Université de Montréal

Caractéristiques des corrections automatiques assurant la précision spatiale d'un mouvement d'atteinte manuelle

par Julien Brière

Département de kinésiologie

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Résumé

Les tâches d'atteintes manuelles représentent probablement l'activité motrice la plus pratiquée par l'être humain. Les chercheurs ont longtemps pensé que l'impulsion motrice initiale de ce type de mouvement était balistique, qu'elle ne pouvait pas être modifiée en cours de route. Or, de récentes études suggéraient que tel n'était pas le cas et que cette première impulsion de mouvement pouvait être modulée de façon fluide sur la base des afférences visuelles. Pour étudier ce phénomène, plusieurs auteurs ont utilisé une tâche de pointage vidéo dans laquelle un curseur, représentant la main d'un participant, était déplacé vers une cible visuelle. Pour étudier de possibles mécanismes de correction du mouvement, la cible visée ou le curseur représentant la main du participant était quelques fois déplacé latéralement (par exemple 15 mm vers la droite) tôt après l'amorce. Afin d'atteindre la cible visée, le participant devait donc corriger le mouvement qu'il avait amorcé en fonction des nouvelles informations disponibles.

Les études utilisant cette procédure de perturbation (« saut de cible » ou « saut de curseur ») montrent que les participants corrigeaient leur mouvement de façon fluide, et ce, malgré le fait qu'ils ne percevaient pas consciemment le saut de cible ou de curseur. En incorporant des sauts de curseur à différents endroits dans le mouvement, Saunders et Knill (2003) ont observé une latence de correction constante et courte, peu importe l'endroit où survenait la perturbation. Ils ont donc émis l'hypothèse que l'humain traite de façon continue les afférences visuelles relatives au déplacement de la main lors d'une tâche d'atteinte.

Dans cette thèse, nous avons voulu déterminer les caractéristiques de ces corrections en ligne. Nos résultats indiquent:

- Que deux perturbations successives n'entrent pas en conflit l'une avec l'autre. Plus spécifiquement, la présentation d'une seconde perturbation n'interfère pas avec le processus de correction mis en branle par la première perturbation. Ces résultats confirment la continuité du processus de traitement des afférences visuelles en cours de mouvement et, du même coup, la faible charge attentionnelle requise pour traiter l'information visuelle relative au déplacement du curseur et amorcer une correction appropriée.
- Que de voir le curseur déplacé de sa trajectoire originale pour aussi peu que 16 ms est suffisant pour observer une modification du mouvement en cours de réalisation. De plus, la grandeur de la correction observée augmente lorsque la période de visibilité du curseur augmente suite à la perturbation. Nous avons utilisé ces résultats pour démontrer que le système nerveux central définissait la position perçue de la main sur la base d'une intégration spatiale de sa position au cours des 70 dernières millisecondes.
- Que la latence de la correction n'est pas tributaire de la grandeur de la perturbation ou de là où elle survient dans la trajectoire du mouvement. Cependant, le gain de cette correction est, lui, fonction de la grandeur de la perturbation. Ces observations suggèrent que l'amorce de la correction relève d'une comparaison entre la trajectoire de mouvement planifiée par l'individu et la trajectoire observée. Le gain de la correction serait plutôt fonction de la position perçue de la main et des caractéristiques de la cible à atteindre (position et dimension).

En conclusion, l'ensemble des résultats de cette thèse montre une efficacité impressionnante du système visuel de détection et de correction des erreurs. Un système

rapide et précis qui, toutefois, ne requiert pas une grande demande attentionnelle. Ces caractéristiques témoignent de la grande efficacité qu'à l'humain d'atteindre des objets grâce, en partie, à un mode de contrôle en continue de la progression de ses mouvements.

Mots clés : Contrôle moteur, vision, correction en continu, modulation en continu, afférence, pointage vidéo, perturbation, saut de curseur, fonctionnalité, échantillonnage, traitement continu,

Abstract

Manual aiming movements are probably the most common motor activities in humans. Researchers have long thought that the initial driving impulse of this type of movement was ballistic, that it could not be modified along the way. However, recent studies suggest that this is not the case and that this first movement impulse could be smoothly modulated on the basis of visual afferent information.

To study this phenomenon, several authors used a video pointing task in which a cursor, representing the hand of a participant, was moved to a visual target. To investigate possible movement execution correction mechanisms, the target or the cursor representing the participant's hand was sometimes moved laterally (for example 15 mm to the right) soon after movement initiation. In order to reach the target, the participant had to correct the movement he had initiated based on the new visual information available.

In the present dissertation, we wanted to determine the characteristics of these online corrections. Our results indicate:

- That two successive perturbations do not conflict with one another. Specifically, the presentation of a second perturbation does not interfere with the correction process set in motion by the first perturbation. These results confirm that visual afferent information is processed online during movement execution. In addition, these results underline the low attentional load associated with the processing of the visual information concerning the displacement of the cursor and the planning and initiation of an appropriate correction.

- That to see the cursor displaced from its original trajectory for as little as 16 ms is enough to observe a correction of the initial movement trajectory. In addition, the magnitude of the correction observed increases when the period of cursor visibility increases following the perturbation. We used these results to demonstrate that the central nervous system evaluated the perceived position of the hand following the spatial integration of its position over the last 70 milliseconds.

- That the latency of the correction is not dependent on the magnitude of the perturbation or where it occurs in the movement trajectory. However, the gain of this correction depends on the magnitude of the perturbation. These observations suggest that the planning of the correction is based on a comparison between the planned and the observed movement trajectories. The gain of the correction would rather depend on the perceived position of the hand and the characteristics of the target to reach (location and dimension).

In conclusion, the results of this dissertation show an impressive efficiency of the visual system for the detection and correction of movement planning or execution errors. A fast and accurate system that requires minimal attentional demands. It does appear that manual aiming movements are under the continuous control of visual afferent information.

Keywords: Motor control, vision, online correction, online movement modulation, video aiming, perturbation, cursor jump, continuous processing.

Table des matières

Chapitre 6 : Article 5 186

Chapitre 7: Discussion générale 214

Liste des tableaux

Chapitre 2 : Article 1

Chapitre 5 : Article 4

Liste des figures

Chapitre 1 : Revue de littérature

Chapitre 2 : Article 1

Chapitre 3 : Article 2

Chapitre 4 : Article 3

Chapitre 5 : Article 4

Chapitre 6 : Article 5

Liste des sigles et abréviations

Abréviations internationales :

al.: collaborateurs
cm: centimètre
Hz: hertz
min: minute
mm: millimètre
mm/s : millimètre par seconde (valeur de vitesse)
mm/s^2 : millimètre par seconde carrée (valeur d'accélération/ décélération)
ms: milliseconde
s : seconde
vs. : versus

Abréviations spécifiques au domaine de recherche et à la thèse :

SNC: Système nerveux central
End: movement endpoint
Fig: figure
rTMS : repetitive transcranial magnetic stimulation

Sigles:

(°): degré
%: pourcentage
$: dollar
R^2: coefficient de détermination

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Introduction

Lors d'un geste de pointage manuel, le système nerveux central (SNC) met en place une série de processus afin d'identifier la cible et sa position pour ensuite transformer cette information en une commande motrice appropriée (pour une revue voir Gaveau et al., 2014). Chacun des processus conduisant à la planification puis à l'exécution d'un tel mouvement possède une variabilité intrinsèque (Fox et al., 2007 ; Osu et al., 2015 ; van Beers et al., 2004). À cause de ce bruit inhérent à chacun des systèmes, et à cause de la grande précision requise dans beaucoup de nos activités quotidiennes, le SNC doit rapidement moduler l'exécution de nos mouvements.

Les processus de détection et de correction des erreurs ont été au centre de plusieurs débats depuis le travail de Woodworth (1899). Alors que plusieurs stratégies ont été utilisées au cours des dernières années pour étudier ces processus, plusieurs chercheurs ont opté pour un paradigme impliquant des perturbations. Dans ce type d'études, certains aspects de la tâche d'atteinte manuelle sont changés juste avant ou tôt après l'amorce du mouvement. Ainsi, pour atteindre la cible, le participant doit corriger le mouvement qu'il a planifié/amorcé afin de contrecarrer les effets de la perturbation. Ces études permettent donc d'étudier le fonctionnement, les limites et les contraintes des processus de détection et de correction des erreurs d'un mouvement d'atteinte manuelle qui ne se déroule pas comme prévu.

Au cours des dernières années, deux méthodes ont principalement été utilisées afin d'étudier ces processus: les tâches impliquant des sauts de cible et celles comprenant des sauts de curseur. Typiquement, dans les expériences de sauts de cible (Bridgeman et al., 1979 ; Day and Lyon, 2000 ; Desmurget et al., 2000 ; Franklin et al., 2012 ; Goodale et al., 1986 ;

Gritsenko and Kalaska, 2010 ; Prablanc et Martin, 1992 ; Sarlegna et al., 2003) les participants tentent d'atteindre une cible présentée devant eux depuis une position de départ fixe. Les participants doivent d'abord stabiliser leur regard sur un point de fixation puis, suivant un délai variable, une cible apparaît en périphérie du point de fixation. Les participants doivent regarder cette cible et tenter de l'atteindre avec le plus de précision possible et souvent le plus rapidement possible. Juste avant ou tôt après l'amorce du mouvement vers la cible (de l'œil ou de la main), l'emplacement de cette dernière est changé. Les participants doivent donc moduler/corriger leur mouvement pour atteindre la cible déplacée.

Dans les études traitant des sauts de curseur (Franklin et Wolpert, 2008 ; Proteau et al., 2009 ; Sarlegna et al., 2003, 2004 ; Saunders et Knill, 2003, 2004, 2005), les participants déplacent un curseur présenté sur un écran vidéo. Ce curseur représente la main du participant (qui n'est jamais visible) et un déplacement de la main entraîne un déplacement équivalent du curseur. Donc, le participant amorce un mouvement en direction d'une cible présentée sur l'écran vidéo puis, de façon inopinée, la position du curseur subit une perturbation (comme par exemple une translation de 2 cm par rapport à la position de la main). Encore une fois, pour atteindre la cible, le participant doit ajuster la trajectoire de son mouvement afin de compenser pour la perturbation imposée au curseur.

Dans ces deux types d'études, les participants rapportent souvent ne pas avoir perçu les perturbations. Néanmoins, les résultats montrent que ceux-ci ont modifié la trajectoire de leur mouvement pour contrecarrer les effets de la perturbation. Fait intéressant, le temps requis pour amorcer ce type de correction est indépendant de l'endroit et du moment auxquels la perturbation prend place. Ainsi, il a été proposé que les mouvements d'atteinte manuelle sont sous le contrôle continu des afférences visuelles (Saunders et Knill, 2003, 2005). De plus, considérant que les perturbations n'étaient introduites que pour une faible proportion des essais réalisés par les participants, et considérant que ces corrections étaient apparentes dès les premiers essais perturbés auxquels les participants étaient exposés, il a été proposé que ces processus de détection et de correction ne requièrent ni d'adaptation ni apprentissage (Proteau et al., 2009).

Finalement, d'autres auteurs (Day et Lyon, 2000 ; Pisella et al., 2000) ont tenté d'évaluer « l'automaticité » de ces réponses. Dans ces études, les perturbations étaient consciemment perçues des participants et ceux-ci devaient arrêter leur mouvement lors de la présentation d'une perturbation. Les données cinématiques montrent que les participants avaient déjà amorcé une correction avant l'arrêt de leur mouvement. Les participants semblaient donc incapables d'inhiber leur réaction habituelle face aux perturbations. Dans la même veine, d'autres chercheurs demandaient aux participants d'accentuer plutôt que de contrecarrer l'effet de la perturbation (Franklin et Wolpert, 2008). Dans cette étude, les participants devaient donc réagir à un saut de curseur en dirigeant leur main dans la même direction que la perturbation (sens inverse d'une correction efficace). Les données révélaient que les participants ne pouvaient s'empêcher d'amorcer une réponse correctrice à contresens de la perturbation avant de produire un mouvement dans la direction de la perturbation. Les auteurs de ces études suggéraient que les corrections au mouvement en fonction de sauts de cible ou de sauts de curseur étaient de nature « réflexe » sous le contrôle d'un pilote automatique localisé principalement au niveau du cortex pariétal postérieur (Desmurget et al., 1999 ; Pisella et al., 2000).

En résumé, plusieurs études ont mis en évidence la capacité qu'a l'humain de corriger en temps réel, efficacement et sans grande ressource attentionnelle, la trajectoire de ses mouvements sur la base des afférences visuelles. Cependant, certains points restent à considérer concernant les caractéristiques de ce processus de correction. Dans la présente thèse, nous avons voulu examiner de façon plus approfondie l'apparente continuité du processus du traitement de l'information visuelle et les particularités des corrections amorcées par le « pilote automatique » auquel il a précédemment été fait mention.

Afin de répondre aux différents objectifs dans cette thèse, nous avons utilisé une tâche de pointage vidéo. Spécifiquement, les participants devaient déplacer un manipulandum à partir d'une base de départ fixe vers différentes cibles. Ces dernières étaient localisées de part et d'autre de l'axe sagittal médian du participant (entre -15° et 15°) et situées à 331 mm de la base de départ. Cent-quinze participants adultes (âgés entre 20 et 30 ans) ont participé volontairement aux études. Quatre stratégies expérimentales ont été utilisées pour atteindre nos objectifs. Premièrement, l'insertion d'un deuxième saut de curseur (conditions « double-saut ») qui annule complètement (article 1), annule partiellement ou surcompense (article 3) le premier saut, nous a permis d'évaluer l'hypothèse d'un traitement continu de l'information visuelle pour le contrôle du mouvement. Si le traitement du deuxième saut de curseur n'est pas influencé par la détection du premier saut et la planification de la correction à ce premier saut et vice-versa, alors nous pourrons véritablement parler d'un traitement continu de l'information visuelle à faible coût attentionnel. Deuxièmement, l'occlusion du curseur à différents moments suite à un saut de curseur (article 2) nous a permis de déterminer la durée de l'information visuelle nécessaire pour détecter la perturbation et planifier une correction efficace. En identifiant la plus courte période de visibilité du curseur, suite à un saut, qui entraîne une évidence de correction du mouvement, nous avons obtenu un estimé fiable de la fréquence d'échantillonnage du système visuel. Les résultats nous ont aussi permis de démontrer que la position de la main est évaluée par le SNC non pas en fonction de la dernière position vue mais plutôt suite à une estimation basée sur les dernières 70 ms de visibilité du curseur.

Troisièmement, la comparaison de deux conditions de saut de curseur, une pour laquelle le curseur était visible lors du saut et une pour laquelle le curseur ne devenait visible que suite à ce saut nous a permis de déterminer si l'information dynamique relative au saut de curseur apportait de l'information supplémentaire au fait d'évaluer que le curseur ne se dirigeait plus là où le participant le souhaitait (article 5). Les résultats indiquent que la visibilité du saut de curseur n'ajoute pas d'information supplémentaire à celle donnée par la trajectoire déviée du mouvement. Finalement, la manipulation de la grandeur des cibles à atteindre et de l'amplitude des sauts de curseur a permis de déterminer si la correction pour un saut de curseur était effectivement de nature « réflexe » ou si cette correction était plutôt de nature fonctionnelle en ce sens qu'elle ne prendrait place que si elle est nécessaire pour l'atteinte de la cible (article 4). Les résultats indiquent que la latence de la correction n'est pas influencée, ni par l'amplitude du saut de curseur, ni par la taille de la cible. Cependant, l'exécution de la correction était fortement modulée par ces facteurs. Ces résultats suggèrent l'existence de mécanismes distincts de détection de l'erreur et de correction de cette erreur.

Chapitre 1 : Revue de littérature

La vision représente certainement la source d'information la plus précise et la plus utilisée de manière consciente par l'être humain pour accomplir les différentes tâches de la vie quotidienne (Proteau, 1992 ; Soucy et Proteau, 2001 ; Woodworth, 1899). Les caractéristiques propres au traitement de cette source d'afférence par le système nerveux central pour contrôler les mouvements humains ont fait l'objet de plusieurs études au cours des dernières décennies. Pour arriver à leur fin, les chercheurs ont souvent utilisé une tâche qui imite un des gestes les plus fréquemment réalisé par l'humain, un mouvement d'atteinte manuel.

1- Les modèles pour l'exécution du mouvement

Depuis la fin du 19ième siècle, différents modèles ont été proposés pour expliquer comment l'être humain contrôle ses réponses motrices. Les différentes considérations théoriques concernant le rôle des informations sensorielles pour le contrôle du mouvement seront présentées dans cette section.

1.1 « Two-component model »

Woodworth (1899) fut un des pionniers dans le domaine du contrôle moteur en proposant la théorie appelée « *Two-component model* ». Dans sa monographie, il propose que les mouvements d'atteintes manuelles sont composés de deux impulsions motrices : une première impulsion (impulsion initiale) suivie, le cas échéant, d'une ou de plusieurs impulsions de correction. Ce modèle propose que l'impulsion initiale d'un mouvement est sous le contrôle du système nerveux et qu'elle serait élaborée de sorte à amener la main à proximité de la cible à atteindre. Cette première phase serait entièrement planifiée avant l'amorce du mouvement et se déroulerait sans que les afférences ne puissent intervenir en cours d'exécution. Cette première impulsion ne permettrait cependant pas d'atteindre la cible visée à toutes les occasions, soit à cause d'une erreur de planification, soit à cause de la variabilité inhérente au mouvement. Lorsque c'est le cas, l'écart entre la position de la main à la fin de cette impulsion initiale et celle de la cible serait évalué, ce qui permettrait de planifier et d'amorcer une impulsion de correction. Il s'agirait donc d'une boucle de rétroaction basée sur l'information visuelle. Si nécessaires, de telles boucles de rétroaction se succèderaient jusqu'à l'atteinte de la cible. Ainsi, Woodworth proposait que la précision du mouvement dépendait du temps disponible pour réaliser ces boucles de correction.

