i.e., equated level and equated performance), using the General Linear Model (GLM), a one-way ANOVA was conducted for each of the pDTC measures (i.e., primary task percent correct and response time, secondary task percent correct and response time) under study. For each analysis 'age' was the between subject variable. The alpha criterion level for each of the analyses of variance was set to 0.05. Effect sizes were calculated as partial eta squared (η_{p2}) values. In addition, for the older adults, to compare the effect of experimental condition (i.e. equated level vs. equated performance); paired t-tests for each pDTC dependent measure were conducted.

Spearman rho correlations using a two-tailed alpha criterion were performed to determine if the participants' performance as measured by the dual-task paradigm, matched their perception of accuracy and effort. For the equated performance level, the four self-reported ratings (i.e., accuracy and effort estimates for the primary word task and secondary tactile task) were correlated with each of the absolute dependent measures obtained under dual task conditions (i.e., dual task word accuracy, dual task word response time, dual task tactile accuracy, dual task tactile response time). Separate correlation matrices were produced for the young and older adults. This procedure was repeated for the equated level condition, producing separate correlation matrices for the two subgroups of older adults. For the resulting 28 comparisons of each correlation analysis, the conservative Bonferroni significance criterion was adopted to control for Type I error (i.e., 0.05/28=.0018). The self-reported estimates of accuracy and effort were further analyzed using the Mann Whitney Rank Sum test, to examine the effect of age and with the Wilcoxon test to examine the effect of experimental condition (i.e. equated level vs. equated performance) across older adults only.

Dual task results

Equated level findings

This section reports the results where the SNR for the audiovisual word recognition task was the same for young and older adults.

Accuracy results

In general, the raw scores obtained from the equated level condition indicate that the accuracy results of older adults were lower than young adults for both the primary and secondary tasks, under single and dual task conditions (see Table 1). Comparing the pDTC

Table 1. Mean and standard deviations of single and dual task results for young and older adults obtained during the equated level condition (speech at 52 dBA, noise at 72 dBA). Accuracy reported as percent correct. Response time reported in seconds.

		Young Adults (n=25)		**Older Adults (n=25)**	
		Mean	SD	Mean	SD
Single Task	Word - Accuracy	79.47	9.49	71.90	13.14
	Tactile - Accuracy	94.38	4.51	89.40	8.96
	Word - Response Time	3.15	0.41	4.11	0.78
	Tactile - Response Time	2.25	0.24	2.77	0.41
Dual Task	Word - Accuracy	73.77	11.09	59.73	12.83
	Tactile - Accuracy	70.20	15.49	51.40	12.93
	Word - Response Time	3.95	0.59	4.91	0.98
	Tactile - Response Time	2.91	1.58	5.24	2.08

data, significant age differences are maintained for both the word task [F(1,48)=7.666, p=.008, η_{p2}=.138] and the tactile task [F(1,48)=13.558, p=.001, η_{p2}=.220]. For both tasks, older adults had significantly larger pDTCs than young adults which indicates a greater difference between single and dual task performance. Mean accuracy results plotted by age and task for the equated level condition, are displayed in Figure 2.

Response time results

Overall, the average response time results of older adults were longer than young adults for the primary and secondary tasks, under both single and dual task conditions (see Table 1). Comparing the relative data, the main effect of age was not significant for the word task pDTC response times [F(1,48)=.890, p=.350, η_{p2}=.018]. However, the pDTC response time data for the tactile task revealed a significant age effect whereby the older adults had larger pDTCs than the young adults [F(1,48)=9.010, p=.004, η_{p2}=.158]. Mean response time results plotted by age and task for the equated level condition, are displayed in Figure 3.

Equated performance findings

This section reports the results of the experimental condition where the level of noise was individually attenuated as required for older adults to achieve the 80% performance criterion on single task word recognition.

Accuracy results

As shown in Table 1, for the equated level condition, the single task word recognition results obtained by young adults, achieved the 80% criterion set for the equated performance condition (i.e., Mean 79%, SD 9.49). As a result, the data initially obtained from young adults was used to compare with the performance of older adults under the equated performance condition. Similarly, 12 of the 25 older adults also met the 80% performance criterion on single task word recognition (i.e., OA Group 1). For the

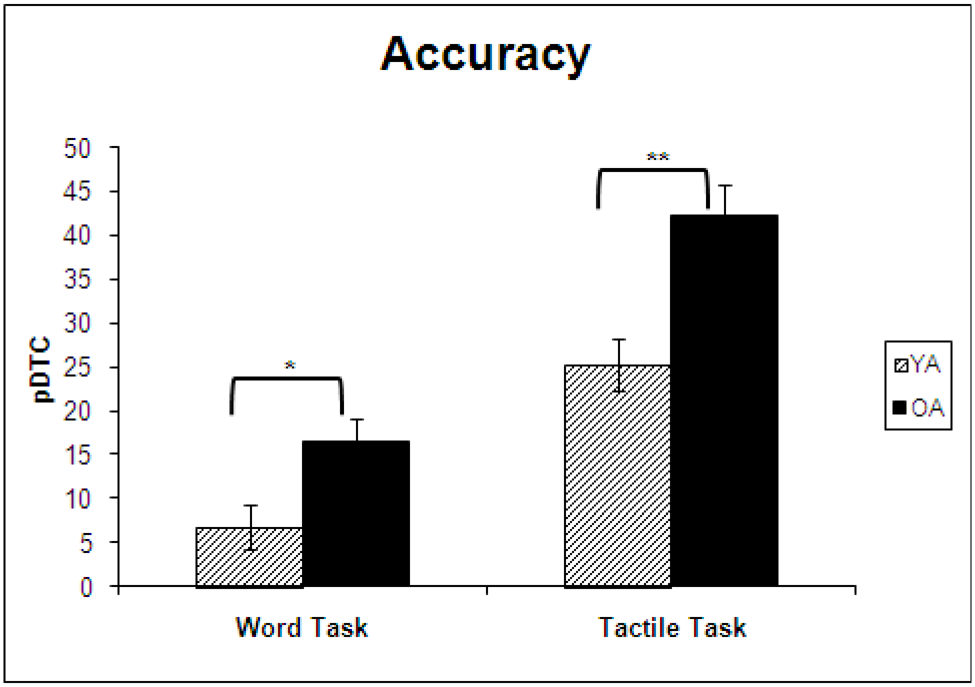


Figure 2. Mean accuracy scores and standard errors plotted as proportional dual task costs (pDTC) by task (word task and tactile task) and age (YA=young adults, depicted by striped bars and OA= older adults, depicted by solid bars) for the equated level condition. Brackets and asterisks denote comparisons that were significant (* p=.008, **p=.001).

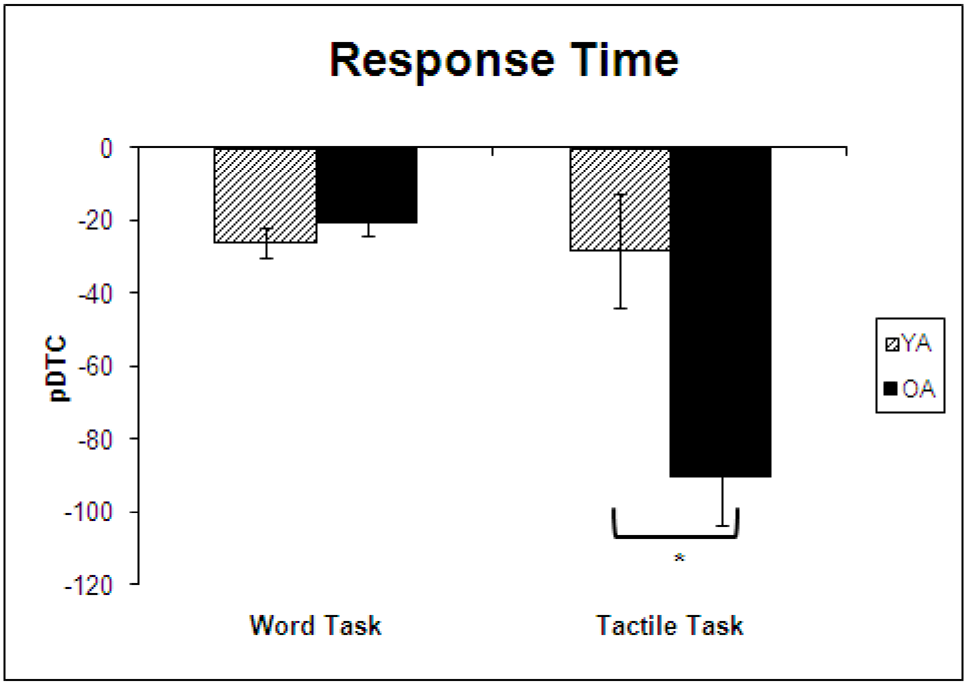


Figure 3. Mean response times and standard errors plotted as proportional dual task costs (pDTC) by task (word task and tactile task) and age (YA=young adults, depicted by striped bars and OA= older adults, depicted by solid bars) for the equated level condition. Brackets and asterisks denote comparisons that were significant (* p=.004).

remaining 13 of the 25 older adults (i.e., OA Group 2), the experimental tasks were performed a second time at a reduced noise level which was individually set for each older adult. The noise level ranged from 66-71 dBA (i.e., Mean 69.31 dBA, SD 1.18). The average single and dual task results for all older adults and the two subgroups of older adults (i.e., OA Group 1 & 2) are summarized in Table 2.

After the level setting procedure, there were no significant differences between the two subgroups of older adults on single task word recognition ability [t(23)=-.967, p=.344] nor were there significant differences in terms of age [t(23)=--.879, p=.389] or performance on the cognitive screening test [t(23)=1.215, p=.237]. As a result, the data from both OA subgroups was collapsed together. The resulting mean single task word recognition for all 25 older adults was 84% (SD 4.52) as shown in Table 2. The 4.5 percentage point difference between young and older adults on single task word recognition was not significantly different (p=.089). Hence, our adaptive level setting procedure was successful in equating the performance between the groups. Similarly, in terms of the pDTC data, there were no significant age-related differences on either the accuracy results for the word task [F(1,48)=3.545, p=.066, ηp2=.069] or the tactile task [F(1,48)=3.303, p=.075, ηp2=.064]. Mean accuracy results plotted by age and task for the equated performance condition, are displayed in Figure 4.

Response time results

The response time data shown in Tables 1 and 2 indicates that generally, the average response time results of older adults were longer than young adults. However, the relative data revealed a trend in which older adults had smaller pDTC's than young adults for the word task response time data [F(1,48)=4.047, p=.050, ηp2=.078]. In contrast, older adults had significantly larger pDTC's for the tactile task response time data [F(1,48)=7.049, p=.011, ηp2=.128]. Mean response time results plotted by age and task for the equated performance condition, are displayed in Figure 5.

Table 2. Mean and standard deviations of single and dual task results for all older adults (OA), and OA Groups 1 and 2 during the equated performance condition. Accuracy reported as percent correct. Response time reported in seconds.

		OA (n=25)		**OA Group 1 (n=12)**		**OA Group 2 (n=13)**	
		Mean	SD	Mean	SD	Mean	SD
Single Task	Word - Accuracy	83.97	4.52	83.06	5.52	84.81	3.37
	Tactile - Accuracy	89.40	8.96	91.46	8.95	87.50	8.90
	Word - Response Time	3.87	0.56	3.95	0.37	3.80	0.70
	Tactile - Response Time	2.77	0.41	2.85	0.27	2.69	0.50
Dual Task	Word - Accuracy	73.30	9.65	67.92	9.56	78.27	6.83
	Tactile - Accuracy	57.90	15.49	49.38	13.28	65.77	13.36
	Word - Response Time	4.55	0.89	4.73	0.74	4.38	1.01
	Tactile - Response Time	4.83	1.69	5.18	1.76	4.51	1.62

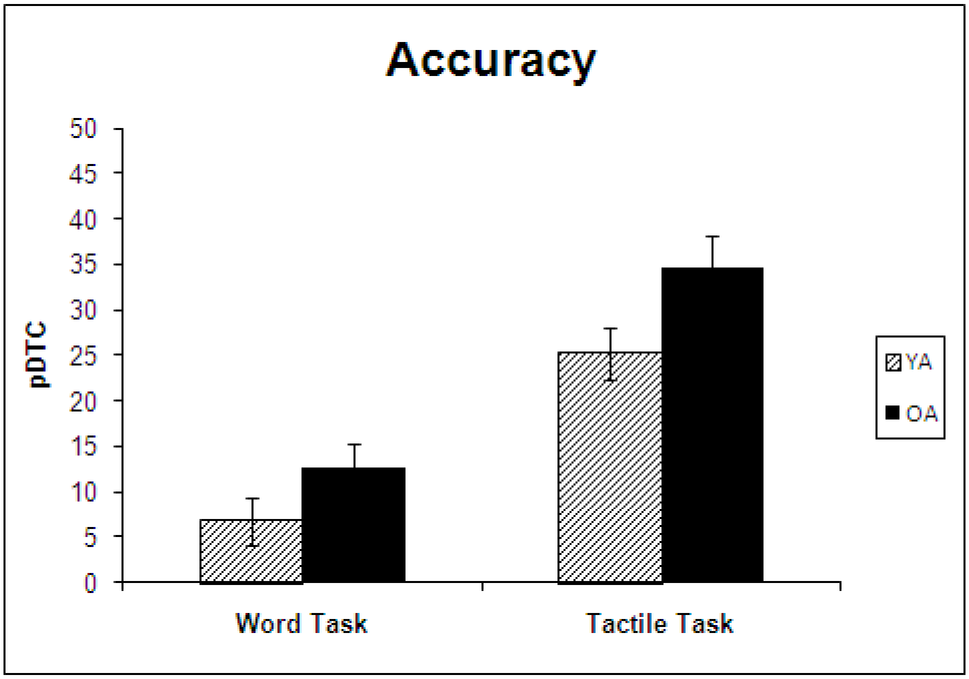


Figure 4. Mean accuracy scores and standard errors plotted as proportional dual task costs (pDTC) by task (word task and tactile task) and age (YA=young adults, depicted by striped bars and OA= older adults, depicted by solid bars) for the equated performance condition.

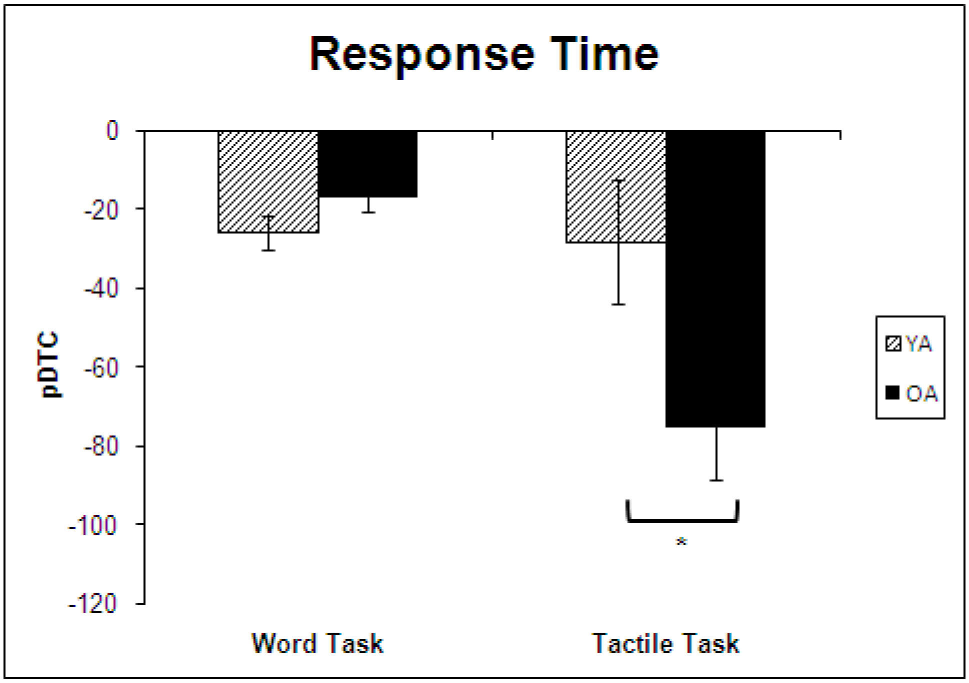


Figure 5. Mean response times and standard errors plotted as proportional dual task costs (pDTC) by task (word task and tactile task) and age (YA=young adults, depicted by striped bars and OA= older adults, depicted by solid bars) for the equated performance condition. Brackets and asterisks denote comparisons that were significant (* p=.011).