1.2 « Iterative correction model »

Le « *Iterative correction model* » a d'abord été proposé par Crossman et Goodeve (1963/1983) pour être rendu populaire par Keele (1968). Ces auteurs proposent que le traitement des afférences visuelles pour assurer la précision du mouvement est impossible pendant la réalisation d'une impulsion motrice. Ils proposent ainsi un modèle déterministe où l'écart initial entre la position de la main et la cible visée est évalué pour planifier une impulsion motrice. Cette impulsion motrice permettrait de réduire cet écart initial de 93%. Ainsi, si le mouvement produit est suffisamment court et si la cible visée est suffisamment grande, une seule impulsion de mouvement sera nécessaire et le temps de mouvement (TM) sera court. Si la cible visée n'était pas atteinte par la première impulsion de mouvement, un nouveau calcul de l'écart entre la main et la position de la cible prendrait place en 190 ms (durée présumée d'une boucle de rétroaction visuelle au tournant des années 70'). La correction qui serait alors amorcée réduirait l'erreur restante de 93%, et ainsi de suite jusqu'à l'atteinte de la cible. Il s'agit donc d'un modèle purement déterministe. Ce qui limiterait la précision finale du mouvement serait donc le nombre de sous-mouvements que l'individu pourrait faire eu égard au temps total alloué pour le déplacement de la main.

1.3 « Optimized submovement model »

Durant plusieurs années, les travaux de Meyer et al. (1988) ont été une référence pour expliquer comment les mouvements d'atteinte manuelle étaient exécutés et corrigés. Selon ces auteurs, lorsque les instructions données aux participants sont d'atteindre une cible le plus rapidement et le plus précisément que possible, ces derniers utilisent une stratégie d'optimisation. Ainsi, il est bien connu que, jusqu'à une certaine limite, plus un mouvement est réalisé à haute vitesse, plus il est variable (Schmidt et al., 1979). Donc, si le participant exécute un mouvement rapide, la première impulsion de mouvement sera très variable. De là, si la cible à atteindre est petite, il se pourrait qu'elle ne soit pas atteinte avec cette première impulsion de mouvement qui est considérée comme étant balistique par les auteurs, et donc qui ne peut pas être corrigée ou modulée en cours de réalisation. Une impulsion de correction devra donc être programmée et exécutée, ce qui augmentera considérablement le temps de mouvement. Ces auteurs proposent que le participant détermine un compromis faisant en sorte que le mouvement soit réalisé rapidement mais pas au point d'augmenter de façon indue le nombre d'essais pour lesquels une coûteuse correction devra être amorcée.

Les modèles proposés ci-haut partent de la prémisse que l'impulsion initiale du mouvement est imperméable aux corrections en temps réel. Tel serait le cas à cause de délais prétendument trop longs du traitement de l'information visuelle. Dans la prochaine section nous nous intéresserons au temps nécessaire pour traiter l'information visuelle relative à un membre en déplacement.

2- Information visuelle en cours de mouvement

2.1 Temps pour traiter l'information visuelle

Avant d'évaluer l'influence que pourrait avoir l'information visuelle sur la précision du mouvement, il faut d'abord connaître le délai associé à son traitement par le SNC. Les premiers chercheurs qui ont tenté de répondre à cette question ont souvent utilisé des protocoles semblables. Les participants réalisent des mouvements d'atteinte manuelle dans une condition pour laquelle leur effecteur et la cible sont visibles tout au long du mouvement (essais en vision) et dans une autre pour laquelle l'effecteur est masqué (essais en non-vision). En plus de faire varier les conditions visuelles, les participants sont amenés à compléter la tâche en différents temps de mouvement. Le raisonnement derrière ces manipulations est que les participants devraient connaître une meilleure performance pour la condition avec vision que pour la condition sans vision seulement pour les essais pour lesquels le temps de mouvement est suffisamment long pour leur permettre de traiter les afférences visuelles. À l'opposé, les mouvements qui seront effectués plus rapidement que le délai minimal requis pour traiter l'information visuelle devraient résulter en des erreurs spatiales équivalentes pour les deux conditions de visibilité de l'effecteur.

Les résultats de plusieurs études montrent que ce délai de traitement semble dépendre d'une foule de facteurs dont principalement le type d'information visuelle disponible (centrale ou périphérique; Carlton, 1981 ; Spijkers et Lochner, 1994), la prévisibilité de la condition expérimentale (le participant est informé ou ne l'est pas de la visibilité de l'effecteur; Elliott and Allard, 1985 ; Zelaznik et al., 1983) et la visibilité ou non de l'effecteur avant même l'amorce du mouvement (pour des revues, Desmurget et al., 1998 ; Prablanc et al., 1979). En tenant compte de tous ces facteurs, et en raffinant les méthodes de mesure et les variables dépendantes utilisées, la durée minimale estimée d'une boucle de rétroaction visuelle passa d'environ 250 ms à la fin du 19^{ième} siècle, (Woodworth, 1899) à 150 ms (Zelaznik et al., 1983) au début des années 80' puis à aussi peu que 100 ms au tournant du siècle dernier (Carlton, 1992 ; Elliott et al., 2001).

2.2 Coordination œil-main

Dans une tâche typique d'atteinte manuelle sans contrainte particulière, le sujet fixe en premier lieu la cible visée, puis amorce son mouvement (Prablanc et al., 1979 ; Helsen et al., 1997 ; Helsen et al., 2000). Cela tient du fait que la latence de la saccade visuelle dirigée vers la cible est plus courte que la latence de la main et aussi que cette saccade ne requiert que très peu de temps pour être complétée. Par exemple, lorsque la cible est située à 20° d'angle visuel d'un point de fixation visuel et du point de départ de la main, la saccade est amorcée environ 150 ms avant le déplacement de la main et elle est complétée environ 100 ms avant l'amorce du déplacement de la main. La précision spatiale du mouvement sera dégradée si le participant doit dévier délibérément son regard de la cible visée (Bekkering et al., 1995 ; Henriques et Crawford 2000 ; Henriques et al., 2003 ; Neggers et Bekkering, 1999 ; Prablanc et al., 1979 ; Vercher et al., 1994). Il a même été démontré que les participants étaient incapables de faire une saccade visuelle vers une nouvelle cible si le mouvement de la main vers la première cible n'était pas terminé (Neggers et Bekkering, 2000 ; 2002). Il en est d'ailleurs ainsi même lorsque le participant ne peut pas voir sa main (Neggers et Bekkering, 2001). Cela tient probablement du fait que la fixation visuelle de la cible assure que cette dernière est vue dans la partie de l'œil ayant la plus grande densité de récepteurs, la fovéa.

Ainsi, lorsque la cible est fixée du regard par le participant, la main amorcera son mouvement alors qu'elle n'est visible qu'à la périphérie de l'œil. La main passera graduellement vers une vision plus centrale pour finalement terminer son déplacement près de la cible.

En 1985, dans un article qui a fait époque, Paillard et Amblard ont proposé que les informations provenant des portions périphériques et centrales de l'œil étaient traitées différemment. Un premier canal visuel traiterait l'information vue à la périphérie de l'œil (> 10 ° d'angle visuel); il serait capable de traiter l'information d'un stimulus (comme la main dans une tâche d'atteinte manuelle) se déplaçant à grande vitesse. Ce canal serait responsable de contrôler la direction des mouvements. Le second canal visuel traiterait plutôt l'information venant d'une partie plus centrale de l'œil (< 10° d'angle visuel) et serait principalement responsable du contrôle de l'amplitude du mouvement alors que la main décélère vers la cible.

La méthodologie généralement utilisée pour déterminer l'influence de chacun de ces canaux visuels sur la précision d'un mouvement était de ne permettre la vision de la main que pour une certaine portion du mouvement, par exemple alors que la main est visible entre 40° et 30° d'angle visuel par rapport à la cible. Les résultats de plusieurs études supportent les propositions de Paillard et Amblard (1985). En effet, la précision directionnelle des mouvements était meilleure lorsque la vision de la main était permise en vision périphérique comparativement à une situation où elle ne l'était pas (Abahnini et Proteau, 1999 ; Abahnini et al., 1997 ; Bard et al., 1985 ; Bard et al., 1990 ; Khan et al., 2004); la disponibilité de la vision centrale avait cependant le même effet. D'autres ont montré que les informations visuelles disponibles en vision centrale augmentaient la précision de mouvements nécessitant un mouvement précis en amplitude (Bard et al., 1990 ; Lawrence et al., 2006 ; Carlton, 1981 ; Temprado et al., 1996).

3- Évidences d'un contrôle en ligne du mouvement

Dans bon nombre d'études, une plus grande précision de mouvements était accompagnée par une augmentation du nombre de sous-mouvements appelés corrections discrètes. Une correction discrète est généralement obtenue lorsqu'un de ces événements survient : (1) renversement de mouvement (sur les profils cinématiques, la vitesse qui passe de positive à négative), (2) élongation de mouvement (sur les profils cinématiques, on note la présence d'une deuxième impulsion de mouvement caractérisée par un profil d'accélération traversant la valeur de zéro pour une deuxième fois, (3) une modification significative dans le profil de décélération indexée par la traversée de la ligne zéro du profile de jerk.

Toutefois, Elliott et al. (1991) ont montré qu'une augmentation de la précision pour des essais réalisés dans une condition de vision normale pouvait être observée sans augmentation du nombre de corrections discrètes; on proposait même qu'une modulation du mouvement pouvait prendre place pendant l'impulsion initiale de mouvement. Ces auteurs ont alors suggéré que le processus de correction pourrait être continu au lieu d'être intermittent. Par la suite, différentes méthodes ont permis de vérifier cette affirmation et de déterminer les caractéristiques de ces corrections dites "en continue".

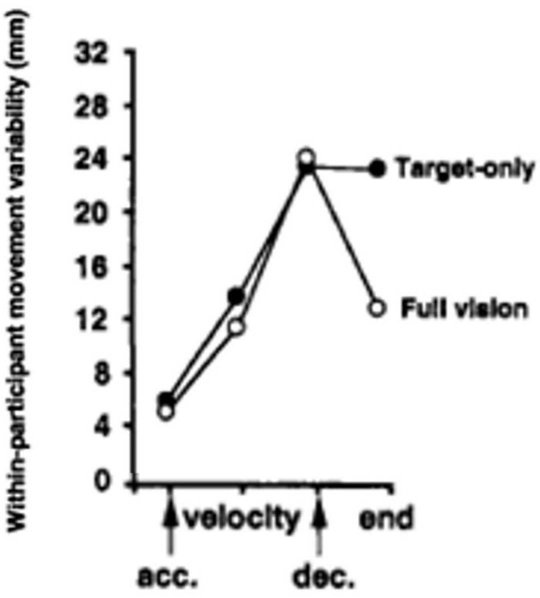
3.1 Analyse cinématique

Pour déterminer si les plus grandes précisions terminales observées précédemment en condition de vision normale étaient réellement dues à la modulation de la première impulsion de mouvement, plusieurs auteurs ont utilisé une méthode basée sur l'analyse de la variabilité du mouvement calculée à différents marqueurs cinématiques (Bédard et Proteau, 2003 ; Khan et Franks, 2000, 2003 ; Khan et al., 2002 ; Lhuisset et Proteau, 2002 ; Proteau et Isabelle, 2002 ; voir aussi Messier et Kalaska, 1999). Ainsi, les principaux marqueurs cinématiques utilisés sont la position initiale de l'effecteur et le moment d'occurrence de la pointe d'accélération, de la pointe de vitesse, de la pointe de décélération, et de la position terminale de l'impulsion initiale de mouvement. La pointe d'accélération est souvent considérée comme indiquant les caractéristiques de l'impulsion initiale de mouvement ou, dit différemment, des caractéristiques de la planification motrice. La pointe de vitesse est souvent considérée comme indiquant la fin de la période pendant laquelle le mouvement est de nature purement balistique. La pointe de décélération est retenue principalement parce qu'elle sépare en deux époques distinctes la portion du mouvement qui pourrait ne plus être de nature balistique. Finalement, la position finale est évidemment retenue parce qu'elle indique le succès relatif du mouvement programmé et éventuellement corrigé en cours de réalisation.

Tel que vu précédemment, les différents processus menant à l'amorce du mouvement sont variables (Fox et al., 2007 ; Schmidt et al., 1979 ; Osu et al., 2015 ; van Beers et al., 2004). Donc, pour une série d'essais consécutifs dirigés vers une même cible, nous devrions observer une trajectoire de mouvement différente pour chaque essai de la série. Ces trajectoires sont essentiellement rectilignes pour des mouvements d'atteinte manuelle (Morasso, 1981 ; Nakato et al., 1999 ; Uno et al. 1989). Donc, si le mouvement est réalisé sans implication des afférences pour en assurer la précision, la position de la main à la pointe d'accélération devrait être un bon prédicteur de sa position à chacun des trois autres marqueurs cinématiques. De plus, pour une série d'essais non corrigés et dirigés vers la même cible, plus la main s'éloigne de la base de départ plus la variabilité inter-essais de la position de la main devrait augmenter. Inversement, si des corrections/modulations surviennent dans les trajectoires de mouvement, l'augmentation de la variabilité inter-essais devrait soit plafonner, soit même être réduite à partir du marqueur cinématique à partir duquel ces corrections/modulations sont possibles. Par ailleurs, si ces corrections/modulations sont le fait du traitement des informations visuelles disponibles en cours de mouvement, alors la stabilisation/diminution de la variabilité inter-essais évoquée ci-avant devrait seulement être évidente (stabilisation de la variabilité) ou être plus importante (diminution de la variabilité) pour des essais effectués alors que la vision de la main est permise par rapport à des essais complétés sans cette information visuelle. De plus, si le profil de variabilité est semblable pour des conditions de vision et de non vision de la main, par exemple une augmentation linéaire en fonction du déplacement, mais que seule la pente de la fonction diffère entre les deux conditions, il faudra alors conclure que les différences observées dépendent de facteurs prenant place avant l'amorce du mouvement (programmation du mouvement).

Tel qu'illustré à la Figure 1, Proteau et Isabelle (2002) ont observé une forte diminution de la variabilité spatiale entre la pointe de décélération et la fin de la première impulsion de mouvement pour les participants qui réalisaient la tâche alors que la vision du curseur était permise; cette diminution n'était pas observée lorsque les participants ne pouvaient pas voir le curseur pendant la réalisation du mouvement.

Figure 1



Variabilité (mm) en amplitude en fonction des conditions visuelles (target-only : seule la cible est visible; full vision : le mouvement est réalisé en condition de vison normale) et des principaux marqueurs cinématiques. (acc = Pointe d'accélération, velocity = Pointe de vitesse, dec = Pointe de décélération, et end = Fin du mouvement). Tiré de Proteau et Isabelle, 2002.

Cette chute de variabilité observée en condition de vision normale a permis aux participants d'être plus précis que dans la condition où seule la cible était visible, même si leur mouvement ne comptait pas d'impulsion de correction (aussi appelée correction discrète). Des résultats semblables ont été obtenus dans plusieurs autres études qui, toutes, démontrent une forte diminution de la variabilité spatiale du mouvement entre la pointe de décélération et la fin de la première impulsion de mouvement lorsque le curseur déplacé est visible (Bédard et Proteau, 2003, 2004 ; Khan et Franks, 2000, 2003 ; Khan et al., 2002 ; Lhuisset et Proteau, 2002, 2004 ; Messier et Kalaska, 1999 ; Proteau, 2005 ; Robin et al., 2005).

Des résultats d'une étude de Bédard et Proteau (2004) supportent d'une autre façon la proposition que l'information visuelle est utilisée en temps réel pour moduler le mouvement. Ces auteurs ont démontré que lorsque les conditions visuelles dans lesquelles le mouvement serait réalisé étaient prévisibles, les participants adoptaient une stratégie différente liée à la présence de cette information. Dans cette expérience, les participants réalisaient des mouvements d'atteintes manuelles sous 4 différentes conditions visuelles. Pour une première condition, le curseur était visible durant tout le mouvement (Full Vision) alors que pour une deuxième il était obstrué dès qu'il quittait la base de départ (Target-Only). Pour une autre condition (40°-15°), le curseur était visible seulement pour la première portion du mouvement, c'est-à-dire, entre 40° et 15° d'angle visuel. Pour la dernière condition (15°-0°) le curseur était visible seulement entre 15° et 0° d'angle visuel, soit alors qu'il se trouvait près de la cible. Il est à noter que, dans cette expérience, les participants ne pouvaient pas effectuer de correction discrète.

Les auteurs ont calculé le moment d'occurrence des différents marqueurs cinématiques présentés plus haut pour les 4 conditions expérimentales. Le rationnel est que si les individus utilisent la vision pour moduler leur première impulsion tard dans le mouvement (principalement entre le pic de décélération et la fin du mouvement), ils souhaiteront alors maximiser le temps passé près de la cible pour les conditions expérimentales où la vision du curseur est possible. Les résultats montrent que les pointes de vélocité et de décélération sont survenues plus tôt pour les conditions Full Vision et 15°-0° que pour les 2 autres conditions expérimentales. En planifiant un tel mouvement, les participants ont ainsi pu passer plus de temps durant la phase de décélération alors que la vision du curseur était disponible. Ce résultat semble donc révéler une stratégie favorisant l'utilisation de la vision pour moduler en cours de route la fin d'un mouvement (Chua et Elliott, 1993 ; Khan et al., 2002 ; Mackrous et Proteau, 2007).

D'autres techniques, aussi basées sur la cinématique du mouvement, ont permis de supporter les conclusions des dernières études. Par exemple, Khan et al. (2003) ont utilisé une technique de corrélation. Ces auteurs ont calculé des indices de corrélation entre le déplacement parcouru à chacun des marqueurs cinématiques définis plus haut. Ainsi, si la position finale du mouvement est déterminée entièrement par les processus de planification du mouvement sans intervention des afférences ou d'un quelconque processus de correction du mouvement, alors on devrait observer une corrélation élevée entre la distance parcourue à chacun des marqueurs cinématiques. Au contraire, si la distance parcourue aux premiers marqueurs du mouvement n'est pas corrélée à la distance totale parcourue, alors il faudra conclure que différents mécanismes sont intervenus en cours de route pour ajuster ou moduler l'impulsion initiale de mouvement. Dans cette expérience, 24 participants effectuaient une tâche de pointage manuelle sous 2 conditions de vision (vision normale, sans vision du curseur) et 4 temps de mouvement (225 ms, 300 ms, 375 ms et 450 ms).

Les résultats indiquent des corrélations très semblables pour le temps de mouvement de 225 ms, peu importe la condition de vision. Les auteurs ont noté une corrélation très élevée (0,91 pour la condition de vision normale et 0,90 pour la condition sans vision du curseur) entre la distance parcourue à l'occurrence de la pointe de décélération et la fin de la première impulsion de mouvement, ce qui suggère que la distance finale parcourue était déjà déterminée à l'occurrence de la pointe de décélération. Il n'y avait donc pas de correction du mouvement, peu importe la condition de vision. Au contraire, pour les deux temps de mouvement les plus longs, les auteurs ont remarqué des coefficients de corrélation moins élevés, et ce, plus particulièrement pour la condition de vision normale (0,56 et 0,48) comparativement à la condition sans vision de curseur (0,68 et 0,62). Cette observation suggérait que l'amplitude d'un mouvement d'atteinte manuelle pouvait être modulée pour des mouvements aussi courts que 375 ms.

3.2 Perturbation de la cible

Au cours des années 80', une autre approche méthodologique a permis d'analyser la capacité des individus à moduler/corriger leur mouvement en cours d'exécution. Cette méthode est appelée « *double step paradigm* » (Bridgeman et al., 1979 ; Day et Lyon, 2000 ; Desmurget et al., 1999 ; Franklin et al., 2012 ; Goodale et al., 1986 ; Gritsenko et Kalaska, 2010 ; Pélisson et al., 1986 ; Prablanc et Martin, 1992 ; Sarlegna et al., 2003 ; Soechting et Lacquaniti, 1983).

Pour un essai typique, les participants fixent du regard un point affiché sur un écran. Après un délai variable, ce point s'éteint et il est remplacé par une cible qui apparaît en périphérie de ce point de fixation. Le participant doit alors fixer la cible du regard et aussi l'atteindre manuellement. Pour une faible proportion des essais, lorsque le participant effectue la saccade visuelle vers la cible, celle-ci change de position, en s'éloignant ou en se rapprochant du point de fixation initial. Si le saut de cible est petit, la saccade visuelle empêche les participants de détecter consciemment le déplacement de la cible.

Les résultats de ces études indiquent que les participants atteignent la cible avec une même précision, peu importe que la position de celle-ci soit demeurée fixe tout au long de l'essai ou ait été déplacée pendant la saccade visuelle (Bridgeman et al., 1979 ; Gritsenko et al., 2009 ; Sarlegna et al., 2003). Par exemple, pour les essais perturbés dans l'étude de Pélisson et al. (1986) la position de la cible pouvait être rapprochée ou éloignée de sa position initiale de 2 à 4 cm. Néanmoins, les premiers résultats montrent que les participants corrigeaient en moyenne 95% de la perturbation imposée. De façon plus intéressante, ces modifications n'étaient pas associées à une augmentation du temps requis pour compléter la tâche (i.e., temps de mouvement) et ne changeaient pas l'allure des profils de vitesse et d'accélération du mouvement. En utilisant des méthodes semblables, d'autres auteurs ont montré qu'il était aussi possible de corriger la direction plutôt que l'amplitude des mouvements (Soechting et Lacquaniti, 1983 ; Prablanc et Martin, 1992).

Finalement, de manière importante, Pélisson et al. (1986) rapportent que les perturbations n'ont jamais été perçues consciemment par les participants. Cela a conduit les auteurs à proposer que la commande motrice programmée pour l'atteinte de la cible initiale est modifiable en cours d'exécution et que ces ajustements ne requéraient pas nécessairement l'implication de processus conscients. Ce point sera discuté en profondeur plus loin dans le texte.

Prablanc et Martin (1992) ont voulu déterminer si la précision des corrections suite à une perturbation serait différente si le participant ne pouvait pas voir sa main lors de ce type de tâche. Le participant réalisait une tâche semblable à celle utilisée par Pélisson et al. (1986) mais sans la possibilité de voir le déplacement de sa main. Ces auteurs rapportent des résultats très semblables à ceux publiés par Pélisson et al. (1986) : (a) les corrections pour des perturbations de 5 cm étaient de l'ordre de 90% (b) les latences de correction variaient entre 155 à 162 ms dans les deux cas et (c) la cinématique des mouvements jusqu'à la pointe de vitesse (la mi-mouvement) était pratiquement identique à celle retrouvée lorsque le participant pouvait voir sa main. Néanmoins, lorsque le participant pouvait voir sa main, les corrections étaient plus importantes (3 mm ou 6%) à partir de la pointe de décélération. Les auteurs ont conclu que les corrections observées pour les deux conditions de vision de la main étaient réalisées à partir d'un même et unique processus de détection et de correction des erreurs.

Il semble donc clair que l'information spatiale concernant la position de la cible à atteindre est traitée et mise à jour en cours de mouvement. Lorsque le plan initial de mouvement ne correspond pas (erreur de planification) ou ne correspond plus (erreur d'exécution) à la position de la cible, une correction/modulation du mouvement est amorcée, et ce, sans intervention consciente de la part du participant.

Étant donné que, dans les études citées plus haut, l'amorce d'une correction ne dépendait pas de la visibilité de la main du participant, il n'est pas clair si l'information visuelle relative à l'effecteur (i.e., la main) est analysée en cours de mouvement et si cette information peut permettre à un individu de moduler la première impulsion de son mouvement. Le problème est d'autant plus important que dans toutes les études où un saut de cible fut utilisé, la tâche impliquait nécessairement que le but visé par le participant soit modifié en cours de mouvement. Une autre façon de simuler la programmation erronée ou l'exécution erronée d'un mouvement d'atteinte manuelle <u>sans changer le but visé par le participant</u> est de perturber la position « vue » de l'effecteur plutôt que la position de la cible. Cette façon de faire permet d'analyser de façon très précise le rôle des afférences visuelles dynamiques relatives à la main lors d'une tâche d'atteinte. La prochaine section traite des études qui ont utilisé la technique du « saut de curseur » pour répondre à notre question initiale.

<u>3.3 Perturbation de l'effecteur</u>

Sarlegna et al. (2003) ont comparé la contribution du feedback visuel relatif à la main et celui lié à la cible dans le contrôle en ligne d'une tâche de pointage vidéo. La contribution relative de ces deux sources d'information était évaluée en changeant la position perçue de la main du participant (position du curseur) ou la position de la cible tôt après l'amorce du mouvement, soit alors que le participant effectuait une saccade visuelle vers la cible visée.

Dans cette expérience, des cibles étaient situées à 31,5 cm, 36 cm, et 40,5 cm directement à la droite de la base de départ (voir la Figure 2). Pour certains essais amorcés vers la cible centrale (36 cm), la position de la cible était déplacée de 4,5 cm en direction de la base de départ ou à l'opposé de celle-ci (essais T- et T+, respectivement) (Figure 2 A). Ainsi, pour les essais T-, les participants devaient raccourcir l'amplitude du mouvement programmé pour atteindre la nouvelle cible alors qu'ils devaient l'allonger pour les essais T+.

Pour d'autres essais, c'était plutôt la position du curseur qui pouvait être déplacée de 4,5 cm en direction de la cible ou à l'opposé de celle-ci (essais H+ et H- respectivement) (Figure 2 B). Si les participants utilisent l'information visuelle relative à la position de la main pour atteindre la cible, ils devraient effectuer des mouvements plus longs pour les essais H- que pour les essais sans perturbation alors que pour les essais H+, le mouvement devrait être plus court.

Figure 2

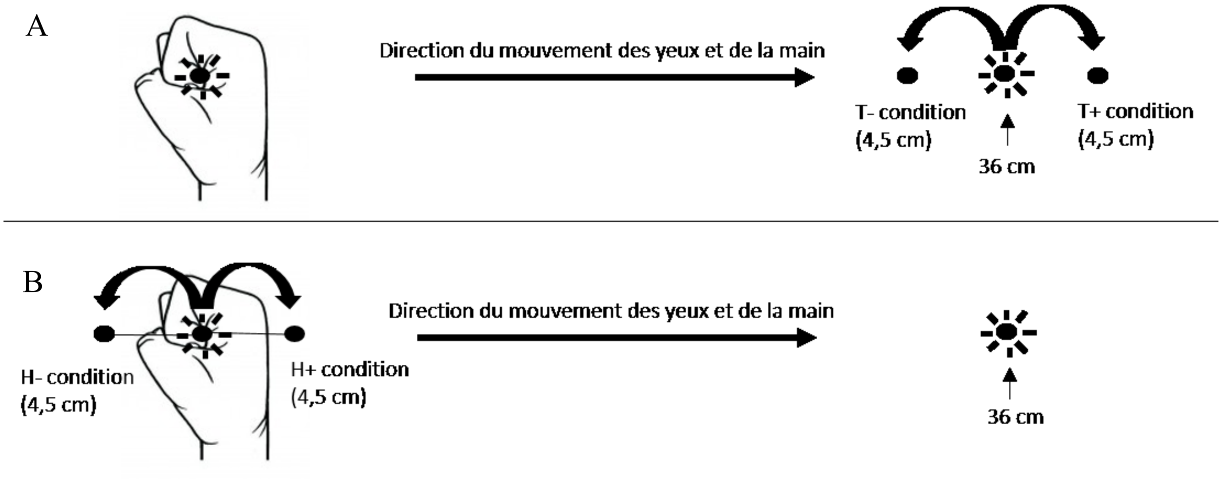
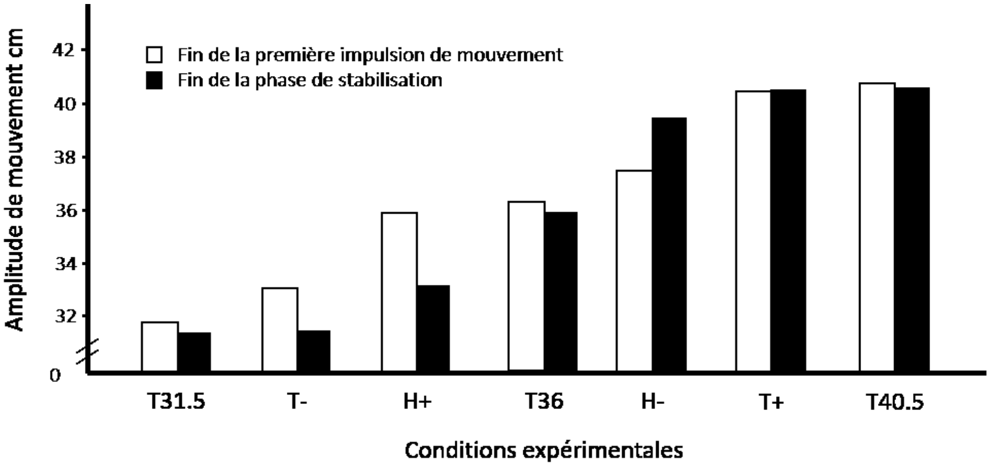


Illustration des conditions expérimentales avec un changement dans la position de la cible (A) et dans la position du curseur (B). A. La cible apparaissait à 36 cm de la base de départ; elle était déplacée de 4,5 cm vers la gauche (T-) ou vers la droite (T+) durant la saccade visuelle. B. Le curseur représentant la position de la main était « déplacé » de 4,5 cm vers la gauche (H-) ou vers la droite (H+) durant la saccade. Tiré de Sarlegna et al., 2003.

Les résultats de cette étude sont présentés à la Figure 3. On remarque facilement qu'à la fin de la première impulsion de mouvement (bandes blanches), pour les essais T- et T+, les participants avaient raccourci ou allongé leurs mouvements en fonction du déplacement de la cible. L'amplitude du mouvement à l'occurrence de la fin de la première impulsion de ces essais ne diffère pas significativement de l'amplitude des essais contrôles (i.e., sans perturbation; T31,5 pour les essais T- et T40,5 pour les essais T+). Il n'en était pas de même lorsque c'était la position de l'effecteur qui était perturbée. En effet, pour les essais H+, pour lesquels la distance entre la position de la cible et celle de la main était diminuée de 36 cm à 31,5 cm, l'amplitude de la première impulsion s'apparentait aux essais contrôles dirigés vers la cible à 36 cm mais pas aux essais contrôles dirigés vers la cible à 31,5 cm. Une tendance similaire, quoique moins prononcée, était observée pour les essais H-. Ces résultats laissaient douter de la capacité d'un individu à corriger l'amplitude de la première impulsion d'un mouvement sur la base des afférences visuelles dynamiques liées à l'effecteur. Toutefois, ces résultats étaient peut-être observés parce que, étant donné les temps de mouvement observés (entre 300 ms et 600 ms), les participants n'avaient pas eu le temps nécessaire pour détecter l'erreur induite par la perturbation et amorcer la correction requise.

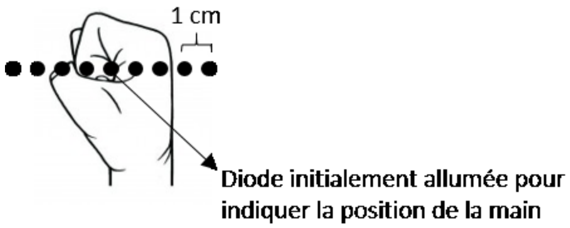
Figure 3



Amplitude moyenne de mouvement (cm) à la fin de la première impulsion (bandes blanches) et de la phase de stabilisation (bandes noires) en fonction des différentes conditions expérimentales. Tiré de Sarlegna et al., 2003.

Dans un deuxième article, Sarlegna et collaborateurs (2004) se sont intéressés à la correction d'une perturbation de la position du curseur qui induisait une erreur directionnelle plutôt qu'une erreur en amplitude. Dans cette étude, les participants réalisaient un mouvement de balayage (plutôt que d'atteinte manuelle) qui devait croiser la position d'une cible visuelle. Pour cette tâche, il n'y avait donc pas d'exigence quant à l'amplitude du mouvement à produire et seule la direction du mouvement devait être contrôlée. La cible était située 44 cm directement devant la base de départ. Le participant déplaçait un manipulandum sur lequel étaient montées 9 diodes électroluminescentes. La diode centrale était activée avant le mouvement et le sujet devait faire en sorte que la position de cette diode croise la position de la cible le plus précisément possible. Pour certains essais, tôt après l'amorce du mouvement, la diode centrale était éteinte et une autre des huit diodes restantes était activée. Ces diodes étaient éloignées de 1, 2, 3, ou 4 cm à la gauche ou à la droite de la diode centrale (Figure 4).

Figure 4



Vue aérienne des 9 diodes qui étaient utilisées pour procurer une rétroaction visuelle réelle ou biaisée de la position de la main. Seulement une diode était allumée à la fois. Tiré de Sarlegna et al., 2004.

Les résultats de cette étude indiquent que les participants ont corrigé leurs mouvements pour toutes les conditions de saut de curseur. Plus précisément, l'amplitude des corrections était de l'ordre de 45% de la perturbation imposée. En valeur absolue, la grandeur de la correction n'était donc pas constante mais augmentait en fonction de l'amplitude de la perturbation sans jamais atteindre, en moyenne, un niveau de correction complète. Ce point est particulièrement intéressant si on considère que les participants produisaient une correction de 1,8 cm pour une perturbation de 4 cm mais qu'ils ne parvenaient pas à produire une correction du même ordre lorsque la perturbation n'était que de 2 cm. Sarlegna et al. proposent que ce résultat indique que le saut de curseur induit un conflit entre la position vue et la position sentie du curseur. Des observations similaires sont rapportées par d'autre auteurs (Saunders et Knill, 2003, 2005) quoique le ratio de correction diffère d'une étude à l'autre. Ce point sera abordé plus avant dans une autre section de la thèse.

En résumé, il apparaît que l'impulsion initiale d'un mouvement d'atteinte manuelle peut être corrigée en cours d'exécution sur la base des afférences visuelles dynamiques du déplacement de la main. Ces corrections pourraient intervenir tant sur la composante en amplitude que directionnelle du mouvement. Ces résultats diffèrent évidemment des prédictions émanant des théories revues en début de section.