Comparison of equated level and equated performance findings

Examining the data from OA Group 2 across the two experimental conditions, we found that when the noise level was reduced (as was the case for the equated performance condition relative to the equated level condition), there was a significant reduction in pDTC for the tactile task accuracy results [t(12)=3.385, p=.005]. Comparing across conditions, there were no significant differences in pDTCs for the remaining measures: Word task percent correct [t(12)=1.453, p=.172], Word task response time [t(12)=-.903, p=.384], Tactile task response time [t(12)=-1.320, p=.211].

Comparison between dual task results and self-reported ratings

In general, for the equated level condition (see Table 3) and the equated performance condition (see Table 4), self-reported ratings of accuracy and effort did not correlate with any of the dual-task measures. However, differences in listening effort were observed using the average dual task data between groups (i.e., older vs. younger adults) and within groups (i.e., OA group 2 across the two experimental conditions). The next sections report between group and within group comparisons using self-reported ratings.

Between-group and within-group comparisons of self-reported ratings

Equated level findings

With the noise level fixed for both young adults (n=25) and older adults (n=25), there were no significant differences between the groups on word accuracy ratings [U=223.5, p=.082] or effort ratings for either the word task [U=301.5, p=.829] or tactile task [U=299.5, p=.080]. In contrast, older adults rated their tactile accuracy significantly lower than young adults [U=127.5, p<.0001]. Mean self-reported ratings by age for the equated level condition are displayed in Table 5.

Table 3. Spearman rho correlations between objective and subjective measures obtained during the equated level condition for 25 young adults (YA) and 25 older adults (OA).

				Subjective Ratings			
				Word Accuracy	Word Effort	Tactile Accuracy	Tactile Effort
Dual Task Measures	Word Accuracy	YA	r	-0.299	-0.042	-0.125	-0.017
			p	0.146	0.843	0.553	0.937
		OA	r	-0.183	-0.233	-0.235	0.091
			p	0.380	0.262	0.258	0.664
	Tactile Accuracy	YA	r	-0.244	0.240	-0.172	0.001
			p	0.239	0.247	0.410	0.996
		OA	r	0.095	0.048	-0.029	-0.108
			p	0.650	0.820	0.890	0.606
	Word Response Time	YA	r	0.368	-0.162	0.114	-0.036
			p	0.070	0.439	0.587	0.863
		OA	r	-0.261	-0.199	-0.120	-0.060
			p	0.207	0.341	0.568	0.776
	Tactile Response Time	YA	r	0.023	0.004	0.071	-0.014
			p	0.914	0.987	0.736	0.949
		OA	r	-0.150	0.049	0.107	0.127
			p	0.475	0.814	0.611	0.546

Table 4. Spearman rho correlations between objective and subjective measures obtained during the equated performance condition for all 25 older adults (OA) and OA Group 1 (n=12) and OA Group 2 (n=13). With a Bonferroni correction applied for multiple comparisons p<.0018 required to reach statistical significance.

				Subjective Ratings			
				Word Accuracy	Word Effort	Tactile Accuracy	Tactile Effort
Dual Task Measures	Word Accuracy	OA	r	-0.194	-0.064	0.572	0.066
			p	0.354	0.762	0.003	0.755
		OA Group 1	r	-0.366	-0.205	0.279	0.305
			p	0.241	0.523	0.380	0.336
		OA Group 2	r	-0.440	-0.011	0.759	-0.058
			p	0.133	0.971	0.003	0.850
	Tactile Accuracy	OA	r	0.162	0.118	0.224	-0.308
			p	0.438	0.575	0.283	0.134
		OA Group 1	r	-0.244	-0.110	0.054	-0.354
			p	0.444	0.735	0.869	0.259
		OA Group 2	r	0.039	0.205	0.056	-0.291
			p	0.900	0.501	0.856	0.334
	Word Response Time	OA	r	0.067	-0.285	-0.281	-0.211
			p	0.749	0.167	0.174	0.312
		OA Group 1	r	-0.449	-0.445	0.100	-0.042
			p	0.143	0.147	0.757	0.897
		OA Group 2	r	0.451	-0.171	-0.382	-0.297
			p	0.122	0.576	0.197	0.325
	Tactile Response Time	OA	r	-0.259	0.038	-0.060	0.219
			p	0.212	0.856	0.774	0.293
		OA Group 1	r	-0.359	-0.247	0.100	0.042
			p	0.252	0.438	0.757	0.897
		OA Group 2	r	-0.194	0.351	-0.078	0.372
			p	0.526	0.239	0.800	0.211

Table 5. Mean subjective ratings and standard deviations by experimental condition and age.

Equated Level Condition

	Young Adults (n=25)		**Older Adults (n=25)**	
	Mean	SD	Mean	SD
Word Accuracy	58.84	20.74	48.60	20.13
Word Effort	82.40	12.26	82.00	14.29
Tactile Accuracy	62.40	17.74	41.72	20.06
Tactile Effort	67.32	26.54	69.20	26.68

Equated Performance Condition

	Young Adults (n=25)		**Older Adults (n=25)**	
	Mean	SD	Mean	SD
Word Accuracy	58.84	20.74	58.80	16.35
Word Effort	82.40	12.26	77.40	15.62
Tactile Accuracy	62.40	17.74	43.32	18.54
Tactile Effort	67.32	26.54	68.60	26.20

Equated performance findings

With performance equated, not surprisingly there were no significant age differences between young adults (n=25) and older adults (n=25) on word task accuracy [U=303, p=.853] or word task effort ratings [U=260, p=.303]. While tactile effort ratings did not differ [U=304.5, p=.876], like the equated level condition, a significant age difference on tactile accuracy ratings was observed [U=135, p=.001]. Mean self-reported ratings by age for the equated level condition are displayed in Table 5.

Comparison of equated level and equated performance findings

Comparing the results of OA Group 2 participants (n=13) across the two experimental conditions, the analyses revealed that when noise was reduced for the equated performance condition, word accuracy ratings increased [Z=-2.596, p=.009] and the word task was rated as requiring less effort [Z=-2.831, p=.005]. In contrast, tactile accuracy [Z=-.071, p=.943] and effort ratings [Z=-.241, p=.809] did not differ between the two experimental conditions. Mean self-reported ratings for OA Group 2 by experimental condition are displayed in Table 6.

Table 6. Mean subjective ratings and standard deviations for OA Group 2 (n=13) by experimental condition.

	Equated Level		**Equated Performance**	
	Mean	SD	Mean	SD
Word Accuracy	35.77	15.12	55.38	17.26
Word Effort	86.15	8.20	77.31	13.63
Tactile Accuracy	35.00	19.90	38.08	17.86
Tactile Effort	71.92	24.71	70.77	23.79

Discussion

Dual task findings – between-group comparisons

The most important result of this study is that the dual task measures demonstrated in a quantitative way that older adults expend more listening effort than young adults to recognize audiovisual speech. For the equated level condition, the primary word task was presented to young and older adults at the same SNR. The mean results from the raw data indicated that older adults scored almost 8 percentage points lower (p=.024) than young adults on single task word recognition (see Table 1). Significant age differences were retained with the relative pDTC data. The results revealed that older adults exerted increased listening effort compared to young adults as shown by significantly larger pDTC's for the concurrent tactile task percent correct scores and response time measures shown in Figure 2 and 3. However, unlike our previous study involving audio-only speech recognition (Anderson Gosselin & Gagné, 2011), for the current study using audiovisual speech recognition, we also found that older adults had significantly larger pDTC's for the primary word task accuracy results (see Figure 2). These results suggest that older adults require more resources than young adults to process audiovisual speech which in turn leaves less resources available for the secondary tactile task (Broadbent, 1958; Kahneman, 1973).

To rule out whether the age effect was influenced by the significant differences observed on single task word recognition performance, we examined a second experimental condition where baseline word recognition performance was equated. Even when performance was equated, the relative pDTC data revealed that older adults still exerted increased listening effort compared to young adults as shown by significantly larger pDTC's for the tactile task response time results, illustrated in Figure 5.

The results of both experimental conditions suggest that older adults expend more listening effort than young adults. Furthermore, the processing demands of audiovisual speech appear to be greater than had been demonstrated previously with audio-alone speech recognition (Anderson Gosselin & Gagné, 2011). Relative to young adults, when speech is presented audiovisually, performance consequences are observed for both the primary and secondary tasks as shown by significantly larger pDTCs for older adults. These results are consistent with previous dual task research (Alsius et al., 2005; Alsius et al., 2007; Fraser et al., 2010).

Using the same tasks as the current study, Fraser et al. (2010) investigated the impact of adding visual cues on the listening effort of normal hearing young adults. One of the experimental manipulations involved equating word recognition accuracy results (i.e., 80% correct) by increasing the level of noise during audiovisual speech presentation compared to audio-only speech presentation. At equivalent accuracy levels, performance on both the word task and tactile task was poorer under the noisier audiovisual condition relative to the audio-only condition. The current study extends these findings to older adults and demonstrates that relative to young adults, older adults expend significantly more listening effort and require more resources to recognize audiovisual speech even when performance levels are equated to 80% correct for both age groups.

Like the current study, Alsius et al. (2007) also used a somatosensory tactile task so as to not interfere with either the audio or visual modalities. Despite this, Alsius et al. (2007) demonstrated dual task costs for the speech task when the tactile task was coupled with audiovisual speech but not with an audio-only or visual-only presentation of speech.

These results suggest that a difficult tactile task can cause crossmodal interference and disrupt audiovisual integration. Presumably the processing demands of audiovisual speech and tactile processing exceeds the available capacity of resources (Alsius et al., 2007). While the current study did not examine the effect of audiovisual integration explicitly, the word accuracy pDTCs observed with audiovisual speech in the current study are greater than the pDTCs observed with audio-only speech in our former study (Anderson Gosselin & Gagné, 2011) during both the equated level condition and equated performance condition. Taken together these findings using different groups of participants for audiovisual vs. audio-only speech recognition provide limited support to the results reported by Alsius et al. (2007). Further study using the same group of older adults to investigate the impact of adding visual cues on listening effort, would strengthen the argument that the binding of audiovisual information can be disrupted when demands are imposed by a concurrent tactile task.

Dual task findings – within-group comparisons

In addition, the dual task measures also provide a sensitive behavioural index to track changes in the amount of listening effort experienced by older adults across experimental conditions. Relative to the equated level condition, the dual task results obtained by OA Group 2 revealed that as the noise level was reduced for the equated performance condition, there was a significant reduction in listening effort as measured by the reduction in pDTCs for the tactile task accuracy results (see Figure 3 & 5). It must be noted that for the current study, this effect was observed even though on average, the noise level was reduced by 3 dB. Using a larger SNR difference (i.e., 12 dB), Fraser et al. (2010) found that when the noise level was increased during audiovisual speech recognition, there was a significant increase in listening effort. Specifically, audiovisual speech recognition under conditions of high background noise (similar to the SNR used in the equated level condition of the current study) or "difficult listening" resulted in dual task decrements on both the primary word task and secondary tactile task relative to audio-only listening with 12 dB less background noise (Fraser et al., 2010). In contrast, under conditions of low background noise levels or "easy listening", the addition of visual cues improved speech recognition but had no effect on listening effort (i.e., no dual task costs were noted) relative to audio-alone processing at the same level of background noise (Fraser et al., 2010). These results emphasize how the level of background noise or processing load (Lavie, 1995) influences both audiovisual speech recognition and listening effort. Despite the addition of visual cues, under high load with high levels of background noise, fewer auditory speech cues are available. As a result, audiovisual speech recognition requires more resources to: 1) extract speech information from noise, 2) extract cues from the visual speech signal and, 3) integrate the redundant and/or complementary cues together (Fraser et al., 2010; Grant, Walden, & Seitz, 1998), which in turn leaves less resources available for secondary task processing (Broadbent, 1958; Kahneman, 1973).

Correlation findings

The correlation analyses revealed that self-reported ratings of effort did not correlate with any of the dual task measures, irrespective of participant group or experimental condition (see Table 3 & 4). These results agree with other studies that included a self-reported measure of "effort" in their evaluation of young adults (Downs & Crum, 1978; Feuerstein, 1992; Fraser et al., 2010) and older adults (Anderson Gosselin & Gagné, 2011; Larsby, Hallgren, & Lyxell, 2005). The lack of correlation supports the idea that both measures assess different aspects of listening effort (Feuerstein, 1992). Self reported ratings of effort do not appear to reflect the availability of or demands on processing resources as measured with a dual task paradigm (Wickens, 1992; Zekveld, Kramer, & Festen, 2010).

Where the current study differs from previous research involving audiovisual speech recognition (Fraser et al., 2010), is that we did not find significant correlations between accuracy ratings and their related dual task measures. While this point of difference remains unclear, it may be accounted for by differences in the statistical analyses conducted. Fraser et al. (2010) reported Pearson correlations, whereas the current study reported Spearman rho correlations corrected for multiple comparisons. It may also be the case that other factors yet to be identified could influence the relationship between self-reported ratings and dual task measures. Future research is required to provide more insight into the relationship between listening effort and cognitive variables such as attention, speed of processing and working memory which have been shown to be affect the effort involved with listening comprehension, written comprehension and communication (Akeroyd, 2008; Daneman & Merickle, 1996).

Despite the lack of correlation, self-reported estimates of listening effort can be useful clinically. Humes (1999) used a factor analysis to demonstrate that self-reported estimates of listening effort represented a unique aspect of hearing aid outcome separate from quantitative speech recognition performance measures.

Self-reported rating findings – between-group comparisons

Unlike the dual task measures which were sensitive to age-related group differences, using the self-reported ratings a different pattern of between-group results emerged. Consistent with previous research (Anderson Gosselin & Gagné, 2011; Larsby et al., 2005), for the equated level condition, we found that older adults did not report higher effort ratings than young adults even though there were significant age differences on quantitative performance measures (see Table 5). In addition, for both experimental conditions, the tactile accuracy ratings were significantly lower for older adults compared to young adults but there were no significant group differences on the tactile task effort ratings (see Table 5). While these findings are consistent with previous research (Anderson Gosselin & Gagné, 2011; Ford et al., 1988; Uchida et al., 2003) which suggests that older adults tend to under-estimate their degree of difficulties, one of the limitations of this interpretation is that the criteria people use to assess their listening effort are unknown (Edwards, 2009; Yeh & Wickens, 1988).

Self-reported rating findings – within-group comparisons

While the shortcomings of between group comparisons of self-reported ratings are evident, the average results obtained for OA Group 2 reveal that both dual task measures and self-reported ratings of listening effort were sensitive to changes across experimental conditions. Relative to the equated level condition, as the noise level was reduced for older adults: the pDTCs for the tactile task accuracy results decreased, self-reported word recognition accuracy ratings increased, and word effort ratings decreased (see Table 6). These findings agree with previous research conducted on older adults using audio-only speech recognition (Anderson Gosselin & Gagné, 2011) and younger adults presented with audiovisual speech (Fraser et al., 2010). Fraser et al. (2010) found that when the background noise level for audiovisual speech was increased across two experimental conditions: both word and tactile task accuracy ratings decreased and the word task was rated as more effortful. Together, the averaged results of the groups suggest that just as young adults can rate a listening task that is harder as being more difficult, so too can older adults rate a listening task that is easier as being less effortful.

Conclusion

In conclusion, dual task measures were sensitive to age-related group differences in listening effort. Older adults expended more listening effort than young adults to recognize audiovisual speech for both the equated level and equated performance conditions. Even when the level of noise was individually attenuated for older adults to ensure a similar level of single task word recognition, older adults still exerted more listening effort than young adults. As a result, one should never assume that two people with equal word recognition performance expended the same level of listening effort to maintain that performance level. Furthermore, the processing demands of audiovisual speech recognition appear to be greater than had been demonstrated previously with audio-alone speech (Alsius et al., 2007; Anderson Gosselin & Gagné, 2011; Fraser et al., 2010). Relative to young adults, older adults demonstrated significantly larger pDTCs for both the primary word task and secondary tactile task. While many studies have shown that older adults require more processing resources compared to young adults to understand speech in noise (Chisolm et al., 2003; Kricos, 2006; McCoy et al., 2005; Salthouse, 1988; Tun et al., 2008; Wingfield & Tun, 2001, 2007), the current study extends these findings to include the recognition of audiovisual speech presented in noise. On average, the group results obtained for OA Group 2 revealed that both dual task measures and the self-reported ratings of listening effort were sensitive to changes across experimental conditions. However, our correlation analyses support the idea that self reported ratings and dual task measures each assess different aspects of listening effort (Feuerstein, 1992). It remains to be determined with further study how other factors including cognitive variables may influence listening effort.

Acknowledgements

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Article 4 – Audition and cognition: The relationship between listening effort and working memory

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Abstract

Objective: Research shows that measures which tap the combination of capacity and processing of working memory predict reading and listening comprehension. Our purpose is 1) to determine to what extent the separate components of working memory (capacity and processing) contribute to the variance observed in listening effort, and 2) to determine if the pattern of working memory predictor variables changes with age. Listening effort involves the attention and cognitive resources required to understand speech.

Method: We used a dual task paradigm to objectively evaluate the listening effort of 25 young and 25 older adults with normal hearing ability. The primary task involved a closed-set sentence-recognition test and the secondary task involved a vibro-tactile pattern-recognition test. Auditory working memory was assessed using the Alpha Span.

Results: Using sequential regression analyses: span size (a capacity measure) predicted listening effort with ~25% accuracy and alphabetical recall (a processing measure) predicted the “cost” of dual task word recognition accuracy with 24% accuracy – but only for young adults. These findings were not replicated by older adults.

Conclusions: To better understand what factors influence the listening effort of older adults, further study using different cognitive measures that tap compensatory strategy use (executive function) are needed.

Key Words: Listening effort, dual task paradigm, audition, speech recognition, cognition, working memory, aging

Introduction

Looking beyond audibility – the relevance of age and cognitive factors

There has been an increasing interest within the field of audiology to learn how auditory and cognitive processes inter-relate to better understand and address the rehabilitative needs of older adults (Baltes & Baltes, 1990; Baltes & Lindenberger, 1997; Kiessling et al., 2003; Pichora-Fuller, 2006, 2009; Pichora-Fuller & Singh, 2006; Schneider, Pichora-Fuller, & Daneman, 2010; Wingfield & Tun, 2001, 2007). Much of this interest has been driven by the growing number of studies published within the last decade that have linked various cognitive measures (e.g., visual letter or digit monitoring, reading span and IQ) with word recognition ability (Akeroyd, 2008). For example, audibility was found to be the primary contributor to the speech-understanding difficulties of older adults with hearing impairment under unaided listening conditions (Humes, 2007). However, when an experimental approach was taken to restore audibility, age and cognitive factors (i.e., IQ and memory) emerged to account for half of the variance associated with word identification performance (Amos & Humes, 2007; Humes, 2007; Humes, Burk, Coughlin, Busey, & Stauser, 2007). In general, research findings in this area have shown that word recognition ability in noise is primarily determined by audibility followed by cognitive abilities (Akeroyd, 2008).

Age is an important factor to consider as it influences both audition and cognition. As adults age, sensory, perceptual and cognitive functions decline (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994; Pichora-Fuller, 2006). One of the consequences of presbycusis and/or listening in noise is that if more resources need to be allocated to the task of auditory perception to determine what is being said, in general less resources are available for higher-level cognitive tasks and poorer memory and comprehension for what was heard can result (Arlinger, Lunner, Lyxell, & Pichora-Fuller, 2009; Kahneman, 1973; McCoy et al., 2005; Pichora-Fuller, 2007; Rabbitt, 1966, 1990; Rakerd, Seitz, & Whearty, 1996). Interestingly, even when older adults have “normal hearing ability”, research has shown that young adults still outperform older adults on word recognition tasks when performed in noise (CHABA, 1988). These results suggest that the observed age-related word-recognition differences extend beyond perceptual factors like the ability "to hear" (CHABA, 1988).

Age-related cognitive declines involve the dynamic or "fluid" aspects of information processing including working memory (Salthouse, 1994, 2004), attentional resources (Craik & Byrd, 1982), speed of processing (Salthouse, 1996) and inhibition from distraction (Stoltzfus, Hasher, & Zacks, 1996). However, on the positive side, static or "crystallized" linguistic and world knowledge are well preserved and this accounts for the ability of many healthy older adults to benefit from and use supportive context in difficult listening situations as a compensation strategy (Craik, 1986; Schneider et al., 2010; Wingfield & Tun, 2007).

Cognitive tests related to speech recognition

To examine the evidence linking word recognition ability in noise and cognitive abilities, Akeroyd (2008) conducted a comprehensive review of 20 studies that had been published since the CHABA (1988) report. Given the limited selection of cognitive tests that had been included in this meta-analysis, Akeroyd (2008) concluded that tests of working memory such as the reading or listening working memory span test showed the most promising results.

Working memory is defined as a limited capacity system that allows for the temporary storage and processing of information until it is either forgotten or consolidated into long-term memory to facilitate comprehension, learning and reasoning (Baddeley, 2000; Baddeley & Hitch, 1974). During a typical working memory span task participants read or listen to a sentence and complete a processing task related to that sentence (i.e., verify the logical accuracy or semantic sensibility of the sentence). Following the presentation of a set of sentences ranging in size from two to six, participants are prompted to recall a target word (i.e., first word or last word) from each sentence using the same order the sentences had been presented. Provided the target words are recalled correctly, the number of sentences per set is increased. The working memory span score typically represents the maximum number of target words recalled (Conway et al., 2005; Pichora-Fuller, 2006) and the processing aspect of the test is rarely scored (Conway et al., 2005).

One of the common features shared among working memory span tasks (i.e., reading span, operation span and counting span) is that a demanding secondary processing task is required to compete with information storage (Conway et al., 2005). In general, working memory span measures which tap the combined processing and storage resources of working memory have been shown to be better predictors of comprehension ability than are measures of storage alone (Daneman & Carpenter, 1980; Daneman & Merickle, 1996). Despite the volume of research in this area, very few studies have examined each of the constituent processes of working memory (Baddeley, 2002) or how the separate contributions of processing and storage may in turn relate to word recognition in noise or the effort involved with listening. The latter issue is the focus of the current study.

Research involving the Alpha Span test (Craik, 1986) is one notable exception. The Alpha Span is a test of auditory working memory that requires participants to repeat words initially presented in a random order in alphabetical order. The Alpha Span test uses a transformation task to assess working memory (i.e., a task where the processing component involves a mental transformation of the target memory items). Research findings have demonstrated that the Alpha Span test measures the same construct as working memory span (Oberauer, Süβ, Schulze, Wilhelm, & Wittmann, 2000). Using the Alpha Span test, Belleville et al. (1998) examined the influence of storage capacity on the processing ability of young and older adults. Specifically, to control for varying storage capacity, the authors assessed recall at each participants word span (i.e., the longest sequence correctly recalled on 50% of the trials). With storage capacity equated, in a series of experiments Belleville et. al (1998) found no significant difference between young and older adults on the alphabetical recall component of the Alpha Span. For the current study, we used a French version of the Alpha Span test and followed the same experimental procedure as outlined by Belleville et al. (1998) to examine the separate influence of the capacity and processing components of working memory.

Alternative measures to speech recognition – listening effort

In the clinical domain, many older adults complain that listening in noise is a challenging and exhausting experience that requires a great deal of "effort". This common dilemma illustrates the distinction between hearing and listening. Hearing is a sense whereas the listening effort involved in listening comprehension is a skill that requires attention and intention to access and use the information that is heard. Listening effort refers to the attentional and cognitive resources required to understand speech (Bourland-Hicks & Tharpe, 2002; Downs, 1982; Feuerstein, 1992; Fraser, Gagné, Alepins, & Dubois, 2010). One way to behaviourally evaluate listening effort is to use a dual task paradigm (Anderson Gosselin & Gagné, 2010, 2011; Bourland-Hicks & Tharpe, 2002; Broadbent, 1958; Choi, Lotto, Lewis, Hoover, & Stelmachowicz, 2008; Downs, 1982; Downs & Crum, 1978; Feuerstein, 1992; Fraser et al., 2010; Rabbitt, 1966; Rakerd et al., 1996; Sarampalis, Kalluri, Edwards, & Hafer, 2009). For the current study, we used a dual task paradigm to examine the listening effort involved with word recognition in noise. A dual task paradigm requires that participants perform two tasks (a primary and a secondary task) separately and concurrently. Our primary task involved closed-set word recognition and the secondary task involved tactile pattern recognition. One of the underlying assumptions of dual task paradigms is that the cognitive system has a limited capacity of resources to process information (Kahneman, 1973). As a result, when the processing capacity for the primary task is exceeded (e.g., when a speech recognition task is conducted in a noisy background), decreases in secondary task performance will be observed when the tasks are performed at the same time (Kahneman, 1973; Lavie, 1995; Pashler, 1994). Typically, increases in listening effort are operationally defined as these declines in secondary task performance under dual task conditions (Bourland-Hicks & Tharpe, 2002; Broadbent, 1958; Fraser et al., 2010).

Objectives and predictions of current study

The objectives of the current study were 1) to determine to what extent the separate components of working memory (i.e., capacity and processing) contribute toward the variance observed in listening effort from word recognition under dual task conditions and, 2) to determine if the pattern of working memory predictor variables changes with age. Under "difficult" listening conditions (i.e., listening in noise) the Ease of Language Understanding (ELU) model (Ronnberg, Rudner, Foo, & Lunner, 2008), predicts that more explicit processing involving both capacity and processing components of working memory are required in the event that there is a mismatch between the incoming multimodal streams of phonological information and the representations stored in long-term memory. Based on working memory span research (Pichora-Fuller, 2007), we expected that those with long span sizes as measured with the Alpha Span test (a measure of auditory memory *capacity*) would expend less listening effort as measured by low costs on tactile task accuracy and response time measures under dual task conditions. In addition, given the strong association observed between a sequential working memory test (i.e., the Letter-Number Sequencing (LNS) subtest of the WAIS-III (Wechsler, 1997)) with rapid speech understanding (Vaughan, Storzbach, & Furukawa, 2006, 2008), we expected to see a similar relationship between alphabetical recall ability and word recognition performance in noise. Specifically, we expected that participants with high alphabetical recall ability (a measure of *processing*) would have high accuracy scores on a word recognition task in noise. However, the nature of the relationship between alphabetical recall and the cost associated with word recognition under dual task conditions is unknown. As for the second objective, we expected to see a similar pattern of results for young and older adults such that age-related declines in working memory (Salthouse, 1994, 2004) would be associated with age-related increases in listening effort.

Method

For the current experiment, the results of the equated performance condition reported in Anderson Gosselin & Gagné (2011) are reanalyzed in conjunction with working memory measures. As a result, an abbreviated version of the dual task description and dual task experimental procedure is provided below.

Participants

Participants included 25 young adults aged 18 to 33 years (M = 23.5, SD = 3.6) and 25 older adults aged 64 to 76 years (M = 69, SD = 4.0). All participants had normal hearing sensitivity (≤ 25 dB HL at octave frequencies between 0.25 and 2.0 kHz, as well as at 3 kHz, re: ANSI, 1996), in both ears and binocular visual acuity of 20/40 or better as measured with Sloan Letters at a distance of 3 metres (NAS-NRC, 1980; Sloan, Rowland, & Altman, 1952). The older adults all had clinically normal cognitive function as determined by the Montreal Cognitive Assessment [MoCA (Nasreddine et al., 2005)]. In addition, all participants reported that: 1) French was regularly used to communicate and perform activities of daily living, 2) they had good self-reported health and, 3) they were able to transport themselves independently to and from the laboratory.

Materials and apparatus

Test of auditory working memory – The Alpha Span

Estimates of auditory working memory were obtained using a French version of the Alpha Span test developed by Belleville, Rouleau & Caza (1998).

Word recognition task

The primary task involved a closed set sentence recognition test presented aurally (i.e. audio only). All sentences were spoken by a female native speaker of Québec-French. Each sentence had the same syntactic structure and contained three critical elements (subject, verb, and adjective). For each of the three critical elements there were seven interchangeable alternatives. The different combinations of alternatives could generate as many as 343 sentences which allowed for the creation of multiple unique lists of sentences for the practice and test sessions. Within each critical element, the words were chosen to have the same number of syllables. The stimuli used for the sentence recognition test and a sample sentence are shown in Table 1.

A customized computer program (Leclab) was used to conduct the experiment. Acoustically, separate audio files, one with the speech stimuli and one with the masking noise (a steady-state speech shaped noise) were routed to an 8 channel stereo mixer (Inkel, MX880E). The output from the mixer was amplified (InterM, PA-935) and presented via a loudspeaker (Realistic, Minimus-77) positioned 1 metre in front of the participant.

After each sentence was presented, participants were required to indicate on a 17 inch touch screen monitor (ELO TouchSystems, ET1725L) the three key words they heard. The target words appeared with a horizontal degree of visual angle (dva) ranging from 1.18 to 2.53 and a vertical dva ranging from 0.25 to 0.38. The software program recorded both the accuracy and the response time for each of the three key words of the sentence. Once completed, the participant touched the word “prochain” (i.e., next) to advance to the following trial.

Prior to each testing session a free-field acoustic calibration was conducted with calibration tones to ensure that the speech stimuli were consistently presented at 60 dBA and broadband speech shaped noise (i.e., pink noise) was presented at an initial level of 72 dBA for all participants.

Tactile pattern recognition task

The secondary task involved a tactile pattern-recognition task in which participants had to identify one of four pulse combinations (i.e. short-short, long-long, short-long or long-short). The pulses emanated from a small oscillator (Radioear B-71) typically used

Table 1. Response alternatives for the speech recognition task

Alternative	**Subject**	**Verb**	**Adjective**
1	amis	cherchent	beiges
2	élèves	donnent	bronzes
3	garçons	gonflent	jaunes
4	madames	soufflent	mauves
5	messieurs	tiennent	noirs
6	parents	trouvent	rouges
7	soldats	voient	verts

Note:

An example of a possible sentence used for the speech recognition task:

"Les parents[a] trouvent[b] des ballons rouges[c]." Where a = subject; b = verb; c = adjective, and these are the critical elements for each sentence. Each of these critical elements can be replaced by any one of the alternatives listed in the column. An English translation of the current sentence would be "The parents found the red balloons". An alternative sentence using the third row of critical elements would read: "The boys inflate the yellow balloons."

for bone-conduction testing in audiometry. ‘Short’ was 250 msec and ‘long’ was 500 msec in duration. The interstimulus interval was 500 msec. Participants held the vibrating device in their non-dominant hand and placed their hand in a box which contained sound attenuating foam material.

To ensure that the onset of the tactile stimuli would not be predictable, the software program would initiate tactile trials with a random variable time delay. The delay ranged from 0 msec to 1000 msec in 250 msec steps. After each trial the participants would indicate which of the four tactile patterns they perceived by touching the corresponding iconic symbol that appeared on the touch screen monitor. The software program recorded the accuracy and response times of participants’ answers.