4- Traitement continu de l'information

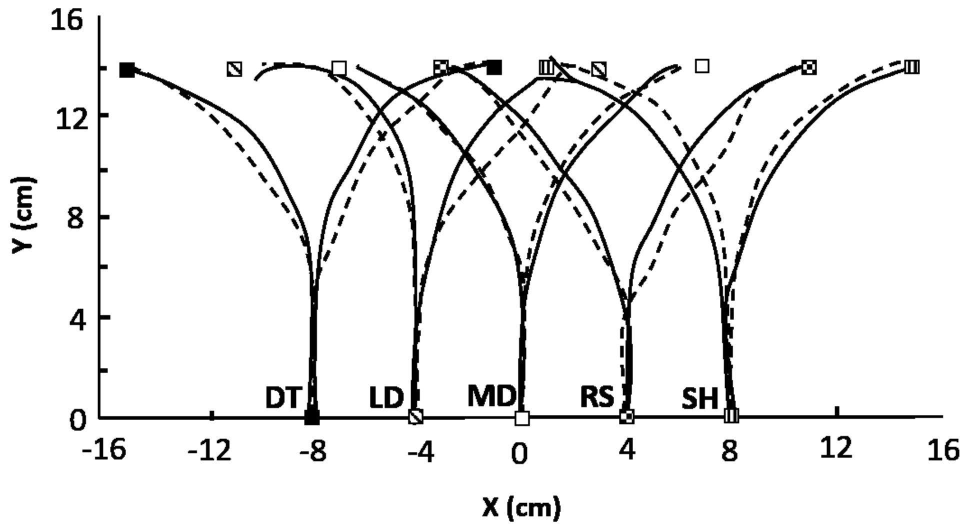
Il semble probable que l'humain traite en continue l'information visuelle de sa main et de la cible durant l'exécution d'un geste d'atteinte ce qui lui permet de corriger son mouvement si la cible ou la main est déviée de la trajectoire prévue. Si tel est effectivement le cas, on pourrait supposer que, si besoin est, de nombreuses corrections peuvent être apportées à un mouvement en cours de réalisation. Nijhof (2003) a voulu déterminer la justesse de cette prédiction. La tâche utilisée consistait à atteindre d'un mouvement fluide et continu (i.e., sans à-coups ou corrections discrètes) une cible située à 14 cm directement devant une base de départ. Le participant déplaçait une souris d'ordinateur et ce déplacement était illustré par le déplacement d'un curseur sur un écran cathodique. La position de la cible était, elle aussi, illustrée sur cet écran cathodique. Pour certains essais (TM), la position de la cible était changée à l'amorce du mouvement. Pour ces essais, la position de la cible était ensuite continuellement modifiée en fonction de la position de la souris déplacée par le participant. Plus précisément, le déplacement horizontal de la cible (X) était couplé avec la position sagittale (Y) de la souris et était définie par la formule

$$X_t = \lambda Y_m$$

où X_t est la position de la cible sur l'axe horizontal, Y_m est la position de la main sur l'axe sagittal alors que λ est une constante qui pouvait varier de -0,5 à 0,5 en fonction des essais. Une valeur positive de λ déplaçait la cible vers la droite alors qu'une valeur négative la déplaçait vers la gauche. Notez que la situation sans perturbation est caractérisée par une valeur de $\lambda = 0$. Dans une deuxième condition expérimentale (PM) c'était le pointeur contrôlé par les participants qui était dévié suite à l'amorce du mouvement; la position de la cible, elle, ne changeait pas.

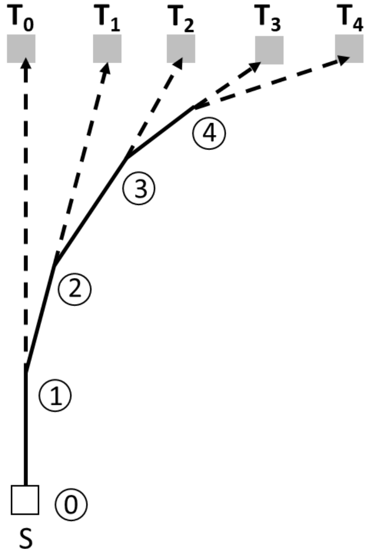
La Figure 5 présente les trajectoires moyennes de six participants pour les essais TM (lignes pointillées). Comme on peut le voir sur cette figure, les participants corrigeaient leur mouvement pour s'ajuster aux déplacements successifs de la cible. Ceci suggère une mise à jour fréquente des informations visuelles relatives à la position de la cible qui permettrait de corriger le mouvement de façon continue sans avoir recours à des corrections discrètes. La Figure 6 montre schématiquement comment, selon les auteurs, les participants ont réussi à adapter leur mouvement aux déplacements successifs de la position de la cible.

Figure 5



Trajectoires de la souris durant les essais TM (lignes pointillées) et PM (lignes pleines) pour 5 participants. Pour plus de visibilité, les trajectoires des participants LD et RS ont été dévié de 4 cm et celles de SH et DT de 8 cm. Tiré de Nijhof, 2003.

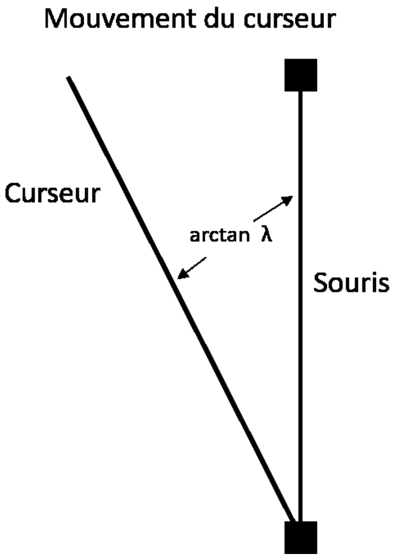
Figure 6



Cascade hypothétique de segments de trajectoire de la souris (ligne pleine). Les lignes pointillées indiquent la direction des mouvements à différents instants. S représente la position de départ et Ti la position (intermédiaire) de la cible. Cet essai nécessiterait 4 corrections afin d'atteindre la cible. Tiré de Nijhof, 2003.

Pour la condition PM, la déviation latérale du curseur suivait les mêmes règles que celles énoncées précédemment pour le déplacement de la cible (Figure 7).

Figure 7



Représentation schématique de la perturbation. La position horizontale du curseur est couplée avec la position sagittale de la souris. Tiré de Nijhof, 2003.

Les trajectoires moyennes pour ce type d'essais sont aussi présentées sur la Figure 5 (lignes pleines). Les résultats montrent que, tout comme pour les essais TM, les participants modulaient leur trajectoire de mouvement pour contre-carrer la perturbation. Les auteurs proposent que ces résultats indiquent que les participants ont réalisé une série de corrections à leur mouvement, ce qui suggère un mode de contrôle en continu. Cette interprétation des données confortait une proposition antérieure de Elliott et al. (1991). Qui plus est, on remarque facilement que les corrections pour les perturbations de type PM étaient beaucoup moins saccadées que celles réalisées pour les essais de type TM. Ceci supporte un traitement en continue des mouvements de l'effecteur qui pourrait être basé sur un mécanisme différent de celui observé lorsque c'est la cible visée qui est déplacée.

Saunders et Knill (2003) ont testé directement l'hypothèse que le traitement des afférences visuelles se fait de façon continue tout au long du mouvement. Dans cette étude, les participants devaient atteindre une cible visuelle à l'aide d'un curseur qui représentait la position de leur main. Contrairement aux études précédentes, dans lesquelles les perturbations du déplacement du curseur survenaient à l'amorce du mouvement ou tôt après celle-ci, la trajectoire du curseur était déviée en début de mouvement (25% de la distance à parcourir) ou à mi-parcours (50% de la distance à parcourir). Tel qu'illustré à la Figure 8, les perturbations déplaçaient « instantanément » la position du curseur de 2 cm sur la composante directionnelle du mouvement. Finalement, dans une première séance expérimentale, les participants devaient compléter leurs mouvements en 450 ms (Fast movements); le temps de mouvement cible était de 650 ms dans l'autre séance (Slow movements). Pour chacune des séances, 30% des essais étaient perturbés.

Figure 8

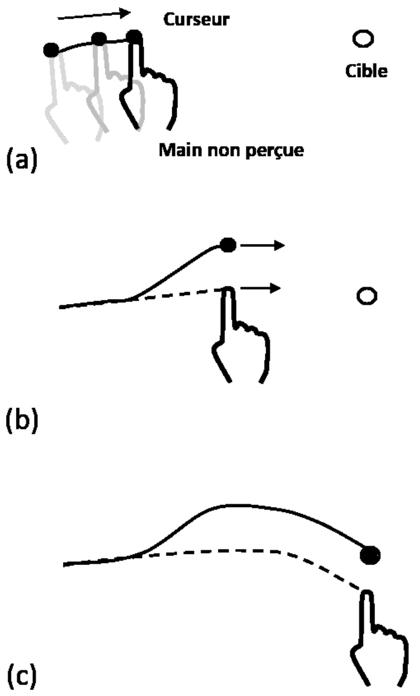
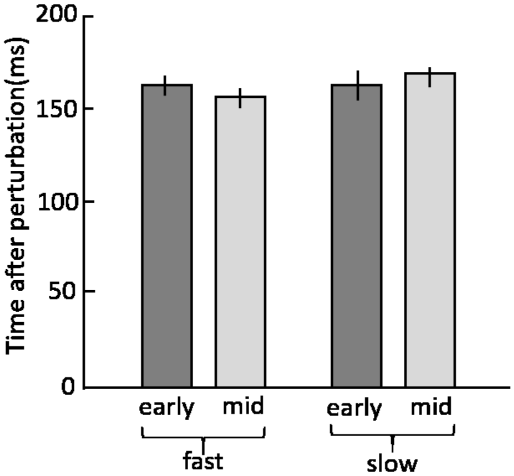


Illustration d'un essai perturbé. **a** Au début du mouvement, la position du curseur (cercle plein) coïncide avec celle du doigt du participant. **b** Durant le mouvement, une perturbation déplace la position du curseur, de sorte qu'elle ne représente plus exactement la position du doigt. **c** Pour que le curseur atteigne la cible, le participant doit compenser pour la perturbation, de sorte que son doigt termine à une position opposée au déplacement du curseur. Tiré de Saunders et Knill, 2003.

Rappelons que l'hypothèse expérimentale était que le mouvement était sous le contrôle continu des afférences visuelles. Donc, la latence de la correction ne devrait pas être influencée par l'endroit d'occurrence de la perturbation ou par le temps de mouvement imposé. Au contraire, si le SNC traite l'information visuelle relative au déplacement de la main uniquement en fin de mouvement, tel que suggéré dans plusieurs modèles présentés en début de chapitre, la latence des corrections devrait être plus longue lorsque la perturbation arrive en début de mouvement plutôt qu'à mi-parcours; elle devrait aussi être plus longue lorsque le temps de mouvement cible était de 650 ms plutôt que de 450 ms. Les délais de correction pour les différents types d'essais sont illustrés à la Figure 9. Comme on peut facilement l'observer, les latences de correction ne variaient pas de façon significative en fonction des conditions expérimentales. La latence moyenne était de 163 ms.

Figure 9



Latence moyenne des corrections pour chacune des combinaisons du moment d'occurrence de la perturbation (early, late) et du temps de mouvement imposé (fast, slow). Tiré de Saunders et Knill, 2003.

À la lumière de ces résultats, les modèles qui suggèrent que le feedback visuel est seulement analysé à la dernière phase des mouvements d'atteinte doivent donc être rejetés (Carlton, 1981 ; Jeannerod, 1988 ; Meyer et al. 1988 ; Rizzo and Darling, 1997 ; Woodworth, 1899). Au contraire, il apparaît que le feedback visuel relatif au déplacement de la main est analysé tout au long du mouvement.

5- Automaticité des corrections

Dans les études présentées plus haut, il était souvent rapporté que les participants ne percevaient pas consciemment les perturbations de la position de la cible ou de l'effecteur.

Ceci suggère que les processus de détection et de correction des erreurs induites expérimentalement dans ces études ne requièrent pas beaucoup de ressources attentionnelles. Dans la même veine, ces corrections ne semblaient pas être apprises avec la pratique puisqu'elles : (a) apparaissaient lors du tout premier essai perturbé et (b) ne s'amélioraient pas de façon significative avec la pratique (Magescas et al., 2009 ; Proteau et al., 2009). Plusieurs chercheurs se sont penchés sur la question de l'automaticité de ces processus.

Dans une étude de Day et Lyon (2000), les participants étaient amenés à pointer vers une cible placée directement devant eux qui était susceptible de changer de position 25 ms après l'amorce de leur mouvement. La cible pouvait être déviée de 10 cm vers la gauche ou vers la droite. Pour certains essais, on demandait aux participants d'aller atteindre cette nouvelle cible (Reach +) alors que pour d'autres essais on demandait au participant d'aller dans la direction opposée au déplacement de la cible (Reach -). Les résultats de cette étude révèlent que le déplacement de la cible a toujours entraîné l'amorce d'une correction dans la direction du déplacement de la cible, et ce, même pour la condition expérimentale pour laquelle on avait demandé aux participants d'aller à contresens de ce déplacement. Ces résultats suggèrent que l'amorce de la correction notée dans ces études n'est pas sous le contrôle volontaire des participants.

Des résultats similaires ont été rapportés par Pisella et al. (2000) qui, plutôt que de demander de produire un mouvement dans la direction opposée au déplacement de la cible demandaient aux participants d'interrompre leur mouvement lorsqu'ils détectaient un déplacement de la cible. Les participants ont néanmoins atteint la cible déviée pour 9% des essais pour lesquels ils devaient interrompre leur mouvement.

Dans le même ordre d'idée mais plus récemment, Franklin et al. (2014) ont tenté de déterminer si cet effet serait aussi présent pour des sauts de curseurs. Dans la 2^e expérience de cette étude, les participants réalisaient des mouvements vers une cible située directement devant eux, à 25 cm de la base de départ. Pour un premier type d'essais (Task relevant), le curseur était dévié latéralement vers la droite (entre 1 et 5 cm) tôt après l'amorce de leur mouvement. Afin de placer le curseur sur la cible, le participant devaient donc apporter une correction équivalente à la grandeur de la perturbation. Pour un deuxième type d'essais (Task irrelevant), le curseur se déplaçait sensiblement de la même façon que dans la situation « Task relevant » mais dans ce cas la perturbation était dirigée vers la gauche. La principale différence pour ce type d'essai était que, suite à la perturbation, le curseur revenait aussitôt et de lui-même sur sa trajectoire initiale de sorte qu'aucune correction n'était nécessaire. Ainsi, tous les essais perturbés vers la droite nécessitaient une correction alors que tous ceux vers la gauche n'en requérait pas.

Les résultats montrent que même après une longue période d'adaptation de plus de 1000 essais, les participants continuaient à produire une réponse correctrice pour un essai perturbé vers la gauche (Task irrelevant). C'est seulement après une durée de 200 ms suivant la perturbation que des différences significatives survenaient entre les 2 types d'essais perturbés. Tout comme dans le cas des sauts de cible, il semble que la réaction correctrice suite à une perturbation de la trajectoire du curseur est « automatique » et donc difficile à inhiber.

En résumé, ces dernières expériences supportent l'idée que les afférences visuelles sont traitées en cours d'exécution et permettent d'ajuster l'impulsion initiale d'un mouvement d'atteinte manuelle. La demande attentionnelle semble minime pour détecter l'erreur induite expérimentalement et pour planifier et amorcer une correction efficace. De plus, plusieurs études ont montré qu'il était difficile (voire impossible) d'inhiber cette réaction. Certains auteurs parlent même de réactions réflexes (Franklin et Wolpert, 2008). Malgré le grand nombre d'études portant sur le sujet, plusieurs caractéristiques restent à analyser concernant ces corrections en ligne. Tout d'abord, est-ce que l'amorce d'une correction de ce type interagit avec le traitement continu des afférences visuelles? De plus, quelle est la source exacte d'information qui est utilisée par le système visuel? Est-ce un rafraîchissement complet et continu de la position perçue de l'effecteur ou une méthode plus économique est-elle mise en place notamment pour tenir compte du bruit inhérent à chaque système? Concernant la correction, est-elle réellement de type réflexe comme le suggèrent Franklin et Wolpert (2008) ou cette correction est-elle fonctionnelle en ce sens qu'elle est adaptée aux contraintes de l'objectif à atteindre ? Finalement, est-ce que l'information visuelle dynamique relative au saut de curseur en tant que tel ajoute aux informations disponibles concernant la trajectoire du mouvement?

Dans la présente thèse, le focus a été placé sur la correction d'erreurs induites expérimentalement en modifiant la position perçue de l'effecteur, soit des « sauts de curseur ». Ce choix a été fait parce que nous nous intéressons plus particulièrement à la capacité d'un individu à corriger un mouvement mal exécuté ou mal planifié dans des conditions pour lesquelles l'objectif initial (la cible à atteindre) demeure le même. À cet égard, malgré des résultats souvent semblables d'une étude à l'autre, rien n'indique que les perturbations de cibles sont traitées de la même façon que celles modifiant la position de l'effecteur (se rappeler de la Figure 6 présentée plus haut et des commentaires s'y rattachant). De plus, une étude récente suggère elle aussi des différences dans les mécanismes et les régions corticales impliquées pour des corrections à un saut de cible ou à un saut de curseur (Reichenbach et al. 2014).