Procedure

The experiment was completed in a single test session. Young adults required approximately 1 hour while older adults typically needed 1 hour and 45 minutes to complete the experiment. Upon arrival to the laboratory, participants were briefed on each of the components of the study and what they were expected to do. After voluntarily signing the consent form approved by our ethics review committee, all participants underwent hearing and vision screening. In addition, older adults completed the cognitive screening. After all of the screening tests were completed, all participants completed the test of auditory working memory, the Alpha Span test followed by the dual task experiment as outlined below. Rest periods were encouraged throughout the practice and test sessions. Upon completion, all participants were offered a small monetary compensation.

Auditory working memory – span measurement

A classical word span procedure was used to determine the longest sequence correctly recalled on 50% of the trials. Beginning with short sequences of two words, the experimenter would read the words at a rate of one word per second. Participants were instructed to recall the items in serial order by repeating them back to the experimenter.

The sequence length was increased by one word every two trials provided the participant recalled the word sequences correctly. If however, the participant made an error on one of the two trials, two additional trials at the same sequence length were administered. When the participant failed to report two of the four sequences correctly, testing stopped, and the sequence length was deemed the span size of the participant.

Auditory working memory – recall measurement

At the span size of each participant, direct and alphabetical recall was assessed. For both recall tasks, the experimenter would read a set of words equivalent to the participants span size. After the entire set of words was presented, participants would recall the words by repeating them back. For direct recall, participants recalled the words in the same serial order they were presented in. However, for alphabetical recall, participants recalled the words (initially presented in a random order) in alphabetical order. For example: "jungle, plâtre, loge, neige" would be recalled alphabetically as "jungle, loge, neige, plâtre". Ten sequences of words were used in both direct and alphabetical recall. The sequences were administered in blocks of 5 following an ABBA design to control for fatigue and practice.

Dual task practice session

The goal of the practice session was to ensure that the participants were familiar with the tasks used in the dual task paradigm. To continue on to the experimental condition, participants had to reach a criterion level of performance (i.e., 80% correct) on 20 trials of both the primary and secondary tasks performed singly without masking noise.

In addition, 20 practice trials of the dual-task condition were given in quiet. For dual-task trials, participants were instructed as follows: "the listening task is the more important of the two, pick the corresponding subject/verb/adjective for the sentence that you hear as quickly as possible and, identify the pulse pattern that you feel as quickly and as accurately as you can." The same verbal instructions were used during the experimental condition as they are similar to other studies where a dual-task paradigm had been used to evaluate listening effort (Bourland-Hicks & Tharpe, 2002; Downs, 1982; Fraser et al., 2010).

Dual task test session

For the current experiment, single task word recognition ability was equated for young and older adults. Based on the results of previous experiments (Fraser et al., 2010) and additional pilot work, a signal-to-noise ratio (SNR) of -12 dB (i.e., speech at 60 dBA and noise presented at 72 dBA) was specifically chosen as normal hearing young adults had been found to complete the closed set sentence recognition task with a mean accuracy rate of approximately 80% at this fixed level. At these SNR settings all participants completed three experimental tasks: 1) the primary task – closed-set sentence recognition in noise, 2) the secondary task – tactile pattern recognition in quiet, and 3) the dual task – sentence recognition in noise and the tactile pattern recognition task concurrently (1 & 2). Single and dual task performance was evaluated with a block of 40 test-trials. The order in which the three tasks were administered was counterbalanced across participants to reduce the possibility of confounds due to presentation order.

As the young adults of the current study performed the word task in isolation within the 80% performance criterion, no further dual-task testing was required. Similarly, 12 older adults (comprising OA Group 1), also met the 80% performance criterion or better on single task word recognition, and were exempt from any further testing (see Anderson Gosselin & Gagné, 2011 for details).

For the remaining 13 older adults (OA Group 2), two additional experimental tasks were performed following an adaptive level setting procedure which was used to determine the noise level required for the participant to obtain 80% correct on single task word recognition using blocks of 10 test sentences. The adaptive level setting procedure employed a bracketing technique. The noise level was reduced by 2 dB and a block of 10 test sentences were administered. If the total target word score was less than the 80% criterion, the noise level was reduced by an additional 2 dB and another block of 10 test sentences were given. If however the total target word score exceeded the 80% criterion, the noise level was increased by 1 dB and another block of 10 test sentences were given. The bracketing technique of decreasing by 2 dB (for scores below the 80% criterion) and increasing by 1 dB (for scores above the 80% criterion) continued until the level of noise that provided the smallest deviation from the 80% criterion was established.

At this individualized noise attenuation level which ranged from 66-71 dBA (i.e., Mean 69.31 dBA, SD 1.65), participants from OA Group 2 completed one block (40 test sentences) of the primary word recognition task and one block (40 trials) of the dual task (i.e., word recognition and the tactile pattern recognition concurrently) in a counterbalanced order.

Results

As reported in Anderson Gosselin & Gagné (2011), the 12 older adults who met the performance criterion during the equated level condition were younger in age (range from 65-73 years; M=66 years; SD 2.19) than the 13 participants who required an individualized noise adjustment (range from 64-76, M=71; SD 3.96). Aside from the significant age difference [t(23)=-3.845, p=.001], there was no significant difference on the cognitive screening results from the MoCA [t(23)=-1.983, p=.059] and, after the level setting procedure there was no significant difference on single task word recognition ability between the two groups of older adults [t(23)=.137, p=.892]. As a result, we collapsed the data together from both sub-groups of older adults for all further analysis to compare with young adults.

Means and standard deviations for the dual task and working memory measures for young and older adults are displayed in Table 2. All dual task measures (i.e., word task percent correct and response time, tactile task percent correct and response time) are

Table 2. Means and standard deviations for dual task and working memory measures

	YA (n=25)		OA (n=25)		t(48)	p
	Mean	SD	Mean	SD		
Dual Task Measures (pDTC)						
Tactile Task - Accuracy	18.28	13.66	28.27	14.28	-2.527	0.015
Tactile Task - Response Time	-45.48	51.91	-75.36	67.74	1.750	0.086
Word Task - Accuracy	3.07	8.21	4.52	7.09	-0.671	0.506
Word Task - Response Time	-20.49	18.75	-16.38	14.74	-0.861	0.393
Working Memory Measures						
Span Size	5.00	0.82	4.52	0.59	2.388	0.021
Alphabetical Recall	6.80	1.44	7.13	1.55	-0.784	0.437
Direct Recall	8.28	1.05	8.53	1.13	-0.770	0.445

Note: pDTC = Proportional Dual Task Cost presented as proportional dual task costs (pDTC) where pDTC= ((single task – dual task)/single task*100). For the response time data, the mean correct response time for both the word and tactile task was calculated for each participant under single and dual task conditions and used in the pDTC measure. "Cost" refers to the cost of doing two tasks together compared to single task performance. The smaller the difference between single and dual task performance, the less the resulting dual task cost. As had been reported with our previous study (Anderson Gosselin & Gagné, 2011), even when single task word recognition ability was equated between groups, based on the tactile task pDTC accuracy results [t(48)=-2.527, p=.015] older adults expended significantly more listening effort than young adults. These results are consistent with previous research which suggests that older adults require more processing resources to recognize speech in noise which in turn leaves less resources available for the concurrent secondary task (Chisolm, Willot, & Lister, 2003; Kricos, 2006; McCoy et al., 2005; Salthouse, 1988; Tun, Benichov, & Wingfield, 2008; Wingfield & Tun, 2001, 2007). In addition, the working memory measures indicate that young adults had significantly longer span sizes than older adults [t(48)=2.388, p=.021]. With direct and alphabetical recall assessed at each participants word span, there were no significant differences between the groups (see Table 2).

Correlation results

To examine the relationship between the listening effort involved with word recognition under dual task conditions and auditory working memory, Pearson correlations were calculated between the pDTCs for each dual task measure and each auditory working memory measure for young and older adults as shown in Table 3. To control for Type I error, the conservative Bonferroni significance criterion for multiple comparisons was adopted. While several correlations did achieve the criterion of p=.002, all significant correlations (i.e., p<.05) are interpreted in the following text along with exact p values.

Table 3. Pearson correlations between the pDTC of each dual task measure and working memory measure for 25 young adults (YA) and 25 older adults (OA)

		Dual Task Measures				**Working Memory Measures**		
		Tactile - Acc	Tactile - RT	Word - Acc	Word - RT	Span Size	Alphabetical Recall	Direct Recall
Age	YA	0.144	-0.160	-0.061	-0.353	-0.127	0.101	0.303
	OA	-0.035	0.025	-0.208	0.205	0.220	-0.331	-.526**
Tactile - Accuracy (Acc)	YA		-0.129	0.332	0.239	-.516**	0.359	0.071
	OA		-.584**	-0.124	0.342	-0.010	0.025	-0.142
Tactile - Response Time (RT)	YA			-0.092	-0.158	.497*	-0.227	-0.271
	OA			0.346	-0.352	0.045	-0.134	-0.036
Word - Accuracy (Acc)	YA				-0.243	-0.360	.591**	0.160
	OA				-.451*	0.112	-0.295	0.085
Word - Response Time (RT)	YA					-0.180	-0.201	-0.258
	OA					-0.152	0.084	-0.059
Span Size	YA						-0.363	-0.287
	OA						-0.339	-.544**
Alphabetical Recall	YA							0.320
	OA							.588**

Note: * p< .05, ** p < .01

Young adult correlation results

From the analyses of young adults, three significant correlations between the dual task and working memory measures emerged: two correlations involved span size and the third involved alphabetical recall. Span size was negatively correlated with the pDTCs for tactile task accuracy (r=-.516, p=.008) indicating that the longer one's span size, the less "cost" associated with tactile task accuracy performance under dual task conditions (see Figure 1a). Span size was also positively correlated with tactile task response time (r=.497, p=.011). Owing to the pDTC formula, which generates a negative pDTC for response time measures, this correlation also indicates that the longer one's span size, the less "cost" associated with the tactile task response time performance under dual task conditions (see Figure 2a). Taken together these results suggest that under dual task conditions, young adults with long span sizes are both more accurate and faster in their tactile task performance under dual task conditions relative to those with short span sizes. The third relationship showed that alphabetical recall was positively correlated with the pDTCs for word task accuracy (r=.591, p=.002) indicating that the higher one's alphabetical recall ability, the more cost associated with dual task word accuracy.

Older adult correlation results

For older adults, there were no significant correlations between the dual task and working memory measures. However, within the working memory measures, span size was negatively correlated with direct recall (r=-.544, p=.005), indicating that the longer one's span size the lower their direct recall ability. In addition, direct recall was positively correlated with alphabetical recall (r=.588, p=.002) which suggests that higher direct recall ability was associated with higher alphabetical recall ability. Within the dual task measures, we found significant negative correlations between the accuracy pDTCs and response time pDTCs for each task. The pDTCs for tactile task accuracy was negatively correlated with the pDTCs for tactile task response time (r=-.584, p=.002) and the pDTCs for word task accuracy was negatively correlated with the pDTCs for word task response time (r=-.451, p=.024). Again, given the negative result for the pDTC response time

Figure 1a

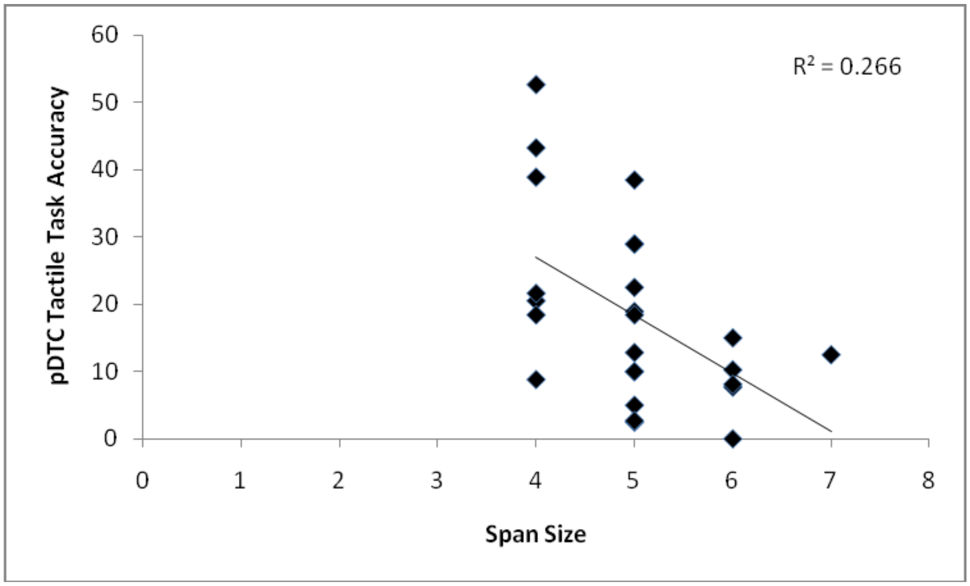

Figure 1b

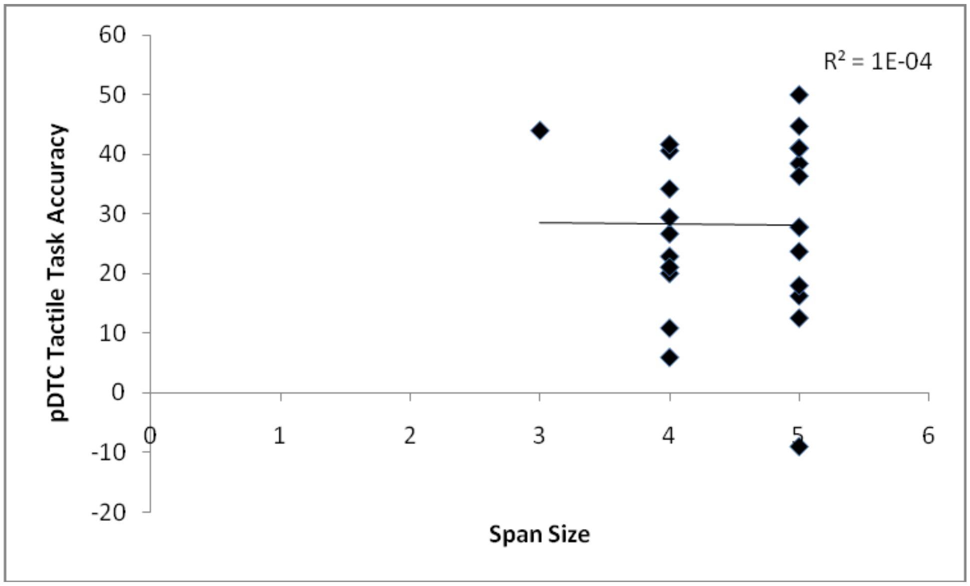

Figure 1. Scatter plot of proportional dual task cost tactile accuracy vs. span size for young adults (panel a) and older adults (panel b).