Références

Abahnini K, Proteau L (1999) The role of peripheral and central visual information for the directional control of manual aiming movements. Can J Exp Psychol 53:160-175

Abahnini K, Proteau L, Temprado JJ (1997) Evidence supporting the importance of peripheral visual information for the directional control of aiming movement. J Motor Behav 29:230–242

Balslev D, Miall RC, Cole J (2007) Proprioceptive deafferentation slows down the processing of visual hand feedback. J Vis 7:1-7

Bard C, Hay L, Fleury M (1985) Role of peripheral vision in the directional control of rapid aiming movements. Can J Psychol 39:151-161

Bard C, Paillard J, Fleury M, Hay L, Larue J (1990) Positional versus directional control loops in visuomotor pointing. Eur J Cogn Psychol 10:145-156

Bédard P, Proteau L (2004) On-line vs. off-line utilization of peripheral visual afferent information to ensure spatial accuracy of goal-directed movements. Exp Brain Res 158:75-85

Bédard P, Proteau L (2003) On the role of peripheral visual afferent information for the control of rapid video-aiming movements. Acta Psychol 113:99-117

Bekkering H, Adam JJ, Aarssen A, Kingma H, Whiting HTA (1995) Interference between saccadic eye and goal-directed hand movements. Exp Brain Res 106:475-484

Bridgeman B, Lewis S, Heit G, Nagle M (1979) Relation between cognitive and motor-oriented systems of visual position perception. J Exp Psychol Hum Percept Perform 5:692–700

Carlton LG (1981) Processing visual feedback information for movement control. J Exp Psychol Human 7:1019–1030

Carlton LG (1992) Visual processing time and the control of movement. In L Proteau & D Elliott (Eds.) Vision and motor control. 3-31 Amsterdam: North Holland

Chua R, Elliott D (1993) Visual regulation of manual aiming. Hum Movement Sci 14:365-401

Carson RG, Chua R, Elliott D, Goodman D (1990) The contribution of vision to asymmetries in manual aiming. Neuropsychologia 28:1215-1220

Crossman ER, Goodeve PJ (1983) Feedback control of hand-movement and Fitts' Law. QJ Exp Psychol A 35:251-278

Day BL, Lyon IN (2000) Voluntary modification of automatic arm movements evoked by motion of a visual target. Exp Brain Res 130:159–168

Desmurget M, Epstein CM, Turner RS, Prablanc C, Alexander GE, Grafton ST (1999) Role of posterior parietal cortex in updating reaching movements to a visual target. Nat Neurosci 2:563–567

Desmurget M, Grafton S (2000) Foward modeling allows feedback control for fast reaching movements. Trends Cogn Sci 4:423-431

Desmurget M, Pélisson D, Rossetti Y, Prablanc C (1998) From eye to hand: planning goal-directed movements. Neurosci Biobehav Rev 22:761-788

Elliott D, Allard F (1985) The utilization of visual feedback information during rapid pointing movements. Q J Exp Psychol A 37:407-425

Elliott D, Garson RG, Goodman D, Chua R (1991) Discrete vs. continuous visual control of manual aiming. Hum Movement Sci 10:393-418

Elliott D, Helsen WF, Chua R. (2001) A century later: Woodworth's (1899) twocomponent model of goal-directed aiming. Psychol Bull 127:342-357

Fisk JD, Goodale MA (1985) The organization of eye and limb movements during unrestricted reaching to targets in contralateral and ipsilateral visual space. Exp Brain Res 60:159-178

Fox MD, Snyder AZ, Vincent JL, Raichle ME (2007) Intrinsic fluctuations within cortical systems account for intertrial variability in human behaviour. Neuron 56:171-184

Franklin DW, Wolpert DM (2008) Specificity of reflex adaptation for task-relevant variability. J Neurosci 28:14165–14175

Franklin S, Franklin DW, Wolpert DM (2014) Fractionation of the visuomotor feedback response to directions of movement and perturbation. J Neurophysiol 112:2218–2233

Franklin S, Wolpert DM, Franklin DW (2012) Visuomotor feedback gains upregulate during the learning of novel dynamics. J Neurophysiol 108:467–478

Gaveau V, Pisella L, Priot A-E, Fukui T, Rossetti Y, Pélisson D, Prablanc C (2014) Automatic online control of motor adjustments in reaching and grasping. Neuropsychologia 55:25-44

Goodale MA, Pelisson D, Prablanc C (1986) Large adjustments in visually guided reaching do not depend on vision of the hand or perception of target displacement. Nature 320:748-750

Gritsenko V, Kalaska JF (2010) Rapid online correction is selectively suppressed during movement with a visuomotor transformation. J Neuphysiol 104:3084-3104

Gritsenko V, Yakovenko S, Kalaska JF (2009) Integration of predictive feedforward and sensory feedback signals for online control of visually guided movement. J Neurophysiol 102:914-930

Helsen WF, Elliott D, Starkes JL, Ricker KL (2000) Coupling of eye, finger, elbow, and shoulder movements during manual aiming. J Motor Behav 32:241-248

Helsen WF, Starkes JL, Buekers MJ (1997) Effects of target eccentricity on temporal costs of point of gaze and the hand in aiming. Motor Control 1:161-177

Henriques DYP, Crawford JD (2000) Direction-dependent distortions of retinocentric space in the visuomotor transformation for pointing. Exp Brain Res 132:179-194

Henriques DYP, Medendorp MP, Gielen CCAM, Crawford JD (2003) Geometric computations underlying eye-hand coordination: orientations of the two eyes and the head. Exp Brain Res 152:70-78

Jeannerod M (1988) The neural and behavioural organization of goal directed movements. Clarendon Press, Oxford

Khan MA, Lawrence GP, Franks IM, Buckolz E (2004) The utilization of visual feedback from peripheral and central vision in the control of direction. Exp Brain Res 158:241-251

Khan MA, Elliott D, Coull J, Chua R, Lyons J (2002) Optimal control strategies under different feedback schedules: kinematic evidence. J Motor Behav 34:45-57

Khan MA, Franks IM (2003) Online versus offline processing of visual feedback in the production of component submovements. J Motor Behav 35:285-295

Khan MA, Franks IM (2000) The effect of practice on component submovements is dependent on the availability of visual feedback. J Motor Behav 32:227-240

Khan MA, Lawrence GP, Fourkas A, Franks IM, Elliott D, Pembroke S (2003) Online versus offline processing of visual feedback in the control of movement amplitude. Acta Psychol 113:83-97

Keele SW (1968) Movement control in skilled motor performance. Psychol Bull 70:387-403

Land MF, Hayhoe M (2001) In what ways do eye movements contribute to everyday activities? Vision Res 41:3559–3565

Lawrence GL, Khan MA, Buckolz E, Oldham ARH (2006) The contribution of peripheral and central vision in the control of movement amplitude. Hum Movement Sci 25:326-338

Lhuisset L, Proteau L (2002) Developmental aspects of the control of manual aiming movements in aligned and non-aligned visual displays. Exp Brain Res 146:293-306

Lhuisset L, Proteau L (2004) Planning and control of straight-ahead and angled planar movements in adults and young children. Can J Exp Psychol 58:245-258

Mackrous I, Proteau L (2007) Specifiity of practice results from diverences in movement planning strategies. Exp Brain Res 183:181–193

Magescas F, Urquizar C, Prablanc C (2009) Two modes of error processing in reaching. Exp Brain Res 193:337–350

Messier J, Kalaska JF (1999) Comparison of variability of initial kinematics and endpoints of reaching movements. Exp Brain Res 125:139–152

Meyer DE, Abrams RA, Kornblum S, Wright CE, Smith JE (1988) Optimality in human motor performance: ideal control of rapid aimed movements. Psychol Rev 95:340-370

Morasso P (1981) Spatial control of arm movements. Exp Brain Res 42:223-227

Nakano E, Imamizu H, Osu R, Uno Y, Gomi H, Yoshioka T, Kawato M (1999) Quantitative examinations of internal representations for arm trajectory planning: minimum commanded torque change model. J Neurophysiol 81:2140-55

Neggers SFW, Bekkering H (1999) Integration of visual and somatosensory target information in goal-directed eye and arm movements. Exp Brain Res 125:97-107

Neggers SFW, Bekkering H (2000) Ocular gaze is anchored to the target of an ongoing pointing movement. J Neurophysiol 83:639-651

Neggers SFW, Bekkering H (2001) Gaze anchoring to a pointing target is present during the entire pointing movement and is driven by a non-visual signal. J Neurophysiol 86:961-970

Neggers SFW, Bekkering H (2002) Coordinated control of eye and hand movements in dynamic reaching. Hum Movement Sci 21:37-64

Nijhof EJ (2003) On-line trajectory modifications of planar, goal-directed arm movements. Hum Mov Sci 22:13-36

Osu R, Morishige K, Nakanishi J, Miyamoto H, Kawato M (2015) Practice reduces task relevant variance modulation and forms nominal trajectory. Scientific Reports 5:17659 DOI: 10.1038/srep17659

Paillard J, Amblard B (1985) Static versus kinetic visual cues for the processing of spatial relationships. Brain Mechanisms and Spatial Vision 21:299-330

Pelisson D, Prablanc C, Goodale MA, Jeannerod M (1986) Visual control of reaching movements without vision of the limb. II. Evidence of fast unconscious processes correcting the trajectory of the hand to the final position of a double-step stimulus. Exp Brain Res 62:303–311

Pisella L, Gréa H, Tilikete C, Vighetto A, Desmurget M, Rode G, Boisson D, Rossetti Y (2000) An ‘automatic pilot’ for the hand in human posterior parietal cortex: toward reinterpreting optic ataxia. Nat Neurosci 3:729–736

Prablanc C, Echallier JE, Jeannerod M, Komilis E (1979) Optimal response of eye and hand motor systems in pointing at a visual target. II. Static and dynamic visual cues in the control of hand movement. Biol Cybern 35:183-187

Prablanc C, Echallier JF, Komilis E, Jeannerod M (1979) Optimal response of eye and hand motor systems in pointing at a visual target. I. Spatio-temporal characteristics of eye and hand movements and their relationships when varying the amount of visual information. Biol Cybern 35:113-124

Prablanc C, Martin O (1992) Automatic control during hand reaching at undetected twodimensional target displacements. J Neurophysiol 67:455-469

Proteau L (1992) On the specificity of learning and the role of visual information for movement control. In L Proteau & D Elliott (Eds.) Vision and motor control. 67-103 Amsterdam: North Holland

Proteau L (2005) Visual afferent information dominates other sources of afferent information during mixed practice of a video-aiming task. Exp Brain Res 161:441-456

Proteau L, Isabelle G (2002) On the role of visual afferent information for the control of aiming movements toward targets of different sizes. J Motor Behav 34:367–384

Proteau L, Roujoula A, Messier J (2009) Evidence for continuous processing of visual information in a manual video-aiming task. J Motor Behav 41:219-231

Reichenbach A, Franklin DW, Zatka-Haas P, Diedrichsen J (2014) A dedicated binding mechanism for the visual control of movement. Curr Biol 24:780-785

Rizzo M, Darling W (1997) Reaching with cerebral tunnel vision. Neuropsychologia 35:53-63

Robin C, Toussaint L, Blandin Y, Proteau L (2005) Specificity of learning in a video-aiming task: Modifying the salience of dynamic visual cues. J Motor Behav 37:367–377

Rossetti Y, Koga K, Mano T (1993) Prismatic displacement of vision induces transient changes in the timing of eye-hand coordination. Percept Psychophys 54:355-364

Sailer U, Eggert T, Ditterich J, Straube A (2000) Spatial and temporal aspects of eye-hand coordination across different tasks. Exp Brain Res 134:163-173

Sarlegna F, Blouin J, Bresciani JP, Bourdin C, Vercher JL, Gauthier GM (2003) Target and hand position information in the online control of goal-directed arm movements. Exp Brain Res 151:524–535

Sarlegna F, Blouin J, Vercher JL, Bresciani JP, Bourdin C, Gauthier GM (2004) Online control of the direction of rapid reaching movements. Exp Brain Res 157:468–471

Saunders JA, Knill DC (2003) Humans use continuous visual feedback from the hand to control fast reaching movements. Exp Brain Res 152:341–352

Saunders JA, Knill DC (2004) Visual feedback control of hand movements. J Neurosci 24:3223–3234

Saunders JA, Knill DC (2005) Humans use continuous visual feedback from the hand to control both the direction and distance of pointing movements. Exp Brain Res 162:458–473

Schmidt RA, Zelaznik H, Hawkins B, Frank JS, Quinn JT Jr (1979) Motor-output variability: A theory for the accuracy of rapid motor acts. Psychol Rev 86:415-451

Soechting JF, Lacquaniti F (1983) Modification of trajectory of a pointing movement in response to a change in target location. J Neurophysiol 49:548-564

Soucy M-C, Proteau L (2001) Development of multiple movement representations with practice: Specificity vs. flexibility. J Motor Behav 33:243-254

Spijkers WAC, Lochner P (1994) Partial visual feedback and spatial end-point accuracy of discrete aiming movements. J Motor Behav 26:283-295

Temprado JJ, Vieilledent S, Proteau L (1996) Afferent information for motor control: the role of visual information in different portions of the movement. J Motor Behav 28:280-287

Uno Y, Kawato M, Suzuki R (1989) Formation and control of optimal trajectory in human multijoint arm movement. Minimum torque-change model. Biol Cybern 61:89-101

van Beers RJ, Haggard P, Wolpert DM (2004) The role of execution noise in movement variability. J Neurophysiol 91:1050-1063

Vercher JL, Magenes G, Prablanc C, Gauthier GM (1994) Eye-head-hand coordination in pointing at visual targets: spatial and temporal analysis. Exp Brain Res 99:507-523

Woodworth RS (1899) The accuracy of voluntary movement. Psychol Rev Monographs 3:1-119

Zelaznik HZ, Hawkins B, Kisselburgh L (1983) Rapid visual feedback processing in single-aiming movements. J Motor Behav 15:217-236

Chapitre 2 : Article 1

Automatic movement error detection and correction processes in reaching movements

Julien Brière and Luc Proteau[1]
Département de kinésiologie
Université de Montréal

[1]Corresponding author:
Luc Proteau, Département de kinésiologie, Université de Montréal, P.O. Box 6128,
Downtown Station, Montréal, Canada, H3C 3J7.
Tel: (514) 343-2039
Fax: (514) 343-2181
Email: luc.proteau@umontreal.ca

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Abstract

Manual aiming movements can be amended during their execution. Recent evidence suggests that error detection and correction are based on automatic and even reflexive processing of afferent information. In this study, we wanted to determine whether these processes are affected by the occurrence of successive events requiring adjustments of the originally planned movement. To reach our goal, we used a video-aiming task. For a small proportion of the trials, the cursor moved by the participant was translated laterally by 15 mm (cursor jump) soon after movement initiation. For some of the cursor-jump trials, a second cursor jump occurred 100 ms after the first one and cancelled or doubled the initial cursor translation. Results showed that participants were able to cancel or double the size of the correction in response to the second cursor jump. More importantly, in double-jump trials, the correction latency for the first and second cursor jumps did not differ from that of single-jump trials. Moreover, the correction for the second cursor jump blended seamlessly with the correction for the first cursor jump. These observations suggest that the processes leading of a correction for a cursor jump do not interfere with incoming visual information.

Keywords: cursor jump, manual aiming, visual feedback, motor control, automatic correction, online control processes

Automatic movement error detection and correction processes in reaching movements

Manual aiming toward a visual target puts into play a series of processes to identify the target and its location and to transform this information into appropriate motor commands (for a review, see Desmurget, Pélisson, Rossetti, and Prablanc 1998). Each process leading to movement planning and then to movement execution has intrinsic variability. Because of this noise inherent to all biological systems, and the high level of accuracy required in many of our daily activities, the CNS must quickly update movement planning and amend movement execution.

Error detection and correction mechanisms have been the center of many research efforts since the seminal work of Woodworth (1899). Although numerous research strategies have been used in the last century, many authors have opted to use a perturbation paradigm. In this paradigm, some aspects of the task are changed just prior to, at, or soon after movement initiation. Because these perturbations occur unexpectedly and often for only a small proportion of the trials, it is expected that participants would plan their movements as if no perturbation would occur. Thus, to reach the target, participants need to correct the movement they have planned and initiated to counteract the perturbation, which opens a window on error detection and correction processes.

In many experiments, the perturbation changed the target location or the visually perceived location/velocity of the participant’s hand. Typically, in target-jump experiments (Bridgeman et al. 1979; Desmurget et al. 1999; Goodale et al. 1986; Prablanc and Martin 1992), participants were asked to move their hand from a fixed start position toward one target shown on a visual display. Participants first gazed at a fixation position and, following a variable foreperiod, a target was illuminated in their peripheral visual field. Participants were asked to look at and to aim at the target quickly and accurately. Just prior to or soon after movement initiation (i.e., during the saccadic suppression period), the location of the target was switched to a different one. In many cursor-jump experiments (Franklin and Wolpert 2008; Proteau et al. 2009; Saunders and Knill 2003, 2004, 2005; Veyrat-Masson et al. 2010), participants moved a cursor shown on a visual display to a target illustrated on the same display. The location of the cursor representing the participant's hand could be translated for example by 2 cm soon after movement initiation.

In both target-jump and cursor-jump experiments, results revealed that although participants did not report having been aware of the perturbation, they quickly and accurately modified their movement trajectory so that their hand (or the cursor) ended close to the target. Interestingly, the time required to initiate a correction was independent of when or where the perturbation took place in the movement trajectory. Therefore, it was proposed that manual aiming movements are under continuous visual control (Saunders and Knill 2003, 2005). Because effective corrections were apparent even for the first perturbed trial to which participants were exposed (Proteau et al. 2009), it was concluded that the error detection and correction processes put into play did not require learning or adaptation. Finally, because participants in target-jump experiments could not refrain from initiating a correction toward the new target location (Day and Lyon, 2000; Johnson et al. 2002; Pisella et al. 2000) it was concluded that an "automatic pilot" relying on spatial vision drives fast corrective arm movements (but see also Cameron et al. 2007). Similarly, because participants could not refrain from initiating a correction in the direction opposite to the cursor jump (Franklin and

Wolpert 2008) even when asked to move their hand in the same direction as the perturbation, it was proposed that the correction was reflexive.

In this study, we used a cursor-jump paradigm to determine whether a correction initiated by the automatic pilot interferes with the detection of a second cursor jump. To reach our goal, for a small proportion of the trials, the cursor moved by the participant was translated laterally by 15 mm, 150 ms after movement initiation. For some of the cursor-jump trials, a second cursor jump occurred 100 ms after the first one and cancelled or doubled the initial cursor translation. For the latter two conditions, recent data has indicated that although the first cursor-jump had been detected by the CNS, a correction had not yet been initiated when the second one occurred (Proteau et al. 2009; Sarlegna et al. 2003, 2004; Saunders and Knill 2003, 2004, 2005). If the correction initiated by the automatic pilot for the first cursor jump interferes with detection and error correction processes of the second cursor jump, then the time required to initiate a correction would be significantly longer for the second cursor jump than it would be for the first cursor jump. This possible interference could also lead to less efficient corrections for the second cursor jump than it would for the single-jump trials. Either one of these two result patterns would indicate that the automatic pilot is not as automatic as first believed. In addition, we also wanted to determine how the correction for the second cursor jump would be integrated with that of the first cursor jump.

Method

Participants

Twelve participants aged between 20 and 30 years and who were students at the Université de Montréal took part in this experiment. The participants were all self-declared right handed and reported normal or corrected to normal vision. The Health Sciences Ethics Committee of the Université de Montréal approved this study.