Figure 2a

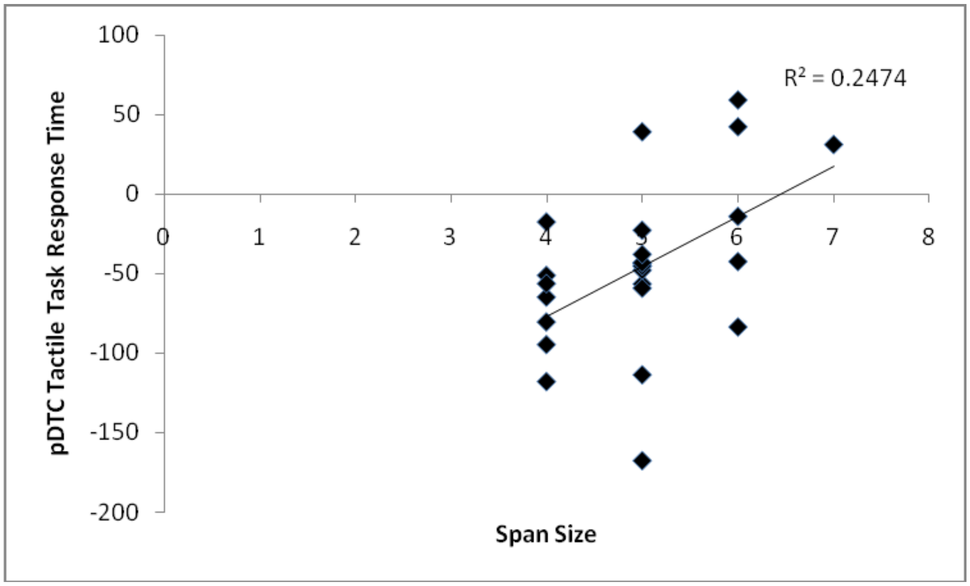

Figure 2b

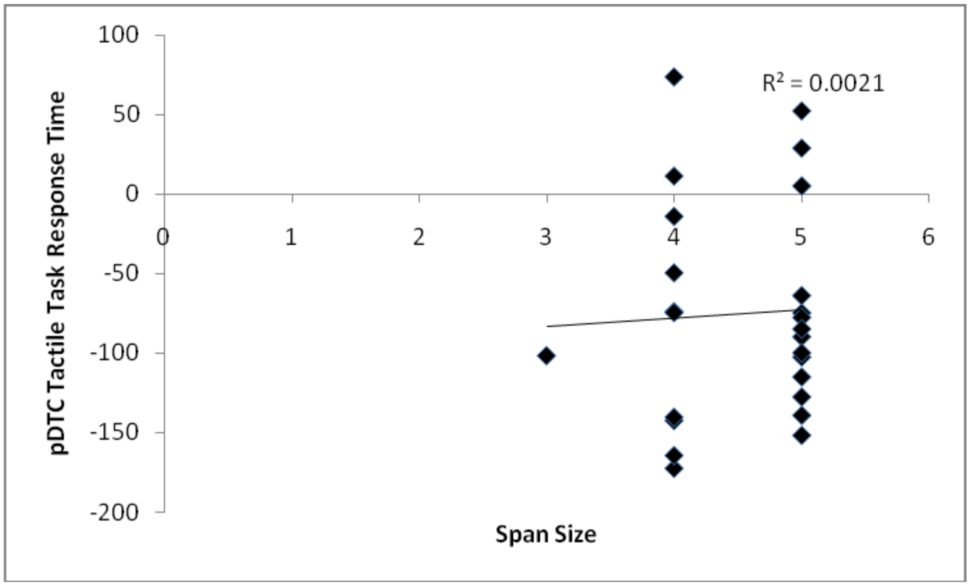

Figure 2. Scatter plot of proportional dual task cost tactile response time vs. span size for young adults (panel a) and older adults (panel b).

calculations, both of these correlations indicate that for each task, high costs on accuracy are associated with high costs on response time. There is no evidence of a speed accuracy trade-off for either task. For the older adults, the only variable that significantly correlated with age was direct recall (r=-.526, p=.007), which suggests that direct recall ability declines as one ages.

Regression results

While the dual task results indicated that older adults expended significantly more listening effort than young adults (see Table 2), a regression analysis conducted on the data of all 50 participants revealed that age alone only accounted for 11.9% of the variance on the pDTC's for tactile task accuracy. Aside from age, to account for the variability in listening effort and dual task performance observed in Table 2, additional regression analyses were conducted for young and older adults using the working memory measures as predictors. Given the collinearity observed amongst the three working memory predictor variables (i.e., span size, alphabetical recall and direct recall) for older adults (see Table 3), to determine the unique variance of each working memory measure a sequential multiple regression analysis was conducted. Priority of entry for the predictors was specified with span size entered first, alphabetical recall entered second, and direct recall entered last. The results of the regression analyses are shown in Table 4.

The predictor variable order was determined by a preliminary stepwise regression analysis which showed that span size accounted for the greatest amounts of variance in listening effort as indicated by secondary task performance. To test whether the order of entry influenced the results, secondary regression analyses were conducted with the predictor variables entered in the following order: alphabetical recall, direct recall and span size. These results also indicated that span size still contributed a significant proportion of variance in the listening effort of younger adults. In addition, the semi partial correlations were calculated to determine the unique variance that each working memory measure contributed. Regardless of order entry, the semi partial correlations were equivalent and are reported below.

Table 4. Regression analyses showing effect of oral working memory on proportional dual task measures by age

Tactile Task - Accuracy

		Young Adults (n=25)			Older Adults (n=25)		
		β	R^2	ΔR^2	β	R^2	ΔR^2
Step 1	Span Size	-0.471	0.266	0.266**	-0.119	0	0
Step 2	Alpha Recall	0.232	0.300	0.034	0.163	0.001	0.001
Step 3	Direct Recall	-0.139	0.317	0.017	-0.303	0.048	0.048

Tactile Task - Response Time

		Young Adults (n=25)			Older Adults (n=25)		
		β	R^2	ΔR^2	β	R^2	ΔR^2
Step 1	Span Size	0.451	0.247	0.247*	0.032	0.002	0.002
Step 2	Alpha Recall	-0.020	0.250	0.002	-0.171	0.018	0.016
Step 3	Direct Recall	-0.136	0.266	0.016	0.082	0.021	0.004

Word Task - Accuracy

		Young Adults (n=25)			Older Adults (n=25)		
		β	R^2	ΔR^2	β	R^2	ΔR^2
Step 1	Span Size	-0.181	0.130	0.130	0.209	0.012	0.012
Step 2	Alpha Recall	0.546	0.374	0.244**	-0.521	0.087	0.075
Step 3	Direct Recall	-0.066	0.377	0.004	0.505	0.220	0.133

Word Task - Response Time

		Young Adults (n=25)			Older Adults (n=25)		
		β	R^2	ΔR^2	β	R^2	ΔR^2
Step 1	Span Size	-0.346	0.032	0.032	-0.257	0.023	0.023
Step 2	Alpha Recall	-0.237	0.114	0.082	0.173	0.024	0.001
Step 3	Direct Recall	-0.281	0.182	0.068	-0.301	0.071	0.047

Note: * $p < .05$, ** $p < .01$

Tactile task performance

For young adults, the predictor span size accounted for a significant 26.6% of the variance on the pDTCs for tactile task accuracy and 24.7% of the variance on the pDTCs for tactile task response time performance (see ΔR^2 values in Table 4). Further analyses of the semi partial correlations revealed that the unique variance contributed by span size was 18% for the pDTC tactile task accuracy results (p=.026) and 17% for the pDTC tactile task response time results (p=.039). In contrast, for older adults, the predictor span size did not significantly account for any of the variance on the pDTCs for tactile task accuracy or response time performance. The results of the first step of the regression analyses showing the contribution of span size as a predictor of pDTC tactile task accuracy are shown in Figure 1, for young and older adults. Similarly, Figure 2 shows the contribution of span size as a predictor of pDTC tactile task response time for young and older adults. Other than span size, alphabetical recall and direct recall did not contribute significantly to explaining any additional variance on the pDTCs for tactile task accuracy or response time measures for young adults (see Table 4). In addition, for older adults, none of the working memory predictor variables accounted for a significant proportion of variance on either pDTC tactile task accuracy or response time performance (see Table 4).

Word task performance

In terms of the cost involved with word task accuracy performance, the only predictor to contribute towards a significant amount of variance was alphabetical recall. For young adults, beyond span size, alphabetical recall accounted for a significant additional 24.4% of variance on the pDTCs for word task accuracy (see ΔR^2 values of Table 4). In addition, the semi partial correlations revealed that the unique variance significantly contributed by alphabetical recall was 24% for young adults (p=.009). Beyond alphabetical recall, direct recall did not contribute significantly towards additional variance on word task accuracy performance for young adults (see Table 4). For older adults, none of the working memory predictor variables accounted for a significant proportion of variance on the pDTCs for word task accuracy (see Table 4). In contrast, for word task response time performance, none of the working memory predictor variables accounted for a significant proportion of the pDTCs for young or older adults (see Table 4).

Discussion

The most important result of this study is that a measure of auditory memory *capacity* (span size) can be a good predictor of listening effort for young adults. Furthermore, when storage capacity is controlled and recall is assessed at each participants word span (i.e., the longest sequence correctly recalled on 50% of the trials), a measure of *processing* (alphabetical recall) can predict the costs associated with young adults word task accuracy performance under dual task conditions.

Listening effort and span size

Our previous study (Anderson Gosselin & Gagné, 2011) demonstrated that even when single task word recognition ability was equated, older adults still expended increased listening effort compared to young adults as shown by higher pDTC's for tactile task accuracy performance (see Table 2). However, age alone only accounted for 11.9% of the variance on the pDTCs for tactile task accuracy. This led us to consider if our working memory measures could account for the variance observed on listening effort and the costs associated with dual task performance. As expected, our working memory measures indicated that young adults had significantly longer span sizes than older adults (Belleville et al., 1998; Salthouse, 2004). Using span size, alphabetical recall and direct recall as predictors of dual task performance, results of our sequential multiple regression analysis indicated that span size was the only working memory measure to account for a significant proportion (~ 25%) of variance on young adults listening effort (see Table 4). These regression results were consistent with the correlation findings obtained for young adults (see Table 3) which indicated that long span sizes were associated with lower costs on tactile task accuracy and response time performance (see Figures 1 and 2).

Clinically, these results suggest that span size is related to the listening effort of young adults (as measured by the pDTC's on tactile task accuracy and response time). Unlike working memory span which taps the combined processing and storage capacity of working memory, the span size measure used in the current study is a measure of short-term memory capacity only (Daneman & Carpenter, 1980). Working memory span measures have been shown to be better predictors of reading and *listening comprehension* ability than measures that tap storage capacity alone (Daneman & Merickle, 1996). The current study demonstrates that a traditional span size measure is a good predictor of the costs associated with the construct *listening effort.* That is, under dual task conditions the short-term memory capacity measured by span size is associated with the capacity of resources remaining for secondary task processing – at least for young adults.

Aside from the clinical significance of the span size findings, the results of this study are also interesting on a theoretical basis as the relationship between span size and listening effort was not observed among the older adults (see Table 4). As shown graphically in the lower panels of Figures 1 and 2, span size did not account for a significant proportion of the listening effort expended by older adults, even though span size was the only memory measure to demonstrate a statistically significant age difference (see Table 2). Span size significantly declined with age and yet was not associated with significant age-related increases in listening effort. This suggests that the listening effort of older adults may depend on a different aspect of working memory (not assessed with the current study) or may be more sensitive to a measure of attention (Craik & Byrd, 1982) or processing speed (Salthouse, 1996).

An alternative view is that older adults may have relied on a different process or compensation strategy when engaged in dual task processing. Neuroanatomical evidence supports the view that older adults use different processes compared to young adults to maintain a comparable level of speech understanding performance. Relative to young adults, older adults show a more widespread cortical activation pattern involving the areas associated with working memory and executive function (Grady, 1998, 2000; Wingfield & Grossman, 2006). The more widespread activation pattern may reflect a reliance on the part of older adults to use context (i.e., top-down processing) as a strategy to compensate for difficult listening situations (Cazeba, Anderson, Locantore, & McIntosh, 2002; Pichora-Fuller & Singh, 2006).

Dual task word recognition and alphabetical recall

As shown in Table 2, significant age-related differences did not emerge on either direct or alphabetical recall ability. These results are consistent with those of Belleville et al. (1998), as the current study also controlled for varying storage capacities by assessing direct and alphabetical recall at each participants word span (i.e., the longest sequence correctly recalled on 50% of the trials). By replicating the procedure used by Belleville et al. (1998), we also found that when storage was controlled, the usual age differences observed with traditional measures of working memory (Craik, 1986; Tun, Wingfield, & Stine, 1991) disappeared. Similar to the dual task literature (Somberg & Salthouse, 1982), these results suggest that older adults are not more impaired or disadvantaged in terms of their processing ability (as measured by alphabetical recall) provided the difficulty of the tasks is made comparable. Furthermore, as Belleville (1998) indicated, these results support the view that it is the capacity component rather than the processing component of working memory that appears to be a primary source of age-related impairment.

Results of our regression analyses indicated that alphabetical recall was the only working memory predictor variable to account for a significant proportion (24%) of variance on young adult's pDTCs for word recognition accuracy performance (see Table 4). These results suggest that a measure of *processing* ability (alphabetical recall) can predict the costs associated with word recognition accuracy performance under dual task conditions for young adults. The regression findings are consistent with the correlation results observed (see Table 3). Intuitively, one may expect that higher alphabetical recall ability would be associated with less costs when performing a word recognition task under dual task conditions (i.e., an efficient "processor" of information would have less dual task costs processing speech in noise) however, our results indicated the contrary. Higher alphabetical recall ability was associated with higher pDTCs for word recognition accuracy performance. One possible interpretation of these results is that higher alphabetical recall ability expends more resources and in so doing is associated with the costs involved with dual task word recognition accuracy performance.

The relationship between alphabetical recall and dual task performance was reported by Belleville et al. (1998). In an experiment designed to evaluate the validity of the alpha span processing task, Belleville et al. (1998) used a dual task paradigm to evaluate young adult's performance on both alphabetical recall and serial recall. The secondary task was a tracking task which involved maintaining a cursor within a diagonally moving rectangle. During 10 second intervals, ascending and descending series of speeds were presented until a speed that met the 70% performance criterion on the tracking task was determined. Unlike the current study, subjects were instructed to maintain accuracy on the secondary tracking task under dual task conditions. Relative to direct recall, the performance decline for alphabetical recall was larger under divided attention conditions than single task conditions. The authors concluded that alphabetical recall was more affected by divided attention than direct recall due to the greater involvement of the central executive in the performance of the processing task (alphabetizing their responses) rather than the more limited processing involved with passive serial recall. Performing a task that requires the central executive (alphabetical recall) is more problematic if the central executive is simultaneously involved in dual-task co-ordination. According to the theoretical framework originally proposed by Baddeley & Hitch (1974), the central executive of working memory refers to a limited capacity attentional system whose functions include: selective attention, co-ordination of concurrent activity, switching attention and retrieval of information from long term memory (Baddeley, 2002). The results of the regression analyses of the current study, lends support to the idea that the processing resources involved with alphabetizing responses for alphabetical recall and the co-ordination resources involved with word recognition in noise under dual task conditions both engage the central executive of working memory (Baddeley, 2002). However, these findings were limited only to young adults and did not extend to the case of older adults.

Conclusions

For young adults, the sequential regression analyses revealed that span size (a measure of storage *capacity*) predicted listening effort as measured by costs on tactile task performance with ~25% accuracy. The capacity measured by span size was associated with the capacity of resources remaining for tactile task processing. In addition, the alphabetical recall ability of young adults (a measure of *processing*) predicted the cost of dual task word recognition accuracy performance with 24% accuracy. These results support the idea that the processing involved with alphabetizing the responses for alphabetical recall as well as word recognition under dual task conditions – a situation which offers ecological validity – both draw upon resources from the central executive of working memory.

Taken together, for young adults each of the separate components of working memory (i.e., capacity and processing) were associated with listening effort and the cost of dual task word recognition accuracy performance respectively. However, neither of these relationships was replicated by older adults. Interestingly, even though span size significantly declined with age, span size was not associated with significant age-related increases in listening effort. Given recent evidence from neuroanatomical studies, to better understand what factors influence the listening effort involved with word recognition under dual task conditions for older adults, further studies using different cognitive measures that tap processing or compensatory strategy use (i.e., executive function) are needed (Cazeba et al., 2002; Grady, 1998, 2000; Wingfield & Grossman, 2006). For example, the Trail Making (TMT) Test (Reitan, 1979) and the Colour Form Sorting (CFS) Test (Goldstein & Scheerer, 1941) are known to tap the executive functions involved with shifting between response sets, learning from mistakes, devising alternative strategies, dividing attention and processing multiple sources of information (Anderson, 2002). It remains to be determined how tests of executive function, the so-called frontal lobe tests relate to listening effort.