Task and apparatus

The task was to move a computer-mouse-like device from a fixed starting position located close to the body toward one of two possible targets located further away from the body. The apparatus is illustrated in Figure 1. It consisted of a table, a computer screen, a headrest, a mirror, and a two-degree-of-freedom manipulandum. Participants sat in front of the table. The CRT computer screen (Mitsubishi, Color Pro Diamond 37 inches, refresh rate 60 Hz, resolution 1024 x 768) was mounted on a ceiling-support positioned directly over the table; the computer screen was oriented parallel to the surface of the table. The screen's image was reflected on a mirror placed directly beneath and parallel to the tabletop. The distance between the computer screen and the mirror was 20 cm; the distance between the mirror and the tabletop was also 20 cm, which permitted free displacement of the manipulandum on the tabletop. The information presented on the computer screen was thus reflected on the mirror and was visible to the participant. A headrest was affixed on the side of the computer screen. It was aligned with the lateral center of the computer screen and was used to standardize the information displayed on the computer screen for all participants.

The tabletop was covered by a piece of Plexiglas over which a starting base and the manipulandum were affixed. The starting base consisted of a thin strip of Plexiglas glued to the tabletop. It was parallel to the leading edge of the table and had a small indentation on its distal face. This indentation was aligned laterally and sagitally with the headrest, was aligned laterally with the participant’s midline, and served as the starting base for the stylus. The indentation made it easy for the participant to position the stylus at the beginning of each trial.

The manipulandum consisted of two pieces of rigid Plexiglas (43 cm) joined at one end by an axle. One free end of the manipulandum was fitted with a second axle encased in a stationary base. The other free end of the manipulandum was fitted with a small vertical shaft (length: 3 cm; radius: 1 cm), i.e. the stylus, which could be gripped by the participant. Each axle of the manipulandum was fitted with a 13-bit optical shaft encoder (U.S. Digital, model S2-2048, sampled at 500 Hz, angular accuracy of 0.0439°), which enabled us to track the displacement of the stylus online and to illustrate it with a 1:1 ratio on the computer screen. Moving the stylus away from the body in the frontal and sagittal planes resulted in an identical displacement of the cursor on the computer screen. The bottom of the stylus and the bottom of the optical encoder located at the junction of the two arms of the manipulandum were covered with a thin piece of Plexiglas. By lubricating the working surface at the beginning of each experimental session, displacement of the stylus was near frictionless.

Procedures

Participants were asked to try stopping the cursor (yellow; 3 mm in diameter) on a target with a 5 mm diameter. Two white targets presented on a black screen were used. The targets were located 320 mm in front of the starting base and 86 mm to the left or right (15˚ to the left or right of the participant's midline).

Participants were asked to use their right hand to initiate their movement as they pleased following presentation of a target (i.e., not a reaction time task) and to perform smooth and continuous movements (i.e., not a stop and go strategy). Participants were also required to gaze at the target during movement execution (their natural behavior to ensure optimal accuracy; Neggers and Bekkering, 1999, 2000, 2001) and to complete their movements in a movement time ranging between 680 ms and 920 ms (800 ms +/- 15 %). When movements were completed outside this movement time bandwidth, the experimenter reminded the participant of the target movement time. We chose a relatively long target movement time and far target locations because we wanted the cursor jump (see below) to occur while the cursor was visible far in the periphery of the retina rather than close to target location in central vision.

At the beginning of each trial, all participants could see the cursor they had to move resting on the starting base. Once the stylus was stabilized on the starting base for 500 ms, a target was presented on the screen. During data acquisition, movement initiation was detected when the cursor had been moved by 1 mm, while movement completion was detected when the cursor did not move by more than 2 mm in a time frame of 100 ms. A preliminary study revealed that the procedure used to detect movement completion during data acquisition made it difficult for participants to use a stop and go strategy. When movement completion was detected, the position of the cursor endpoint and the target remained visible for 1s.

Participants first took part in a familiarization phase consisting of 10 trials. This was followed by two sets of 240 experimental trials separated by a 15-minute break. In each set, half of the trials were aimed at the left target while the other half were aimed at right target. Target presentation was randomized across trials with the restriction that each target was presented five times in each successive block of 10 trials.

A cursor jump occurred for 20% of the experimental trials (96 trials). Trials were presented randomly with the restriction that one trial of each of the six types of cursor-jump trials described below occurred once for each target within each successive block of 60 trials. Details concerning the different types of cursor-jump trials are summarized in Table 1. First, for the "early-15" trials, the cursor was translated by 15 mm, 150 ms after movement initiation. Second, for the "15+15" condition, a first 15-mm cursor jump took place 150 ms after movement initiation; this was followed 100 ms later by a second cursor jump of 15 mm in the same direction, thus doubling the size of the correction required to reach the target. Third, for the "15-15" condition, a first 15-mm cursor jump took place 150 ms after movement initiation; this was followed 100 ms later by a second cursor jump of the same amplitude but in the opposite direction, thus cancelling the need for a correction for the first cursor jump. For these double-jump trials, a 100-ms inter-jump delay was chosen because previous work from our laboratory (Proteau et al., 2009) showed that this delay provided enough information for participants to detect the first cursor jump and plan an effective correction without running the risk of the two visual stimuli being considered as one because of temporal and spatial summation. For the "late-15" trials, a 15-mm cursor jump took place 250 ms after movement initiation, while a 30-mm cursor jump took place 150 ms or 250 ms after movement initiation for the "early-30" and "late-30" trials respectively. Note that the delay between the stimulus that triggered a cursor jump and the actual jump on the monitor oscillated between 14 and 21 ms.

For all cursor-jump trials, the first and often only cursor jump translated the cursor perpendicularly to a straight line connecting the starting base and the target. The cursor jumped to the right when participants aimed at the right target and to the left when they aimed at the left target. Thus, a correction for the cursor jump would be observed if the position of the stylus migrated closer to the participant’s midline for the cursor-jump trials than it did for the no-jump trials. Performance for the six types of cursor-jump trials was contrasted to that of randomly selected no-jump trials (i.e., no cursor jump) with the restriction that they did not immediately follow a cursor-jump trial.

Participants were asked to gaze at the target at all times and were not informed that the cursor would jump on some trials. Informing the participants in this way could have interfered with their natural behavior during the task (i.e., gazing at the target). The experimenter noted any comments made by the participants regarding their performance or about anything strange or peculiar happening during a trial.

Data reduction

The tangential displacement data of the stylus over time were first smoothed using a second order recursive Butterworth filter with a cut-off frequency of 10 Hz. The filtered data were then numerically differentiated once using a central finite technique to obtain the velocity profile of the aiming movement, a second time to obtain the acceleration profile, and a third time to obtain a jerk profile. From the kinematic profiles, we determined the end of the movement's primary impulse (Meyer et al. 1988). This occurred when one of the following events was detected on the kinematic profiles: (a) movement velocity fell below 20 mm/s, (b) movement reversal (velocity going from positive to negative), (c) movement lengthening (presence of a secondary movement impulse as indexed by the acceleration profile crossing the zero value for a second time) or (d) a significant disruption in the deceleration profile as indexed by zero-crossing on the jerk profile. For a secondary movement impulse to be considered a discrete correction, its duration had to be at least 80 ms and its extent had to be at least 2 mm. Note that less than 5% of the trials in all conditions showed a secondary corrective impulse. These trials were withdrawn from all analyses.

To provide quick feedback to the participant during data acquisition, movement initiation was detected once the stylus had been moved by 1 mm. However, for the main analyses, movement initiation was defined as the moment at which the tangential velocity of the cursor reached 10 mm/s and was maintained above this value for at least 20 ms. Visual inspection of the data revealed that once 10 mm/s had been reached, movement was clearly underway. Movement endpoint was defined as the end of the movement’s primary impulse using the parsing algorithm defined above. The difference between the procedure used for detecting movement initiation during acquisition and the procedure used in the main analyses explains why the movement times reported below were longer than the target movement time used during data acquisition.

To determine the efficacy of the correction for the cursor jumps, we determined the end of the movement’s primary impulse for all trials (hereafter called endpoint). Endpoint frontal and sagittal errors (in mm) were computed in Cartesian coordinates. Errors refer to the position of the stylus in relation to the center of the target. For the frontal error, a positive value indicates a movement ending to the right of the target, while a negative value indicates a movement ending to the left of the target. For the sagittal error, a positive value indicates that the target had been overshot, while a negative value indicates that it had been undershot. From these data, we computed the constant and variable aiming errors on the frontal and sagittal components of the task. The constant error is the mean signed difference between the target and endpoint location. It indicates whether participants showed a bias in their movements (too long, too short, to the right of the target, to the left of the target). The variable error is the within-participant variability in endpoint location.

For each of these dependent variables, we computed an ANOVA contrasting 7 types of trials (no-jump, early-15, late-15, early-30, late-30, 15+15, 15-15) x 2 targets (left, right) with repeated measures on the two factors. A similar analysis was computed on movement time data. Geisser-Greenhouse correction was applied when Epsilon was smaller than 1. All significant main effects involving more than two means were broken down using Dunn's technique. Significant interactions were broken down by computing simple main effects that were followed by post hoc comparisons (Dunn's technique) when they involved more than two means. All effects are reported at $\underline{p} < .05$ (adjusted for the number of comparisons).

Results

Participants were not aware of cursor jumps

On few occasions, some participants commented on the "poor" orientation of the initial portion of their movement, but they were never aware that it could have resulted from our experimental manipulation. Even after having been debriefed, participants reported that they were not aware that the cursor had jumped on some trials. This aspect of the results replicates previous observations (Bédard and Proteau 2003; Proteau et al. 2009), even when a cursor jump occurred for a high proportion of the trials (though during saccadic visual suppression, Sarlegna et al. 2003, 2004; see also Saunders and Knill 2003, 2005). It should be noted that, on average, the cursor jump occurred at 38.3° and 30.5° of visual angle for early- and late-jump conditions, respectively. As expected, this is quite far in the periphery of the retina, which may explain why participants did not notice it.

Effective correction for a cursor jump

In the present section, we wanted to determine whether participants corrected their movements for the cursor jump, and if so, how effectively. Movement trajectories of a randomly selected participant are illustrated in Figure 2 for no-jump trials and the six types of cursor-jump trials. As in previous work, the four leftmost panels of this figure illustrate that the participant modified the trajectory of his movements to compensate for both 15-mm and

30-mm cursor jumps (Sarlegna et al. 2004) occurring both sooner and later following movement initiation (Saunders and Knill 2003, 2005). More interestingly, the upper and lower rightmost panels of this figure illustrate that the movement trajectory was modified to cancel (upper panel) or double (lower panel) the correction needed by the first cursor jump in the 15-15 and 15+15 conditions, respectively. The results of the endpoint constant frontal and sagittal errors of all participants (see Figure 3) supported the above observations and revealed that these corrections significantly differentiated movement endpoints of no-jump and cursor-jump trials.

Frontal component. The ANOVA on endpoint constant frontal error revealed a significant Target x Types of trials interaction, F(6, 66) = 212.8, p < 0.001; its breakdown revealed a significant effect of types of trials for both the left and the right targets, F(6, 66) = 9.58, p < 0.001. Post hoc comparisons revealed that for both the left and the right targets, participants ended their movements significantly closer to their midline for the single-jump trials than they did for the no-jump trials. This last observation denotes a correction for the cursor jumps (see Figure 3a). For both targets, correction for the cursor jump was significantly larger for the 30-mm cursor jump than it was for the 15-mm cursor jump (18.5 mm vs. 11.1 mm, p < 0.005), but did not differ significantly as a function of the moment of occurrence of the cursor jump (p = 1.0). Thus, participants corrected their movements as a function of cursor-jump size. For the double-jump trials, the 15-15 trials did not differ significantly from the no-jump trials (p = 1.0) but differed significantly from all other types of jump trials (early-15, late-15, early-30, late-30, 15+15), indicating that participants were able to cancel the correction needed by the initial cursor jump. Similarly, the 15+15 trials did not differ significantly from the early- 30 and late-30 trials (p > 0.27) but differed significantly from all other types of trials (no-jump, early-15, late-15, 15-15), indicating that participants detected the second cursor jump and doubled the correction needed by the initial cursor jump. In short, the results concerning the amplitude of the correction can be summarized as follows: no jump = 15-15 < early-15 = late-15 < early-30 = late-30 = 15+15. Note that the Target x Type of trial interaction resulted from corrections for the early-15, late-15, early-30, late-30, and 15+15 trials having opposite effects on stylus displacement for the left and right targets.

The results illustrated in Figure 3a also suggest that corrections for the cursor jump were larger when aiming at the right target than they were when aiming at the left target. To test for this possibility, we computed an ANOVA on the absolute value of the frontal constant error and contrasted 2 Targets x 6 Types of perturbed trials. The results of this ANOVA revealed that for all types of trials except for the 15-15 trials, the correction was significantly larger when aiming at the right target than when aiming at the left target (in relative terms, 86% vs. 62% of the imposed perturbation, respectively), $\underline{F}(5, 55) = 11.29$, $\underline{p} < 0.001$.

Concerning frontal variability, the ANOVA revealed a significant main effect of Type of trials, $\underline{F}(6, 66) = 12.39$, $\underline{p} < 0.001$. As illustrated in Figure 3b, frontal variability of the 15-15 trials was significantly smaller than that of all other types of jump trials. In addition, late-30 trials had a significantly larger frontal variability than no-jump trials ($\underline{p} = 0.001$).

No adaptation through practice. All cursor jumps required a correction toward the participant's midline. Although cursor jumps occurred for only 20% of the trials, and participants reported that they had not been aware of the cursor jump, participants might have benefited from this aspect of our experimental design in planning a better correction for the cursor jump. If so, correction for the cursor jump should have been more effective later than earlier in practice. To test for this possibility, we contrasted the frontal constant error of the first and the last trials performed in our six cursor-jump conditions. The results of an ANOVA contrasting 2 Times of occurrence (first and last) x 2 Targets x 6 Types of trials did not reveal a significant main effect of Times of occurrence ($p = 0.60$) or any significant interaction involving this variable ($p > 0.14$). In short, this reveals that the correction for a cursor jump was efficient even for its very first occurrence and remained equally efficient throughout the experiment.

Sagittal component. The cursor jump was perpendicular to the reference vector joining the starting base and the target. Therefore, when using Cartesian coordinates, not only was the cursor displaced laterally, but it was also displaced sagittally. This sagittal component was 3.9 mm and 7.8 mm for the 15-mm and 30-mm cursor jumps, respectively. The results illustrated in Figure 3c indicate that participants corrected for approximately 70% of the perturbation imposed on this dimension of the task (2.7 mm and 5.5 mm for the 15-mm and 30-mm cursor jumps, respectively). This last observation is supported by a significant main effect of Type of trials, $\underline{F}(6, 66) = 44.8$, $p < .001$. Post hoc comparisons revealed significantly longer movements for the 30-mm than for the 15-mm cursor jump (325.7 mm and 322.9 mm, respectively, $\underline{p} < 0.05$), which in turn, were significantly longer than the no-jump and the 15-15 trials (320.2 mm and 319.7 mm, respectively, $\underline{p} < 0.05$). No significant main effect of interaction was observed on sagittal movement variability (all p values > 0.18; see Figure 3d).

Movement time. The ANOVA revealed a significant Type of trials x Targets interaction, $\underline{F}(6, 66) = 3.5$, $\underline{p} = 0.005$. The breakdown of this interaction revealed a longer movement time when a large correction had to be made while aiming at the right target than when it had to be made while aiming at the left target. Specifically, significantly longer movement times were noted for the right targets than for the left targets for the late-15 (945 ms vs. 908 ms), early-30 (954 ms vs. 915 ms), and late-30 (976 ms vs. 915 ms) conditions. No other significant differences were noted.[1]

Continuous visual monitoring of the cursor

So far, we have shown that participants were not aware of the cursor jump but nevertheless corrected their movement to compensate for both the frontal and sagittal errors the jump imposed on the planned movement trajectory. In addition, larger corrections were observed for larger cursor jumps regardless of their moment/location of occurrence. Finally, effective correction for the cursor jump was observed even for the first perturbed trial. Of major interest in the present study is that participants are shown to have adapted this correction when a second cursor jump cancelled or doubled the size of the initial cursor jump. These observations suggest that detection of the initial cursor jump and consequent planning of an appropriate correction did not engage processes that interfered in one way or another with the visual monitoring of the cursor. Alternative explanations could be that participants did not detect the first cursor jump or that they summed up the visual information available over a relatively long interval that included the two cursor jumps in the 15+15 and 15-15 conditions. If so, no correction was needed for the 15-15 condition, which would explain why endpoint accuracy of these trials did not differ from those of no-jump trials. Similarly, participants may only have reacted to the location of the cursor sometime after the second cursor jump in the 15+15 condition, which would explain why endpoint location of these trials did not differ significantly from those of the early-30 and late-30 trials.

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[1] It should be remembered that the procedure use to define movement time during data acquisition differed from that used during data analysis, which explains why the movement times reported above appear longer than the upper limit of the target movement time bandwidth.

The first explanation of the results for the double-jump trials detailed above would be supported if we could show that a correction for the first cursor jump was initiated and (a) then aborted for the 15-15 trials and (b) amplified for the 15+15 trials. To determine if and when participants initiated a correction for the first cursor jump, we used the unfiltered displacement data of the stylus on the frontal axis. As in Proteau et al. (2009), we chose to analyze the frontal displacement of the cursor because the cursor jump, and thus the expected correction, largely occurred on this axis. For each participant, we computed a mean trajectory for the 15-15, early-15, and no-jump trials aimed at each target. Then, at every 20 ms, we computed the difference in location between these mean trajectories. A correction for the first cursor jump (see Figure 4) was detected when (a) early-15 trials deviated from the no-jump trials by more than 1 mm in the direction opposite to the cursor jump as compared with the position of the cursor at the occurrence of the cursor jump) and (b) continued to deviate as movements progressed toward the targets. A correction for the second cursor jump was detected when the 15-15 trials deviated from the early-15 trials by at least 1 mm in the direction opposite to the second cursor jump as compared with the position of the cursor at the occurrence of the second cursor jump and continued to deviate as movements progressed toward the targets.