Recognizing the significant contribution of non-auditory factors to the difficulties experienced when listening in challenging situations and environments, underscores the need to develop clinical tests that will allow us to better understand the inter-relationship between auditory and cognitive processes.

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Chapter 3

General discussion

The purpose of the current set of studies was to quantify and compare the amount of listening effort that young and older, normal-hearing adults with normal (or corrected normal) vision expend when speech is presented in background noise. The focus of Study 1 (Article 2) was to determine the listening effort associated with auditory speech recognition (hearing a speaker), while Study 2 (Article 3) examined the listening effort involved with audiovisual speech recognition (hearing and seeing the face of a speaker). Listening effort was measured behaviourally using a dual task paradigm, in which a word recognition task was paired with a tactile pattern recognition task. For both studies, word recognition was investigated under two experimental conditions: 1) equated level – where the noise level of the speech task was the same for all participants and, 2) equated performance – where single task word recognition ability did not differ between the groups. As indicated by the cost associated with tactile task performance under dual task conditions, the results revealed that older adults expended more listening effort than young adults to recognize speech under both experimental conditions (i.e., equated-noise level and equated-performance level) whether speech was presented in an audio-only condition or audiovisually. Furthermore, the results of Study 2 (Article 3) suggested that the processing demands of audiovisual speech recognition were greater than those of audio-alone speech recognition. Listening effort was also evaluated with self-reported ratings of each task when performed concurrently. The results of Study 1 and Study 2 suggested that dual task measures and self-reported ratings each assess different aspects of listening effort. As listening effort involves both auditory and cognitive factors, the goals of Study 3 (Article 4) were to quantify to what extent auditory working memory measures obtained from the Alpha Span Test (Belleville et al., 1998) contribute towards the variance observed in listening effort and to determine if different patterns of the working memory predictor variables (capacity and processing measures) would emerge across the age groups. For young adults, span size, a measure of *capacity* accounted for roughly 25% of the variance in listening effort while alphabetical recall, a measure of *processing* accounted for roughly 24% of the variance for the cost associated with word recognition accuracy performance under dual task conditions. However, neither of these relationships extended to the data obtained by older adults.

Dual task findings

The dual task results obtained from Study 1 and Study 2 clearly demonstrated that older adults expend more listening effort than young adults. For the equated level condition, a fixed signal to noise ratio was presented to all participants to quantify the effort required to listen under comparable conditions between groups. For both tasks, the absolute data revealed that older adults had lower percent correct scores and longer response times regardless of presentation modality (audio-only or audiovisual). Using a stringent measure of cost, relative data were used to compare across the age groups and between the two experimental conditions by calculating the proportional dual task cost (pDTC = (dual task – single task)/single task) for each dependent variable under study. The results of both Study 1 and Study 2 revealed that older adults exerted increased listening effort compared to young adults as shown by significantly larger pDTC's for the concurrent tactile task accuracy and response time measures. Although a medium effect size (Tabachnick & Fidell, 2007) was obtained for each age-related significant difference in listening effort for both studies, the effect sizes were slightly larger with audiovisual speech recognition than audio-only speech recognition. For example, the effect sizes of the pDTCs for tactile task accuracy performance were as follows: audiovisual speech recognition (ηp2=.22) compared to audio-only speech recognition (ηp2=.186). Similarly the effect sizes of the pDTCs for tactile task response time performance were: audiovisual speech recognition (ηp2=.158) compared to audio-only speech recognition (ηp2=.128). However, from these dual task findings, it was not clear whether the differences observed could be attributed to an age effect or if the discrepancies between groups on single task word recognition influenced the dual task results. In other words, relative to young adults, older adults may have found the task was more "effortful" simply because it was more difficult from the beginning as demonstrated by their poorer single task word recognition scores. To tease these possibilities apart, we investigated an equated performance condition in which baseline word recognition ability was equated between the groups. To ensure that older adults performed the word task under single task conditions at the same average accuracy level as young adults (i.e. approximately 80%), the noise level was individually attenuated as required. Importantly, even when performance was equated, using relative data to compare across the age groups, the results revealed that older adults still exerted increased listening effort compared to younger adults. Older adults showed significantly larger pDTC's for the tactile task accuracy measure in Study 1 (ηp2=.117) and the tactile task response time measure in Study 2 (ηp2=.128). The medium effect sizes observed (Tabachnick & Fidell, 2007) were generated for both age-related significant pDTC differences on tactile task performance.

Taken together, the results of both experimental conditions suggest that older adults require more resources to recognize speech, leaving less resources available for the tactile task (Broadbent, 1958; Kahneman, 1973). Based on research drawing on capacity theory and the availability of attentional resources, age-related differences on secondary task processing under dual task conditions are supported in the literature (Chisolm et al., 2003; Kahneman, 1973; Kricos, 2006; McCoy et al., 2005; Salthouse, 1988; Tun et al., 2008; Wingfield & Tun, 2001, 2007). Studies involving young adults that have examined the listening effort associated with speech understanding abilities have demonstrated similar decrements in secondary task performance under dual task conditions (Bourland-Hicks & Tharpe, 2002; Broadbent, 1958; Downs, 1982; Downs & Crum, 1978; Feuerstein, 1992; Fraser et al., 2010; Rabbitt, 1966; Rakerd et al., 1996). Study 1 extends these results to include the listening effort of older adults and Study 2 extends to the specific case of the effort involved with audiovisual speech recognition by older adults.

In addition to the age-related differences observed on tactile task performance, age-related differences on the speech recognition task also emerged for Study 2. Specifically, for the equated level condition a medium effect size was observed wherein older adults showed significantly larger pDTCs for the word task accuracy measure than young adults (ηp2=.138). These results suggest that despite the addition of visual cues there is a greater cost associated with audiovisual word recognition in noise for older adults compared to young adults. When audiovisual speech is presented with competing noise, processing resources are needed to: 1) extract speech information from noise, 2) extract cues available from the visual speech signal and, 3) integrate the degraded auditory speech with the redundant and/or complementary cues offered from the visual speech information. The combination of resources required likely exceeded the overall processing capacity of older adults with significant performance costs for both tasks relative to young adults (Broadbent, 1958; Kahneman, 1973).

Comparing the results of Study 1 with Study 2 in general, the accuracy pDTCs were larger in Study 2 when speech was presented audiovisually compared to Study 1 where speech was presented in an audio-alone condition (see Figure 1). Results of all statistical comparisons using an ANOVA with two between subject factors (Study: audio-only speech (Study1) vs. audiovisual speech (Study 2) and, Age: young adults vs. older adults) are summarized in Table 1. For the equated level condition, with the addition of visual cues significantly larger pDTC differences emerged on the accuracy measures for both the speech recognition task (ηp2=.120) and the tactile task (ηp2=.072) relative to audio-only speech recognition (see Table 1a). Although the effect sizes were smaller, a similar pattern emerged for the equated performance condition such that the pDTCs for word task accuracy (ηp2=.091) and tactile task accuracy (ηp2=.042) were both significantly larger when speech was presented audiovisually compared to an audio-alone condition (see Table 1b). Consistent with previous research, the results of Study 1 and Study 2 suggest that the processing demands of audiovisual speech are greater than audio-only speech (Alsius, Navarra, & Soto-Faraco, 2007; Fraser et al., 2010) and extend these findings to demonstrate that the largest costs to performance are experienced by older adults when presented with audiovisual speech. Fraser et al. (2010) found that while visual cues can improve audiovisual speech recognition performance, they may also place an extra demand on processing resources depending on the level of background noise. Additionally, Alsius

Figure 1a

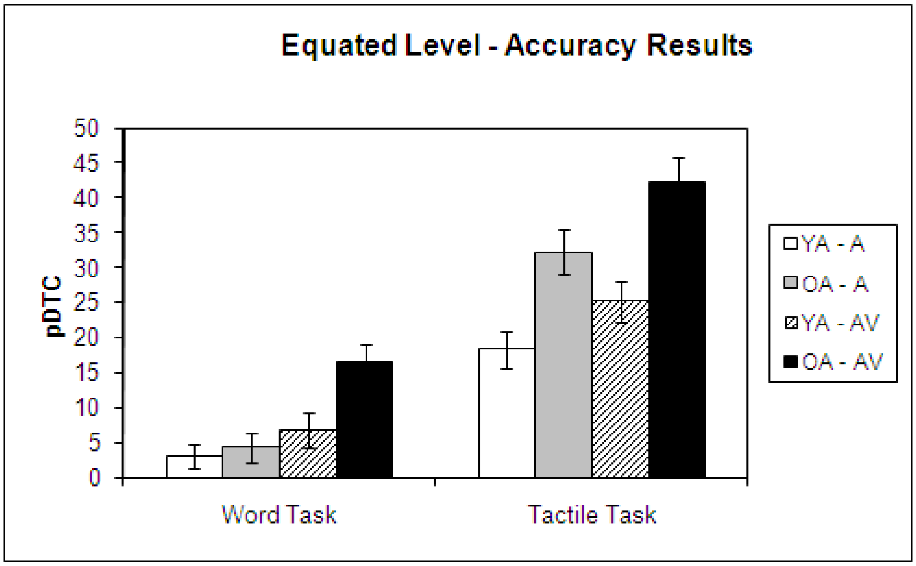

Figure 1b

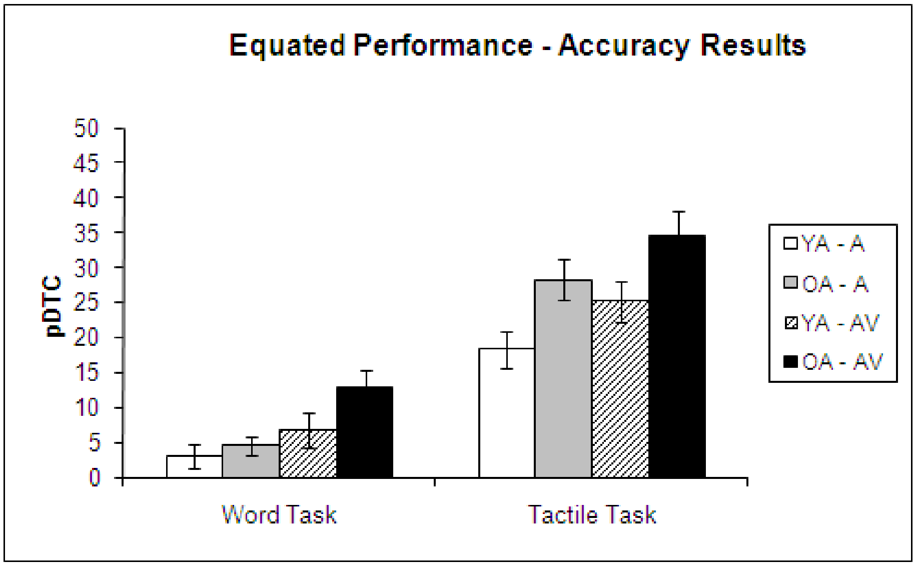

Figure 1. Accuracy results of word task and tactile task by a) equated level condition and b) equated performance condition.

Notes: pDTC = proportional dual task cost, YA = younger adult, OA = older adult, A – Audio-only speech presentation (Study 1), Audiovisual speech presentation (Study 2).

Table 1. ANOVA results summarizing effect of study and age by a) equated level condition and b) equated performance condition.

Table1a) Equated Level Results.

		F(1,96)	**p**	**ηp^2**	**Significance**
pDTC Word Task Accuracy	Study	13.046	0.000	0.120	*
	Age	6.192	0.015	0.061	*
	Study x Age	3.779	0.055	0.038	ns
pDTC Tactile Task Accuracy	Study	7.402	0.008	0.072	*
	Age	24.518	0.000	0.203	*
	Study x Age	0.241	0.625	0.003	ns
pDTC Word Task Response Time	Study	2.217	0.140	0.023	ns
	Age	1.818	0.181	0.019	ns
	Study x Age	0.002	0.964	0.000	ns
pDTC Tactile Task Response Time	Study	0.543	0.463	0.006	ns
	Age	16.039	0.000	0.143	*
	Study x Age	0.257	0.614	0.003	ns

Table 1b) Equated Performance Results.

		F(1,96)	p	ηp^2	Significance
pDTC Word Task Accuracy	Study	9.573	0.003	0.091	*
	Age	3.743	0.056	0.038	ns
	Study x Age	1.395	0.240	0.014	ns
pDTC Tactile Task Accuracy	Study	4.174	0.044	0.042	*
	Age	8.875	0.004	0.085	*
	Study x Age	0.008	0.927	0.000	ns
pDTC Word Task Response Time	Study	0.991	0.322	0.010	ns
	Age	3.990	0.049	0.040	*
	Study x Age	0.536	0.466	0.006	ns
pDTC Tactile Task Response Time	Study	0.492	0.485	0.005	ns
	Age	9.765	0.002	0.092	*
	Study x Age	0.476	0.492	0.005	ns

et al. (2007) demonstrated dual task costs on speech recognition when a tactile task was coupled with audiovisual speech but not with an audio-only or visual-only presentation of speech. The authors interpreted these findings as an indication that a tactile task can create crossmodal interference and disrupt audiovisual integration. While audiovisual integration was not explicitly studied within the scope of the current thesis, the results of Study 1 and Study 2 using different groups of participants provide limited support to the findings reported by Alsius et al. (2007). Further research to investigate the effect of adding visual cues with the same group of older adults would strengthen the argument that the binding of audiovisual information can be disrupted when demands are imposed by a concurrent tactile task.

Findings from self-reported ratings of effort

Overall, the correlation analyses conducted for Study 1 and Study 2 revealed that self-reported ratings of effort did not correlate with any of the dual-task measures irrespective of experimental condition or participant group. These findings are consistent with other studies that have included self-reported ratings of "effort" in their evaluation of young adults (Downs & Crum, 1978; Feuerstein, 1992; Fraser et al., 2010) and older adults (Larsby et al., 2005). Feuerstein (1992) reported that the lack of correlation supports the idea that the two measures assess different aspects of listening effort. For example, an individual who expends more listening effort is more likely to indicate that completing a speech recognition task in noise would be more difficult. However, it is also possible that expending more resources to recognize speech under difficult listening conditions may not be perceived as more effortful for some listeners (Wickens, 1992; Zekveld et al., 2010).

More recently Kuchinsky et al. (2011) offered the following insights to explain the limitations of self-reported ratings. First, the ratings are typically completed "offline" meaning at a time when the participant is no longer under the strain of the task. As a result, due to a period of retrospection the self-reported ratings may reflect an average perceived effort across many different conditions (Kuchinsky et al., 2011). Second, given the subjective nature of self-reported ratings, it is unknown what criteria people use to assess their listening effort (Edwards, 2009; Kuchinsky et al., 2011; Yeh & Wickens, 1988). This in turn makes the interpretation of self-reported ratings between different groups of listeners particularly difficult. For example, in Study 1 and Study 2, older adults did not report significantly higher effort ratings than young adults on either task under both experimental manipulations even though age-related differences in the tactile task pDTC's indicated that older adults expended significantly more listening effort than young adults for both studies under each experimental condition. In other domains, research has also shown that older adults tend to under-estimate their degree of difficulties compared to young adults (Ford et al., 1988; Uchida et al., 2003).

Despite the lack of consistency between self-reported ratings and dual task findings when drawing between group comparisons, self-reported ratings can be useful in the clinical domain where the focus is on individual client care. Research by Humes (1999) demonstrated that estimates of "sound quality or listening effort" represent unique aspects of hearing aid outcome which is separate from speech recognition performance measures. While intra-individual variability was not specifically addressed, within group comparisons were made with the subgroups of older adults that participated in both experimental conditions for Study 1 (n=13) and Study 2 (n=13). In general, the subgroups of older adults for each study revealed that self-reported ratings and dual task measures were sensitive to changes in listening effort between the equated level condition and the equated performance condition. Specifically, relative to the equated level condition, as the noise level was reduced the following significant changes were noted: the pDTCs for the tactile task decreased, self-reported word recognition accuracy ratings increased and, word effort ratings decreased. In effect, these results suggest that on average, older adults are capable of rating a listening task that is made easier (due to a reduction in background noise) as being "less effortful".