The 1-mm criterion was chosen arbitrarily. In addition, to ensure that we did not obtain a false positive, movement onset was detected only when the change in direction continuously increased as movement unfolded and then became significant. This technique was used by Proteau et al. (2009), who reported latency in the same range as that reported by others (Brenner and Smeets 2003; Saunders and Knill 2003, 2005).

15-15 vs. no-jump trials. For both the right and the left targets, starting approximately 178 ms (s.d.=77 ms) and 212 ms (s.d.=133 ms) after the initial cursor jump, respectively, the position of the stylus for the perturbed trials moved closer to the participant's midline than it did for the no-jump trials. This indicates that a correction for the first cursor jump had been initiated. Seven of the twelve participants showed this correction for the first cursor jump when aiming at both the left and right targets; two additional participants showed it only when aiming at the left target, and two other participants showed it only when aiming at the right target. For these participants, the peak deviation between the no-jump and the 15-15 trial trajectories was 3.6 mm (s.d. = 2.2 mm) and 4.6 mm (s.d. = 2.5 mm) when aiming at the right and left targets, respectively.

In the previous analysis, we showed that most participants initiated a correction for the initial cursor jump. In a second series of analyses, we sought to determine whether the processes involved in detecting the initial cursor jump (planning and initiating a correction) interfered with the visual monitoring of the cursor. Specifically, for the seven participants who showed a correction for the initial cursor jump when aiming at both the left and right targets, we determined the latencies of their correction for the first and second cursor jumps. The results of the ANOVA contrasting the latency of the first and second corrections for the 15-15 trials did not reveal any significant difference in the latency of these two corrections. Mean latency of the first correction was 195 ms (s.d. = 108 ms), whereas that of the second correction was 192 ms (s.d.= 82 ms). In addition, an ANOVA contrasting the latency of the first and second corrections for the 15-15 trials to that of the correction for the first (15+15) or only cursor jump in other conditions (i.e., early-15, late-15, early-30, late-30; see Table 2) did not reveal any significant difference, $\underline{F}$ (6, 36) < 1.

Supplementary analysis. The results reported above suggest that most participants reacted to the first cursor jump and then cancelled this correction when the second cursor jump was detected. To further support our position that participants detected the first cursor jump, we had additional participants perform the same task as in the main experiment. Cursor jump occurred for 20% of the trials. The first condition was similar to the early-15 condition used in the main experiment. In the second condition (early-15, no-vision) there was a 15-mm cursor jump that occurred 150 ms after movement initiation. Then, 100 ms later, the cursor was blanked and the trial was completed without vision of the cursor. If participants did not detect the cursor jump, movement endpoint in the latter condition should not differ from that of the no-jump trials. On the contrary, if the cursor jump was detected with sufficient accuracy to enable the participants to plan an efficient correction, movement endpoint of the 15-no-vision and early-15 trials should not differ significantly from one another. The results of 11 participants are illustrated in Figure 5. Again, no participant reported having been aware of the cursor-jump trials, but the results clearly indicate that participants corrected their movement in both the 15-no-vision and early-15 conditions, which clearly supports the second hypothesis proposed above.

15+15 vs. no-jump trials. For the 15+15 trials, our rationale was that if participants made two successive corrections in response to the two cursor jumps, the 15+15 trials should have had a trajectory that first corresponded to that of the early-15 trials and, following the second cursor jump, migrated to that of the late-30 trials (Gritsenko et al., 2009; Veyrat-Masson et al., 2010). Unexpectedly, as illustrated in Figure 6, the correction for the 15+15 mm jump closely followed that of the 30-mm jump, indicating that the correction for the second cursor jump blended seamlessly with the correction for the first cursor jump, most likely because the corrections were in the same direction. Nonetheless, if participants had only reacted to the position of the cursor sometime after the second cursor jump, the latency of the correction for the cursor jump that took place 150 ms after movement initiation should have been 100 ms longer than the latency of the correction for the cursor jump that occurred 250 ms after movement initiation. Clearly, this was not the case. Latency for the 15-mm jump that occurred 150 ms and 250 ms after movement initiation was 206 (s.d.=83 ms) and 167 ms (s.d.=114 ms), respectively. Similarly, latency for the 30-mm jump that occurred 150 ms and 250 ms after movement initiation was 182 (s.d.=77 ms) and 170 ms (s.d.=75 ms), respectively.

Discussion

In the present study, we sought to determine whether detection and correction for a cursor jump are based on automatic processes. If so, the error detection and correction processes for two cursor jumps occurring in close succession should not interfere with one another.

As in previous work (Proteau et al. 2009; Sarlegna et al. 2003, 2004; Saunders and Knill 2003, 2004, 2005), participants were not aware of the first or second cursor jump but nonetheless corrected their movement so that it ended close to the target. More importantly, participants were also able to abort or to double their correction for a first cursor jump when a second one cancelled or doubled the need for correction. One could argue that these results simply indicate that participants did not detect the first cursor jump or had not yet engaged in the correction processes and reacted only to the second cursor jump. Two lines of evidence argue against this position.

First, for nine of the twelve participants, regardless of the target location, we observed initiation of a correction for the first cursor jump in the 15-15 trials. Then, this correction was cancelled so that movement endpoint was not significantly different from that of the no-jump trials. Thus, for these participants, the cursor jump was detected, although participants were not aware of it. Because the latency of the correction did not differ significantly for the first and second cursor jumps, it suggests that the monitoring of visual feedback was not affected in any way by the processes responsible for the planning of the appropriate correction. Similarly, it indicates that planning such a correction did not interfere with the detection of a second cursor jump. This suggests continuous and attention-free monitoring of visual feedback.

Second, if the first cursor jump had not been detected, withdrawing vision of the cursor soon after its occurrence should have resulted in a movement endpoint similar to that obtained in a similarly blanked cursor condition, but with no cursor jump. The results of a complementary experiment clearly indicate that participants corrected for the cursor jump even when the cursor was blanked soon after it occurred (see also Proteau et al. 2009 for a similar observation). Thus, there is no doubt that the first cursor jump was detected by the CNS.

Automaticity of the correction

The latency of the correction for the second cursor jump did not differ from that of the first cursor jump even if the second jump occurred prior to the initiation of the correction for the first cursor jump. Similarly, latency of the correction for the first and second cursor jumps of double-jump trials did not differ from that of single-jump trials. Finally, movement endpoint and variability of the double-jump trials did not differ from that of no-jump trials or large single-jump trials (i.e., early-30 or late-30 trials). Thus, the efficacy of the error detection and correction processes for the second cursor jump were not delayed or impaired by the planning of the correction for the first cursor jump. These observations strongly suggest that detection and correction for the cursor jump do not require large attention resources.

These observations concur with recent results reported by Franklin and Wolpert (2008). In their study, participants performed video aiming movements much like those in the present study. For some trials, the position of the cursor was smoothly displaced away from the current hand position, and participants were asked to react to these visual perturbations by making a movement as fast as possible in the <u>same</u> direction as the visual shift of the cursor. Franklin and Wolpert (2008) noted that before the requested voluntary response, participants initiated an involuntary correction in the direction opposite to the visual shift. Thus, it appears that the initiation of a movement in a direction opposite to the cursor jump is reflex-like (Franklin and Wolpert 2008), which would explain why monitoring of the visual feedback does not interfere with the movement's initiation.

It is noteworthy that the latency of the correction observed in this study and in other cursor-jump experiments (Franklin & Wolpert, 2008 [~150 ms]; Proteau et al., 2009 [~ 138 ms]; Saunders & Knill, 2003 [~160 ms]; Veyrat-Masson et al., 2010 [~ 160 ms] are typically larger than those observed in target-jump experiments (Day & Lyon, 2000 [125-160 ms]; Gritsenko et al. (2009); [~125 ms]; Prablanc & Martin (1992) [~ 115 ms]). In target-jump experiments, the participants need to look and to point at a target shown in the periphery of the retina. It is well known that even for control (no-jump) trials, the first saccade will often not end on the target and that a corrective saccade will be issued. Thus, the CNS expects to issue a fine-tuning command and, as suggested by Goodale et al. (1986), the correction for a target jump reflects the normal updating of the motor programming at the end of the first saccade on any trial. On the contrary, the cursor jump used in most experiments (> 15 mm) is outside the normal variability of one's movement which in target-jump trials might trigger a more complex error-correction process, albeit an "automatic" on (Franklin & Wolpert, 2008).

Amplitude of correction

In the present study, the moment of occurrence of the cursor jump had no significant impact on endpoint accuracy or variability (early-15, late-15, early-30, and late-30 trials); we found that the amplitude of the corrections was independent of the timing of the perturbations. This seems to be in conflict with recent studies using cursor (Saunders and Knill 2003, 2005) and target (Liu and Todorov, 2007; Hesse and Franz 2009) perturbations, which show a smaller correction for late perturbations. This difference is likely due to the longer interval between the early and late perturbations in these studies (Saunders and Knill 2003, 2005; Liu and Todorov, 2007; Hesse and Franz 2009) as compared to those in the present study.

Left versus right target

Finally, we noted that corrections for the 30-mm cursor jump were significantly larger for the target located to the right than for the target located to the left of the participants' midline. This observation might be explained by the longer movement times observed for the 30-mm cursor-jump conditions. This explanation is supported by previous observations showing that movement times to the right target should have been shorter than for those to the left target (Binsted et al., 2001; Carson et al., 1990; Fisk and Goodale, 1985; Hodges et al., 1997) because of either or both biomechanical factors (Carey and Otto de Haart 2001; Gordon et al., 1984; Mackrous and Proteau 2007) and ipsilateral "facilitation" (Fisk and Goodale, (1985)[2]. Thus, finding a longer than expected movement time for the right target than for the

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[2] Gordon et al. (1994) showed that movements initiated from a starting position located along one's midline had a larger acceleration when aimed to the right than they did when aimed to the left of the starting position because of a larger inertial resistance in the latter (due to a larger involvement of the shoulder) than in the former direction (see also Carey and Otto de Haart 2001; Mackrous and Proteau 2007 for a similar observation). This difference in inertial resistance is usually compensated by an increase in movement time in the direction of larger inertia (Gordon et al. 1994; Mackrous and Proteau 2007). Conversely, it could be that more

left target explains why corrections were more accurate for the right target than they were for the left target. Thus, the larger correction for the right target cursor jumps likely results from longer movement times for this target.

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accurate and faster movements are made when the position of the target is processed, at least initially, in the same hemisphere as the motor and sensory information of the reaching hand, because of more efficient within- than between-hemisphere visuomotor transmission of target information and/or visual feedback from the hand.

Authors' note

This study was supported by a grant from the Natural Sciences and Engineering Research Council of Canada (NSERC). Requests for reprints should be addressed to Luc Proteau, Département de kinésiologie, Université de Montréal, P.O. Box 6128, Downtown Station, Montréal, Canada, H3C 3J7. Email: luc.proteau@umontreal.ca.

References

Bédard P, Proteau L (2003) On the role of peripheral visual afferent information for the control of rapid video-aiming movements. Acta Psychol 113:99-117

Binsted G, Chua R, Helsen W, Elliott D (2001) Eye-hand coordination in goal-directed aiming. Hum Mov Sci 20: 563-585

Brenner E, Smeets JB (2003) Fast corrections of movements with a computer mouse. Spat Vis 16:365-76

Bridgeman B, Lewis S, Heit G, Nagle M (1979) Relation between cognitive and motor-oriented systems of visual position perception. J Exp Psychol Hum Percept Perform 5:692-700

Cameron BD, Franks IM, Enns JT, Chua R (2007) Dual-target interference for the 'automatic pilot' in the dorsal stream. Exp Brain Res 181:297-305

Carey DP, Otto-de Haart EG (2001) Hemispatial differences in visually guided aiming are neither hemispatial nor visual. Neuropsychologia 39:885-94

Carson RG, Chua R, Elliott D, Goodman D (1990) The contribution of vision to asymmetries in manual aiming. Neuropsychologia 28:1215-20

Day BL, Lyon IN (2000). Voluntary modification of automatic arm movements evoked by motion of a visual target. Exp Brain Res 130:159-68

Desmurget M, Epstein CM, Turner RS, Prablanc C, Alexander GE, Grafton ST (1999) Role of posterior parietal cortex in updating reaching movements to a visual target. Nat Neurosci 2:563-567

Desmurget M, Pélisson D, Rossetti Y, Prablanc C (1998) From eye to hand: planning goal-directed movements. Neurosci Biobehav Rev 22:761-88

Fisk JD, Goodale MA (1985) The organization of eye and limb movements during unrestricted reaching to targets in contralateral and ipsilateral visual space. Exp Brain Res 60:159-78

Franklin DW, Wolpert DM (2008) Specificity of reflex adaptation for task-relevant variability. J Neurosci 28:14165-75

Franklin DW, Franklin S, Wolpert DM (2014) Fractionation of the visuomotor feedback response to directions of movement and perturbation. J Neurophysiol 112:2218-2233

Goodale MA, Pélisson D, Prablanc C (1986) Large adjustments in visually guided reaching do not depend on vision of the hand or perception of target displacement. Nature 320:748-50

Gordon J, Ghilardi MF, Cooper SE, Ghez C (1994) Accuracy of planar reaching movements. II. Systematic extent errors resulting from inertial anisotropy. Exp Brain Res 99:112-30

Gritsenko Y, Yakovenko S, Kalaska, JF (2009) Integration of predictive feedforward and sensory feedback signals for online control of visually guided movement. J Neurophysiol 102: 914-30

Hesse C, Franz VH (2009) Corrective processes in grasping after perturbations of object size. J Motor Behav 41:253-73

Hodges NJ, Lyons J, Cockell D, Reed A, Elliott D (1997) Hand, space and attentional asymmetries in goal-directed manual aiming. Cortex 33 :251-69

Johnson H, Van Beers RJ, Haggard P (2002) Action and awareness in pointing tasks. Exp Brain Res 146:451-9

Liu D, Todorov E (2007) Evidence for the flexible sensorimotor strategies predicted by optimal feedback control. J Neurosci 27:9354-68

Mackrous I, Proteau L (2007) Specificity of practice results from differences in movement planning strategies. Exp Brain Res 183:181-93

Meyer DE, Abrams RA, Kornblum S, Wright CE, Smith JE (1988) Optimality in human motor performance: ideal control of rapid aimed movements. Psychol Rev 95:340-70

Neggers SFW, Bekkering H (1999) Integration of visual and somatosensory target information in goal-directed eye and arm movements. Exp Brain Res 125:97-107

Neggers SFW, Bekkering H (2000) Ocular gaze is anchored to the target of an ongoing pointing movement. J Neurophysiol 83: 639-51

Neggers SFW, Bekkering H (2001) Gaze anchoring to a pointing target is present during the entire pointing movement and is driven by a non-visual signal. J Neurophysiol 86: 961-70

Pisella L, Gréa H, Tilikete C, Vighetto A, Desmurget M, Rode G, Boisson D, Rossetti Y (2000) An 'automatic pilot' for the hand in human posterior parietal cortex: toward reinterpreting optic ataxia. Nat Neurosci 3:729-36

Prablanc C, Martin O (1992) Automatic control during hand reaching at undetected two-dimensional target displacements. J Neurophysiol 67:455-69

Proteau L, Roujoula A, Messier J (2009) Evidence for continuous processing of visual information in a manual video-aiming task. J Motor Behav 41:219-31

Sarlegna F, Blouin J, Bresciani JP, Bourdin C, Vercher JL, Gauthier GM (2003) Target and hand position information in the online control of goal-directed arm movements. Exp Brain Res 151:524-35

Sarlegna F, Blouin J, Vercher JL, Bresciani JP, Bourdin C, Gauthier GM (2004) Online control of the direction of rapid reaching movements. Exp Brain Res 157:468-71

Saunders JA, Knill DC (2003) Humans use continuous visual feedback from the hand to control fast reaching movements. Exp Brain Res 152:341-52

Saunders JA, Knill DC (2004) Visual feedback control of hand movements. J Neurosci 24:3223-34

Saunders JA, Knill DC (2005) Humans use continuous visual feedback from the hand to control both the direction and distance of pointing movements. Exp Brain Res 162:458-73

Veyrat-Masson M, Brière J, Proteau L (2010) Automaticity of online control processes in manual aiming. Submitted for publication.

Woodworth RS (1899) The accuracy of voluntary movement. Psychol Rev 3(Monograph Suppl.):1–119

Table 1. Amplitude and moment of occurrence of the cursor jumps for the different types of cursor-jump trials.

	First jump		Second jump	
Type of trial	Amplitude (mm)	Occurrence (ms)	Amplitude (mm)	Occurrence (ms)
Early-15	15	150		
Late-15	15	250		
Early-30	30	150		
15+15	15	150	15	250
Late-30	30	250		
15-15	15	150	-15	250

Table 2. Mean latency (standard deviation) of the correction for the different types of cursor-jump trials.

	Type of trial						
	Early-15	Late-15	Early-30	15+15	Late-30	15-15 1st	15-15 2nd
Correction latency	206 ms (83)	167 ms (114)	182 ms (77)	215 ms (74)	170 ms (75)	195 ms (108)	192 ms (85)

Figure captions

Fig 1 View of the experimental set-up.

Fig 2 Stylus trajectory for no-jump trials (full lines) and the different types of cursor-jump trials (dashed lines) for a randomly selected participant. Each line represents a single trial. Note that the correction for the first cursor jump was cancelled or doubled for the 15-15 and 15+15 trials, respectively.

Fig 3 Endpoint error and variability for each type of trials directed to the left and right targets. Error bars indicate standard error of the mean: (a) endpoint constant error; (b) within-participant variability for the frontal component of the task; (c) endpoint constant error; and (d) within-participant variability for the sagittal component of the task.

Fig 4 Illustration of the method used to calculate the latency of the corrections for the first and second cursor jump in double-jump trials.

Fig 5 Left panel: Mean difference in frontal position of the stylus between cursor-jump and no-jump trials over time for early-15 and early-15-no-vision trials. Right panel: Frontal constant error for early-15 and early-15-no-vision trials. Note the similarity of results for these two types of trials.