Relationship between dual task measures and working memory

The results of Study 1 demonstrated that even when single task word recognition ability was equated, older adults still expended increased listening effort compared to young adults as shown by significantly higher pDTC's for tactile task accuracy. A regression analysis conducted on the data of all 50 participants revealed that age alone only accounted for 11.9% of the variance in the pDTC's for tactile task accuracy. To account for the variability observed in the dual task results obtained from Study 1, separate regression analyses were conducted on the data of young and older adults using working memory measures from the Alpha Span test (i.e., span size, alphabetical recall and direct recall) as predictors of dual task performance (Belleville et al., 1998; Craik, 1977). The results of Study 3 revealed that span size, a measure of auditory memory *capacity,* was the only working memory measure to account for a significant proportion of variance on the pDTC's associated with tactile task accuracy and response time measures for young adults. For the young adults, these results suggest that span size can predict with roughly 25% accuracy listening effort. While previous research has shown that measures such as working memory span which tap the combined processing and storage capacity of working memory are superior predictors of *listening comprehension* ability (Daneman & Carpenter, 1980; Daneman & Merickle, 1996), Study 3 demonstrates that a measure of short-term memory capacity alone is a good predictor of *listening effort*.

Of theoretical significance is the fact that the relationship between span size and listening effort was not observed among the older adults. For the current study, span size was the only memory measure to decline with age and yet it was not associated with age-related increases in listening effort. These results suggest that the listening effort of older adults may involve a different aspect of working memory (not assessed with the current study), attention (Craik & Byrd, 1982) or processing speed (Salthouse, 1996). Alternatively, older adults may have relied on a different process or compensation strategy when engaged in dual task processing. Neuroanatomical research lends support to the idea that older adults use different processes compared to young adults to maintain a comparable level of speech understanding performance. Relative to young adults, the cortical areas associated with working memory and executive function are used to a greater extent by older adults (Grady, 1998, 2000; Wingfield & Grossman, 2006). The more widespread activation pattern observed in older brains may be reflective of compensatory processing such as using context (i.e. top-down processing) to make up for challenging listening situations (Cazeba, Anderson, Locantore, & McIntosh, 2002; Pichora-Fuller & Singh, 2006).

In contrast, a measure of *processing* - alphabetical recall accounted for a significant proportion (24%) of variance on young adult's pDTC's for word recognition accuracy performance. These results suggest that alphabetical recall can predict the costs associated with word task accuracy performance under dual task conditions for young adults. In addition, similar to the research by Belleville et al. (1998), the regression results of Study 3 lend further support to the idea that the alphabetizing involved during alphabetical recall and the co-ordination associated with listening in noise under dual task conditions – a situation which offers ecological validity – both draw upon the central executive of working memory for young adults (Belleville et al., 1998). However, the relationship observed between alphabetical recall and word task accuracy performance under dual task conditions did not extend to older adults. As with the previous findings involving span size, the alphabetical recall results suggest that older adults may have relied on a different cognitive process or compensation strategy when engaged in dual task processing.

To determine if the relationships observed with auditory working memory could be extended to the case of audiovisual speech recognition (Study 2), we repeated the same analysis sequence. Even with the addition of visual cues, Study 2 demonstrated that under the equated performance condition, older adults expended more listening effort than young adults as shown by significantly larger pDTC's for the tactile task response time measure. Using the data from all 50 participants, a subsequent regression analysis of the tactile task response time pDTC's indicated that age accounted significantly for 14% of the total variance observed. However, unlike Study 3, results of the separate multiple regression analyses conducted on the young and older adult data revealed that none of the working memory predictors contributed a significant proportion of variance to any of the pDTC measures (see Table 2). In addition, there were no significant correlations amongst the dual task and working memory measures (see Table 3). These results are consistent with those

Table 2. Regression analyses showing effect of auditory working memory on proportional dual task measures by age for Study 2

Tactile Task - Accuracy

		Young Adults (n=25)			Older Adults (n=25)		
		β	R^2	ΔR^2	β	R^2	ΔR^2
Step 1	Span Size	-0.311	0.141	0.141	0.262	0.017	0.017
Step 2	Alpha Recall	-0.010	0.144	0.002	0.060	0.039	0.023
Step 3	Direct Recall	0.121	0.150	0.007	0.230	0.070	0.031

Tactile T**ask - Response Time**

		Young Adults (n=25)			Older Adults (n=25)		
		β	R^2	ΔR^2	β	R^2	ΔR^2
Step 1	Span Size	0.173	0.066	0.066	-0.047	0.036	0.036
Step 2	Alpha Recall	0.160	0.066	0	0.191	0.099	0.063
Step 3	Direct Recall	-0.296	0.105	0.039	0.171	0.116	0.017

Word Task - Accuracy

		Young Adults (n=25)			Older Adults (n=25)		
		β	R^2	ΔR^2	β	R^2	ΔR^2
Step 1	Span Size	0.163	0.032	0.032	0.310	0.067	0.067
Step 2	Alpha Recall	-0.112	0.035	0.003	-0.027	0.068	0.001
Step 3	Direct Recall	0.080	0.038	0.003	0.117	0.076	0.008

Word Task - Response Time

		Young Adults (n=25)			Older Adults (n=25)		
		β	R^2	ΔR^2	β	R^2	ΔR^2
Step 1	Span Size	-0.078	0.024	0.024	-0.428	0.117	0.117
Step 2	Alpha Recall	-0.398	0.033	0.010	-0.111	0.139	0.022
Step 3	Direct Recall	0.508	0.149	0.116	-0.104	0.145	0.006

Table 3. Pearson correlations between proportional dual task costs and working memory measures for 25 young adults (YA) and 25 older adults (OA) from Study 2

		Dual Task Measures				Auditory Working Memory Measures		
		Tactile - Acc	Tactile - RT	Word - Acc	Word - RT	Span Size	Alphabetical Recall	Direct Recall
Age	YA	.486*	-0.012	0.114	-0.125	-0.351	0.329	0.332
	OA	0.001	-0.357	-0.073	0.283	-0.317	-0.289	0.054
Tactile - Accuracy (Acc)	YA		-.567**	0.010	0.120	-0.376	0.249	0.296
	OA		-.418*	0.124	0.120	0.129	0.105	0.131
Tactile - Response Time (RT)	YA			-0.019	-0.355	0.256	-0.144	-0.283
	OA			0.323	-0.183	-0.190	0.297	0.297
Word - Accuracy (Acc)	YA				-.514**	0.179	-0.146	-0.094
	OA				-0.192	0.259	-0.057	-0.052
Word - Response Time (RT)	YA					-0.154	0.004	0.274
	OA					-0.342	-0.039	0.050
Span Size	YA						-.556**	-.584**
	OA						-0.302	-.501*
Alphabetical Recall	YA							.705**
	OA							.541**

Note: * p< .05, ** p < .01

of Zekveld et. al (2009) and Feld & Sommers (2009) and suggest that for a working memory measure to be predictive it must tap the same kind of process or skill as the dependent variable under study. For example, Zekveld et. al (2009) found that working memory capacity as measured by a spatial working memory test was not related to the speech comprehension benefit obtained from textual information. Similarly, using a multiple regression analysis, Feld & Sommers (2009) demonstrated that a measure of spatial working memory as opposed to a verbal working memory measure accounted for a significant proportion of the variance in lipreading ability. Given the association between spatial working memory and lipreading ability, it has yet to be determined if spatial working memory would be a better predictor of the effort associated with audiovisual speech recognition.

Limitations and future directions

Hearing sensitivity

For all studies of the current thesis, the hearing ability of young and older adults was screened at 25 dB HL at octave frequencies between 0.25 and 2.0 kHz, as well as at 3 kHz. While this means that our results are generalizable to healthy aging older adults, whom most clinical audiologists would regard as having age-related “normal hearing”, varying degrees of peripheral hearing loss above 3 kHz due to presbycusis may have influenced the speech recognition performance and listening effort results of older adults (Amos & Humes, 2007; Hull, 1995; Weinstein, 2002). To determine the magnitude of this effect, the specific hearing detection thresholds of all participants should be measured rather than screened, in future studies.

Beyond subtle differences in high frequency hearing sensitivity, it is well known that aging can affect many processes including the auditory temporal processing of neural-type presbycusis (Gates, 2009; Gates, Feeney, & Higdon, 2003; Pichora-Fuller & MacDonald, 2008). As a result, some older adults may have experienced increased difficulties understanding speech in noise without having any significant detection threshold elevations in the speech range. In this regard, an interesting aspect of Study 1 and Study 2 is that roughly half of the older adults required an individualized noise level setting to achieve the equated performance level criterion of 80% on single task word recognition ability. For those participants, individual differences in auditory temporal processing may have played a role (Gates, 2009; Pichora-Fuller & Singh, 2006). Future studies involving participants who experience difficulty due to auditory temporal processing vs. those who do not, would help determine the influence of this effect on listening effort.

In addition, future studies investigating the influence of age and hearing loss on listening effort would help to further extend the findings reported by Tun et. al (2009). Using a dual task paradigm Tun et. al (2009) paired a recall task with a visual tracking task and found that older adults with mild hearing loss exhibited more listening effort than young and older adults with normal hearing or young adults with mild hearing loss. As diagnostic tools become more readily available to easily identify the different subtypes of presbycusis, with future studies it would be interesting to investigate the combined influence of age and the different subtypes of presbycusis on listening effort (Gates, 2009; Schneider et al., 2010).

For those with hearing loss wearing amplification devices (i.e., hearing aids, assistive listening devices or cochlear implants), a variety of future studies could also be undertaken to learn how listening effort is influenced by binaural vs. unilateral fittings, as well as the effects of specific device settings involving compression in both the amplitude (i.e. digital noise reduction) or frequency (i.e., frequency lowering technologies) domains. Research has only begun to explore the complex inter-relationships involving cognitive ability, listening conditions and amplification device settings (Foo et al., 2007; Gatehouse & Akeroyd, 2006; Gatehouse et al., 2006; Lunner & Sundewall-Thoren, 2007; Rudner, Foo, Ronnberg, & Lunner, 2007; Sarampalis, Kalluri, Edwards, & Hafer, 2009). For example, Sarampalis et al. (2009) used a dual task paradigm to determine if the digital noise reduction (DNR) used in modern hearing aids reduces the listening effort needed when processing speech in background noise. The results revealed that the noise reduction algorithm did not improve the accuracy scores on a test of word recognition in noise across a range of SNRs. However, at the poorest SNR tested, the addition of noise reduction was shown to improve memory performance in Experiment 1, and reduce visual reaction times in Experiment 2. Taken together, these results suggest that noise reduction algorithms reduce listening effort and free up cognitive resources for other tasks (Sarampalis et al., 2009).

Vibrotactile sensitivity

One of the inclusion criteria for all studies of the current thesis was that participants had to pass the 80% minimum criterion on the tactile task when presented in isolation during the practice session. However, the vibrotactile sensitivity of participants was never assessed nor was any attempt made to equate the vibrotactile sensitivity of all participants. As a result, it is possible that the older adults may have had a poorer absolute sensitivity to the tactile pattern recognition task, which may in turn have influenced the results. While the exact influence of vibratory sensitivity is uncertain in the current studies, research involving tactile temporal processing has found that whether an older adult had good or poor vibratory sensitivity, it did not appear to have an effect on their temporal order judgements (Craig, Rhodes, Busey, Kewley-Port, & Humes, 2010). For this study, participants identified both the tactile pattern and order of presentation of three tasks: 1) two patterns presented to the same finger, 2) four patterns presented to the same finger and, 3) two patterns presented to different hands (i.e., one pattern to the right index finger and another pattern to the left index finger) (Craig et al., 2010). Despite these findings, future studies that plan to use a tactile pattern recognition task should consider evaluating and equating the vibrotactile sensitivity of all participants to rule out the possibility of this confounding effect. It has yet to be determined if the significant age-related differences would hold if the vibrotactile sensitivity of all participants was equated for the tactile task.

Tasks and stimuli employed for dual task and cognitive measures

The generalizability of the results from the current studies is limited by the specific tasks and stimuli that were chosen for both the dual task measures and the cognitive measures. With respect to the dual task paradigm, it remains to be determined with future study whether similar age-related differences in listening effort would be obtained with a different secondary task. The tactile pattern recognition task used in the current studies was explicitly chosen so as to not interfere with the auditory or visual modalities. Despite this, significant age-related differences on tactile task performance were noted for both experimental conditions with audio and audiovisual word recognition. Future studies using a secondary task that involves the auditory or visual domains would likely generate increased dual task costs. In general, by incorporating a secondary task which does not involve the same perceptual modality as the one used for the primary task, the possibility of structural interference is decreased (i.e., overlapping demands due to the same perceptual system) and the effects of capacity interference can be analyzed (Kahneman, 1973).

As for the competing noise for the word recognition task, speech shaped noise (i.e. pink noise) was used as the masker for all studies. Previous investigators have demonstrated that older adults in particular are more disadvantaged than young adults with background noise that fluctuates or contains meaningful content (Larsby et al., 2005). Notwithstanding this finding, the studies of the current thesis were still able to establish age-related differences in listening effort using a continuous noise source. For ecological validity, it would be of interest to replicate the current studies using a multitalker babble background. While significant age-related differences would still be anticipated, the effect sizes would likely increase.

In terms of the cognitive measures employed in Study 3, our results are limited to the Alpha Span test (Belleville et al., 1998; Craik, 1977) and how that test of auditory working memory was conducted. For Study 3 which involved audio-only speech recognition, a relationship between listening effort and span size as well as between the pDTCs of word recognition ability and alphabetical recall was demonstrated for young adults. However, these results did not extend to the specific case of audiovisual speech recognition or to older adults. Given the connection reported by Feld & Sommers (2009) between spatial working memory and lipreading ability, future studies involving spatial working memory may reveal that it is a better predictor of the variance associated with the effort involved in audiovisual speech recognition than auditory working memory. Additionally, future studies involving tests that tap different cognitive processes or compensatory strategy use (i.e., executive function) are needed to better understand what factors influence the listening effort of older adults. For example, both the Trail Making (TMT) Test (Reitan, 1979) and the Colour Form Sorting (CFS) Test (Goldstein & Scheerer, 1941) address the *cognitive flexibility* domain of executive function which according to Anderson (2002) encompasses "the ability to shift between response sets, learn from mistakes, devise alternative strategies, divide attention and process multiple sources of information."

Practice effects

Given that the order of presentation of the equated level vs. equated performance condition was not counterbalanced for Study 1 and Study 2, we cannot entirely rule out the possibility of a practice effect. Specifically, the reduction in listening effort observed for the subset of older adults that participated in both experimental conditions for each study could have been influenced by practice as each of these participants all had experience with the equated level condition prior to the equated performance condition. We hypothesized that if practice was indeed an issue that we would see gains in accuracy and reductions in response time if we compared the first 10 vs. the last 10 trials during the dual task blocks. Under both experimental conditions we found that there were no significant differences in the first 10 or last 10 trials in terms of word task accuracy and response time or tactile task accuracy and response time results. These results suggest that performance during both experimental conditions was stable throughout the 40 dual task trials for both Study 1 and 2. To rule out the effects of practice and fatigue, future studies should counterbalance the equated level vs. equated performance condition. In addition, if the current studies were to be replicated, rather than establishing an exemption for participants that achieved the criterion level of performance, to facilitate the counterbalancing of conditions, all participants should undergo the same level setting procedure to determine the appropriate noise level followed by the experimental tasks for the equated performance condition.

Conclusion

In conclusion, the results of the current dissertation highlight the relationship between speech processing and cognition when young and older adults perform a speech recognition task in noise. The dual task results of Study 1 (Article 2) and Study 2 (Article 3), demonstrated age-related increases in listening effort for both the equated level condition and the equated performance condition regardless of the modality used for speech presentation (i.e., audio-only and audiovisually presented speech). Importantly, the clinical message to be derived from this body of research for hearing healthcare practitioners is that equal word recognition performance does not guarantee equivalent amounts of listening effort as demonstrated by the results from the equated performance condition for both Study 1 and Study 2. In general, even when the level of noise was individually attenuated as required for older adults to ensure a similar level of single task word recognition performance, older adults still exerted more listening effort than young adults.

While the current studies involved young and older adults with normal hearing sensitivity and normal (or corrected normal) vision, extending our results to those of the general population with hearing loss, we would expect the age-related differences in listening effort observed in Study 1 and Study 2 to be exacerbated. Dual task research conducted by Tun et al. (2009) that paired a recall and visual tracking task together lends support to this prediction. Under dual task conditions, Tun et. al (2009) showed that older adults with mild hearing loss had the poorest recall and highest concurrent tracking costs compared to young and older adults with normal hearing or young adults with mild hearing loss. Similar to the information processing theory proposed by Kahneman (1973) the results of Tun et. al (2009) emphasize the influence of hearing loss at the sensory-perceptual level such that if more resources need to be directed to auditory perception, less resources are available for higher level cognitive tasks (i.e. recall).

The importance of the present findings as well as those reported by Tun et. al (2009) is that they demonstrate how a dual task paradigm can provide a performance index sensitive to one's cognitive capacity and availability of processing resources to differentiate groups of listeners on the basis of age and/or hearing loss (Broadbent, 1958; Kahneman, 1973). In situations where word recognition scores are equivalent, dual task measures can provide an alternative – a measure of listening effort.

Comparing the results of Study 1 vs. Study 2, significantly higher pDTCs emerged for both the word recognition and tactile tasks when visual cues were available (Study 2) compared to an audio-alone presentation of speech (Study 1) under both experimental conditions. The cost in performance was highest for older adults when speech was presented audiovisually. These results suggest that while visual cues can improve audiovisual speech recognition (Grant & Braida, 1991; Macleod & Summerfield, 1987; Macleod & Summerfield, 1990; Sumby & Pollack, 1954), they can also place an extra demand on processing resources with performance consequences for the word and tactile tasks under dual task conditions (Fraser et al., 2010). In addition, though different groups of participants were involved in Study 1 and Study 2, our combined results provide limited support to the finding that a difficult tactile task can cause crossmodal interference and disrupt the binding of audiovisual information (Alsius et al., 2007).

Despite the potential performance cost involved with processing visual cues with competing background noise, lipreading and speech reading should still be advocated especially for those with hearing loss (Fraser et al., 2010; Legault, Gagné, Rhoualem, & Anderson Gosselin, 2010; Rigo, 1986). Dual task research that paired lipreading with an auditory processing task found that under dual task conditions performance costs were significantly less for highly proficient speech-readers (Rigo, 1986). In addition, research from our lab has shown that visual cues enhance speech understanding in noise, even in situations where visual acuity is not optimal (Legault et al., 2010).

In terms of self-reported ratings of listening effort, the correlation analyses conducted for Study 1 and Study 2 revealed that self-reported ratings of effort did not correlate with any of the dual-task measures irrespective of experimental condition or participant group. These results suggest that dual task measures and self-reported ratings each assess different aspects of listening effort (Edwards, 2007; Feuerstein, 1992; Kuchinsky et al., 2011). Even though a significant correlation did not emerge, self-reported ratings of listening effort represent a unique aspect of hearing aid outcome (Humes, 1999) and can be useful in direct client care where the focus is on the individual. To that end, the recently developed Device Oriented Subjective Outcome (DOSO) Scale (Cox et al., 2009) should be considered for clinical practice as well as future research involving listening effort. It remains to be determined whether the refinement of the construct of listening effort offered in the DOSO would correlate with dual task measures of listening effort such as used in the current studies.

Study 3 (Article 4) demonstrated that span size, a measure of auditory *capacity* was associated with listening effort and a measure of auditory *processing* was associated with the cost of word recognition accuracy performance under dual task conditions – but only for young adults. Importantly, the relationships observed between audition and cognition in Study 3 did not extend to the case of audiovisual word recognition (Study 2) or to older adults. As a result, it is still unclear what cognitive factors predict the listening effort of young and older adults engaged in everyday communication settings which typically involve audiovisual speech recognition.

Looking ahead, there is still much work to be done to determine what specific cognitive factors relate to the listening effort of older adults and to translate how this knowledge should be incorporated into clinical practice. It’s possible that a cognitive measure that is sensitive to changes in listening effort could be used in a way to help optimize hearing aid settings for speech understanding or to evaluate the outcomes of an aural rehabilitation program (Pichora-Fuller & Singh, 2006; Schneider et al., 2010). Beyond aural rehabilitation, a provocative next step would be to consider cognitive training – to train the identified cognitive factor(s) and determine if listening effort is eased. While research has shown that training healthy older adults can improve specific cognitive skills (i.e., memory training using the Method of loci to memorize and retrieve words), it remains to be determined how cognitive training could benefit listeners with hearing loss (Arlinger et al., 2009; Nyberg, Sandblom, Jones, Neely, & Petersson, 2003; Schneider et al., 2010).

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Annex A

Formulaire de consentement à votre participation à un projet de recherche

Université de Montréal Faculté de médecine **École d'orthophonie et d'audiologie**	**CRIUGM** **Centre de recherche de l'institut universitaire de gériatrie de Montréal**

FORMULAIRE DE CONSENTEMENT À VOTRE PARTICIPATION À UN PROJET DE RECHERCHE

1. Titre du projet de recherche

L'effort associé à la perception de la parole chez des jeunes adultes et des personnes aînées

1. Nom, qualifications et coordonnées des chercheurs

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2. Préambule

Nous vous demandons de participer à un projet de recherche. Cependant, avant d'accepter de participer au projet de recherche, veuillez prendre le temps de lire, de comprendre et de considérer attentivement les renseignements qui suivent.
Ce formulaire de consentement vous explique le but de l'étude, les procédures, les avantages, les risques et les inconvénients, de même que les personnes avec qui vous pouvez communiquer au besoin.

Le présent formulaire de consentement peut contenir des mots que vous ne comprendrez pas. Nous vous invitons à poser toutes les questions que vous jugerez utiles.

3. Présentation du projet de recherche et ses objectifs

Nous nous intéressons à l'effort requis pour percevoir la parole dans le bruit. Nous voulons savoir si les personnes aînées et les personnes qui ont une déficience auditive consacrent plus ou moins d'effort que les jeunes adultes à la perception de la parole dans le bruit. Cinquante personnes seront recrutées pour chaque expérience dont 25 jeunes adultes de l'Université de Montréal et 25 personnes aînées.

Pour mesurer l'effort requis pour accomplir une tâche de perception de la parole, nous utilisons une technique nommée '*double tâche*'. Dans cette approche, un participant est amené à faire une tâche principale et une tâche secondaire simultanément. La tâche principale consiste à identifier des mots d'une phrase et la tâche secondaire consiste à différencier des stimuli tactiles appliqués sur la paume de la main. Lorsqu'accomplies séparément, ces deux tâches sont simples à compléter et elles exigent peu d'effort. Cependant, les tâches peuvent devenir plus difficiles, et exiger plus d'effort lorsqu'elles sont présentées simultanément.

4. Nature et durée de votre participation

Si vous acceptez de participer à ce projet de recherche, vous effectuerez plusieurs tests de dépistage. Les résultats de ces tests détermineront si votre vision et votre audition concordent avec les critères de la recherche. Si vous êtes une personne aînée, des questionnaires additionnels seront utilisés pour évaluer votre mémoire et attention.

Pour la recherche en elle-même, vous participerez à trois expériences. La première est une tâche de perception de la parole. Vous pourrez entendre ou entendre et voir le locuteur. Les stimuli utilisés sont des phrases simples telles que : « Les soldats soufflent les ballons jaunes ». Pour chaque phrase, vous devrez identifier les trois mots clés dans une liste. Ici, vous indiqueriez «soldats, soufflent, jaunes». Vous entendrez toujours un bruit de fond qui sera ajusté pour contrôler le niveau de difficulté de la tâche.

Pour la deuxième expérience, vous tiendrez dans votre main un petit appareil qui produit des vibrations. Il vous sera demandé d'identifier les signaux de vibration que vous sentez en cliquant sur l'écran tactile.

Pour la troisième expérience, nous vous demanderons d'effectuer les deux tâches simultanément. La tâche de perception de la parole est la plus importante mais vous devrez répondre aux deux le plus vite et le plus précisément possible. Si vous êtes une personne aînée, la réalisation de trois tâches additionnelles de même nature sera nécessaire.

Au total, pour compléter le projet de recherche, nous prévoyons une seule session d'environ 1 heure pour les jeunes adultes et d'environ 2 heures pour les personnes aînées.

5. Avantages pouvant découler de votre participation

Vous ne retirerez aucun avantage direct de votre participation à ce projet de recherche. Toutefois, vous pourriez en retirer la satisfaction d'avoir participé à un projet qui pourrait contribuer à l'avancement des connaissances sur la compréhension de la parole dans le bruit chez les personnes aînées.

6. Inconvénients pouvant découler de votre participation

Aucun inconvénient majeur ne peut découler de votre participation au projet de recherche. Cependant, outre le temps et le déplacement consacrés à votre participation, vous pourriez ressentir un certain état de frustration, de stress ou de fatigue.

7. Compensation financière

Une compensation financière de 15,00$ pour les jeunes adultes et 25,00$ pour les personnes aînées, reflétant la durée de votre participation, vous sera remise en guise de dédommagement pour le temps que vous consacrerez à l'expérimentation et pour toute autre contrainte que vous pourriez subir à cause de votre participation au projet de recherche.

8. Participation volontaire et possibilité de retrait

Votre participation à ce projet de recherche est volontaire. Vous êtes donc libre de refuser d'y participer. Vous pouvez également vous retirer de ce projet à n'importe quel moment, sans avoir à donner de raisons, en faisant connaître votre décision au chercheur responsable du projet ou à l'un des membres du personnel affecté au projet.

Pour le personnel de l'Université de Montréal et les étudiants, votre participation au projet ou votre décision de vous retirer du projet de recherche, ne saurait modifier votre statut présent ou futur d'étudiant ou d'employé à l'Université de Montréal.

Le chercheur responsable du projet de recherche ou le comité d'éthique de la recherche de l'IUGM, peuvent mettre fin à votre participation, sans votre consentement, si de nouvelles découvertes ou informations indiquent que votre participation au projet n'est plus dans votre intérêt, si vous ne respectez pas les consignes du projet de recherche ou s'il existe des raisons administratives d'abandonner le projet.

9. Confidentialité

Durant votre participation à ce projet de recherche, le chercheur responsable du projet ainsi que son personnel recueilleront et consigneront dans un dossier de recherche les renseignements vous concernant. Seuls les renseignements nécessaires à la bonne conduite du projet de recherche seront recueillis.

Ces renseignements peuvent comprendre les résultats de tous les tests, examens et procédures que vous aurez à subir lors de ce projet de recherche. Votre dossier peut aussi comprendre d'autres renseignements tels que votre nom, votre sexe, votre date de naissance et votre origine ethnique.

Tous ces renseignements recueillis au cours du projet de recherche demeureront strictement confidentiels dans les limites prévues par la loi. Afin de préserver votre identité et la confidentialité de ces renseignements, vous ne serez identifié que par un numéro de code. La clé du code reliant votre nom à votre dossier de recherche sera conservée par le chercheur responsable du projet de recherche dans un lieu sécuritaire.

Le chercheur responsable utilisera les données du projet de recherche à des fins de recherche dans le but de répondre aux objectifs scientifiques du projet de recherche décrits dans le formulaire d'information et de consentement. Vos renseignements personnels seront détruits cinq ans après la fin du projet de recherche.

Les données du projet de recherche pourront être publiées dans des revues médicales ou partagées avec d'autres personnes lors de discussions scientifiques. Aucune publication ou communication scientifique ne renfermera quoi que ce soit qui puisse permettre de vous identifier.

À des fins de surveillance et de contrôle, votre dossier de recherche, s'il y a lieu, pourra être consulté par une personne mandatée par le comité d'éthique de la recherche de l'Institut universitaire de gériatrie de Montréal, par une personne mandatée par L'Université de

Montréal, par une personne mandatée par le ministre de la Santé et des Services sociaux ou par des organismes gouvernementaux mandatés par la loi. Toutes ces personnes et ces organismes adhèrent à une politique de confidentialité.

Vous avez le droit de consulter votre dossier de recherche pour vérifier l'exactitude des renseignements recueillis aussi longtemps que le chercheur responsable du projet de recherche, l'établissement ou l'institution de recherche détiennent ces informations. Cependant, afin de préserver l'intégrité scientifique du projet de recherche, vous n'aurez accès à certaines de ces informations qu'une fois l'étude terminée.

10. Personnes ressources

Si vous désirez de plus amples renseignements au sujet de cette étude, si vous souhaitez nous aviser de votre retrait de l'étude, si vous avez des plaintes ou des commentaires à formuler, vous pourrez toujours communiquer avec la personne ci-dessous : *Jean-Pierre Gagné, Ph.D. ou Penny Anderson Gosselin, M.Cl.Sc.,* École d'orthophonie et d'audiologie, Université de Montréal, C.P. 6128, succursale Centre-ville, Montréal (QC) H3C 3J7. Tél : (514) 343-7458. Nous répondrons à toute question que vous poserez à propos du projet de recherche auquel vous acceptez de participer.

Pour toute question concernant vos droits en tant que sujet participant à ce projet de recherche, ou si vous avez des plaintes ou des commentaires à formuler, vous pouvez communiquer avec le commissaire local aux plaintes et à la qualité des services de l'Institut universitaire de gériatrie de Montréal à l'adresse suivante : 4565, chemin Queen Mary, Montréal (H3W 1W5). Tél. : (514) 340-3517.

11. Information sur la surveillance éthique du projet

Le comité d'éthique de la recherche de l'Institut universitaire de gériatrie de Montréal a approuvé ce projet de recherche et s'assure du respect des règles éthiques durant tout le déroulement de la recherche. Pour toute information, vous pouvez joindre le secrétariat du comité d'éthique de la recherche au (514) 340-2800 poste 3250.

Consentement du sujet de recherche

Je déclare avoir lu et pris connaissance du projet, de la nature et de l'ampleur de ma participation, ainsi que des risques auxquels je m'expose tels qu'exprimés dans le présent formulaire.

Ma signature apposée ci-dessous indique que j'ai lu et compris le formulaire de consentement, qu'on a répondu de manière satisfaisante à mes questions et que je consens à participer à l'étude intitulée :

L'effort associé à la perception de la parole chez des jeunes adultes et des personnes aînées

De plus, je reconnais que ma participation à ce projet est tout à fait volontaire et que je suis libre d'y participer. Je certifie que l'on m'a aussi donné le temps voulu pour prendre ma décision. Finalement, je reconnais être libre de me retirer en tout temps, sans préjudice d'aucune sorte.

________________________________	________________________________
Nom du sujet	Signature du sujet

Fait à ______________________________, le ________________________________

Formule d'engagement du chercheur et signature

Je, soussigné ______________________________, certifie :

a) avoir expliqué au signataire intéressé les termes du présent formulaire de consentement;

b) avoir répondu aux questions qu'il m'a posées à cet égard;

c) lui avoir clairement indiqué qu'il reste à tout moment libre de mettre un terme à sa participation au projet de recherche décrit ci-dessus

d) que je lui remettrai une copie signée et datée du présent formulaire.

_________________________________ _______________________________________

Nom du chercheur Signature du chercheur ou de son représentant

Fait à ________________________________, le _________________________________