Fig 6 Mean difference in frontal position of the stylus between the cursor-jump and no-jump trials over time for the left target (upper panels) and right target (lower panels). Note the similarity of the stylus trajectory for the early-30 and 15+15 trials.

Figure 1

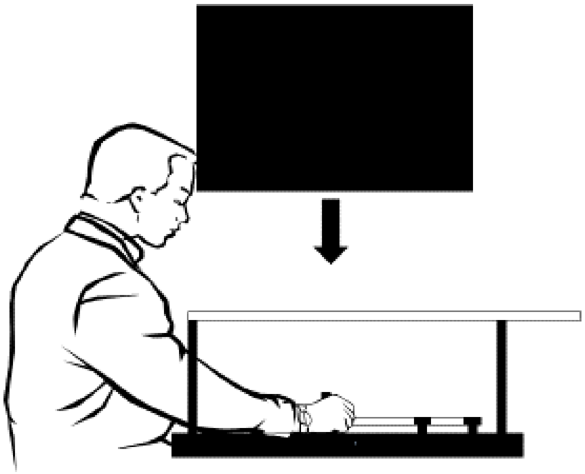


Figure 2

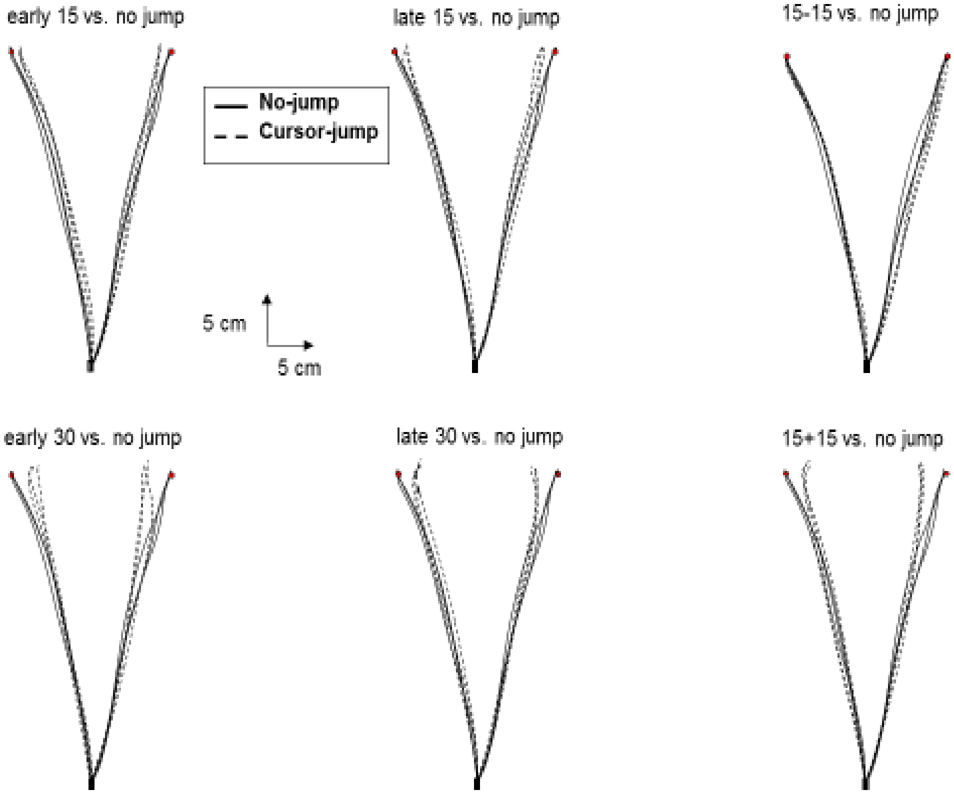

early 15 vs. no jump
late 15 vs. no jump
15-15 vs. no jump
No-jump
Cursor-jump
5 cm
5 cm
early 30 vs. no jump
late 30 vs. no jump
15+15 vs. no jump

Figure 3

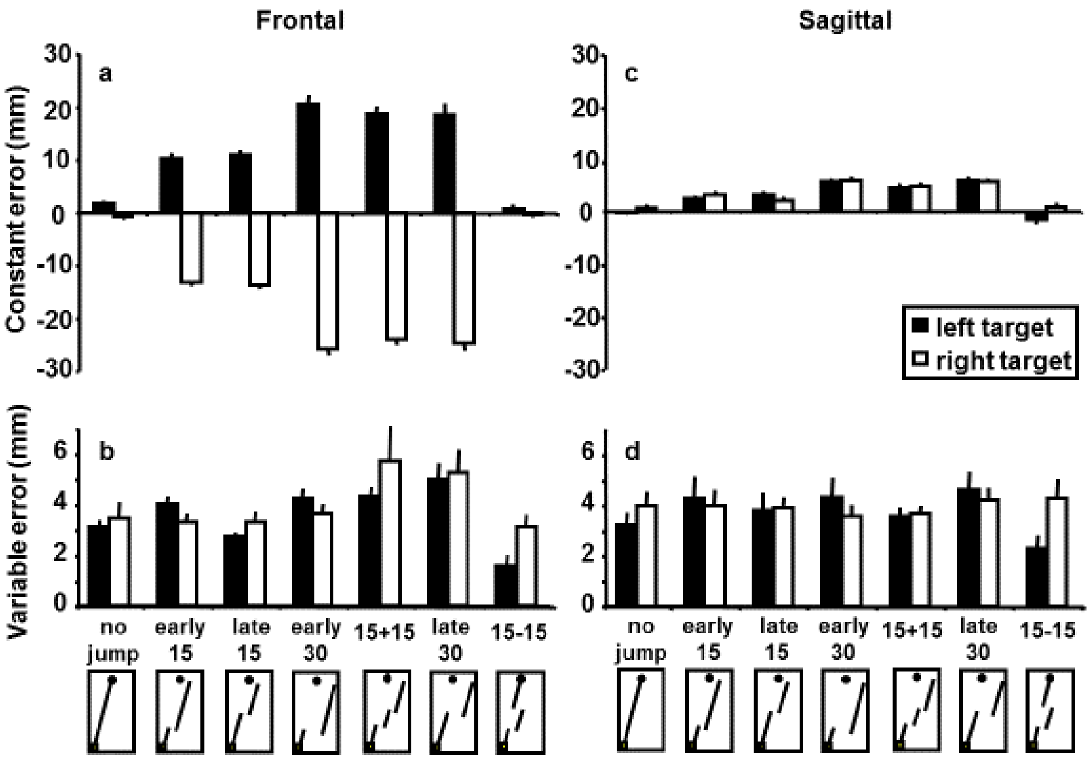

Frontal
Sagittal
a
b
c
d
Constant error (mm)
Variable error (mm)
30
20
10
0
-10
-20
-30
6
4
2
0
■ left target
□ right target
no jump
early 15
late 15
early 30
15+15
late 30
15-15

Figure 4

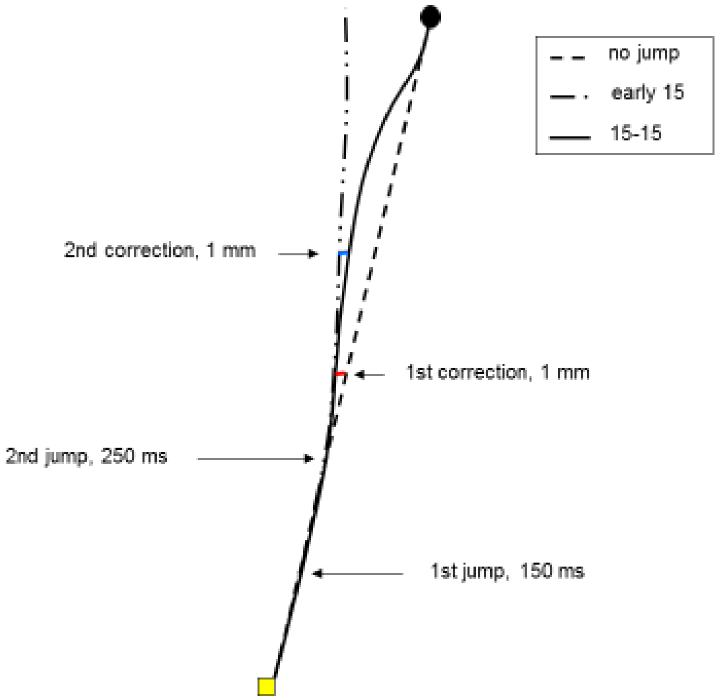

no jump
early 15
15-15
2nd correction, 1 mm
1st correction, 1 mm
2nd jump, 250 ms
1st jump, 150 ms

Figure 5

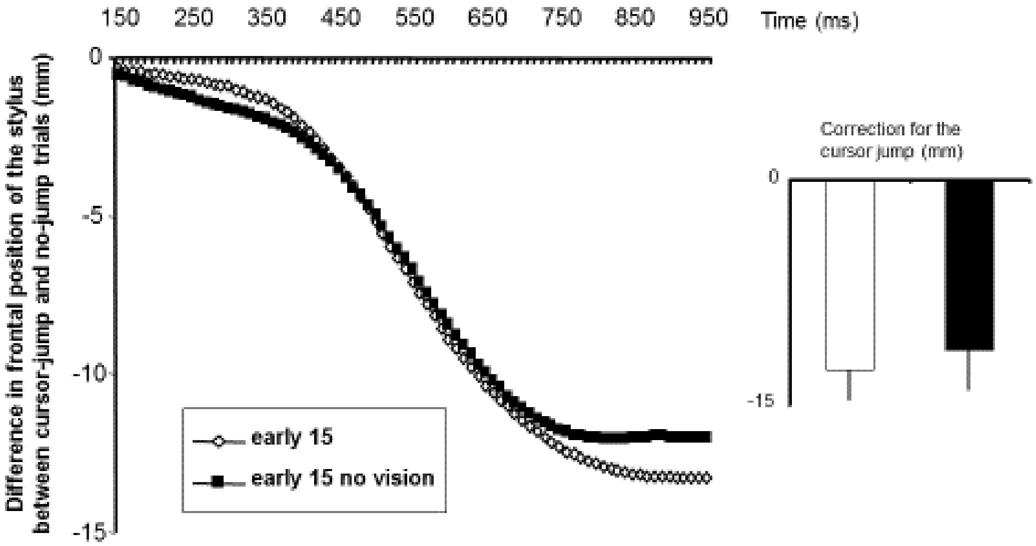
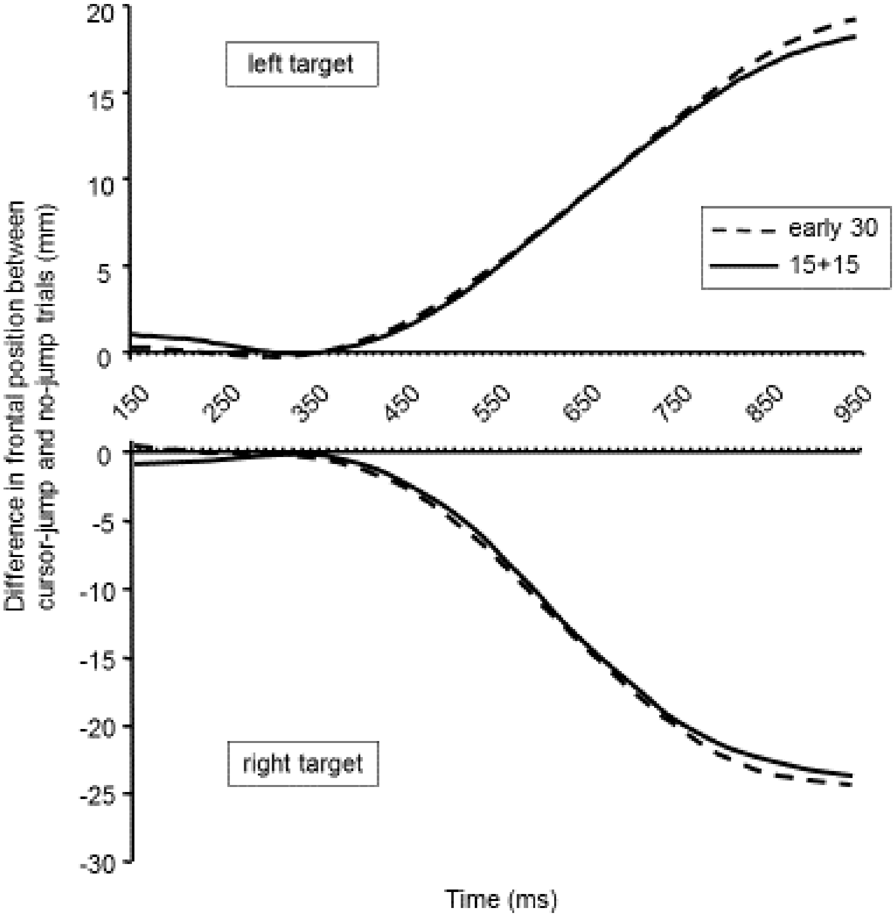

150
250
350
450
550
650
750
850
950
Time (ms)
0
-5
-10
-15
Difference in frontal position of the stylus between cursor-jump and no-jump trials (mm)
early 15
early 15 no vision
Correction for the cursor jump (mm)
0
-15

Figure 6


left target
right target
early 30
15+15
Difference in frontal position between cursor-jump and no-jump trials (mm)
Time (ms)
20
15
10
5
0
150
250
350
450
550
650
750
850
950
0
-5
-10
-15
-20
-25
-30

Chapitre 3 : Article 2

Visual monitoring of goal-directed aiming movements

Julien Brière and Luc Proteau[1]
Département de kinésiologie
Université de Montréal
Montréal, Canada

[1] Corresponding author:
Luc Proteau, Département de kinésiologie, Université de Montréal, P.O. Box 6128,
Downtown Station, Montréal, Canada, H3C 3J7.
Tel: (514) 343-2039
Fax: (514) 343-2181
Email: luc.proteau@umontreal.ca

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Abstract

Goal-directed movements are subject to intrinsic planning and execution variability, which requires that the central nervous system closely monitor our movements to ensure endpoint accuracy. In the present study, we sought to determine how closely the visual system monitored goal-directed aiming movements. We used a cursor-jump paradigm in which a cursor was unexpectedly translated soon after movement initiation. Some of the trials included a second cursor jump, and the cursor remained visible for different durations. The results indicate that seeing the cursor for only 16 ms after the second cursor jump was sufficient to influence the movement endpoint, which suggests that the visual system continuously monitored goal-directed movements. The results also suggest that the perceived position/trajectory of the effector was likely averaged over a period of approximately 70 ms.

Keywords: cursor jump, online visual control, goal-directed movements, motor control, feedback processes, forward model

Visual monitoring of goal-directed aiming movements

Goal-directed movements put into play a series of processes to identify the target and its location and transform this information into appropriate motor commands. Practice leads to the development of accurate motor commands (e.g., movement planning and execution processes), but the intrinsic variability that is present in all human processes and the high level of accuracy needed for many of our daily activities require that the central nervous system (CNS) closely monitor our movements and quickly update movement planning to amend movement execution (Desmurget & Grafton, 2000; Franklin, Wolpert, & Franklin, 2012; Franklin & Wolpert, 2008; Vesia, Yan, Henriques, Sergio, & Crawford, 2008). In this study, we examined how brief a display of visual information can be while remaining sufficient for the CNS to detect that the movement is not progressing as planned and issue a correction.

Many researchers have used a perturbation paradigm to investigate error detection and correction processes. If the perturbations are infrequent and unexpected, then participants plan their movements as if no perturbation would occur. Therefore, participants in the perturbed trials need to correct the movement that they have planned and initiated to counteract the perturbation, and this correction provides insight into error detection and correction processes.

The perturbations in many studies were cursor jumps. In these studies, participants moved a cursor towards a target on a visual display (Brière & Proteau, 2011; Franklin & Wolpert, 2008; Proteau, Roujoula, & Messier, 2009; Sarlegna, Blouin, Bresciani, Bourdin, Vercher, & Gauthier 2003; Sarlegna, Blouin, Vercher, Bresciani, Bourdin, & Gauthier, 2004; Saunders & Knill, 2003, 2004; Veyrat-Masson, Brière, & Proteau, 2010). For example, in a perturbed trial, the location of the cursor representing the participant’s hand is translated by 2 cm 100 ms after movement initiation.

Participants in cursor-jump experiments have often reported that they were not aware of the perturbation (Bédard & Proteau, 2003; Brière & Proteau, 2011; Proteau et al., 2009; Saunders & Knill, 2003, 2004; Veyrat-Masson et al., 2010). However, the results indicate that they corrected their movements quickly and accurately to counteract the perturbation. These corrections are apparent, even in the first perturbed trial to which participants were exposed (Proteau et al., 2009). Therefore, the authors concluded that error detection and correction processes were 'automatic/attention free' and did not require learning or adaptation. Similarly, when participants consciously detected the perturbation, they could not refrain from initiating a correction in the direction opposite to the cursor jump (Franklin & Wolpert, 2008), even when they were asked to move their hand in the same direction as the cursor jump.

The time required to initiate a correction was independent of when or where the perturbation occurred in the movement trajectory, which suggests that goal-directed movements are under continuous visual monitoring (Saunders & Knill, 2003).[3] We recently investigated this idea further and found that the detection of a first cursor jump and the planning of a correction did not interfere with the detection of, or the correction for, a second cursor jump that occurred 100 ms after the first jump (Brière & Proteau, 2011). We also demonstrated that occluding the cursor as soon as 100 ms after a jump did not prevent participants from correcting their movements as accurately as when the cursor remained visible throughout the movement execution. Therefore, a relatively brief sample of visual information was sufficient for the CNS to detect an error in movement planning or execution processes and to plan and initiate an appropriate correction. Taken together, these results are congruent with the proposition that the visual system 'continuously' monitors goal-directed

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[3] This observation does not deny the role played by proprioceptive feedback for motor control. See the Discussion section.

movements (Cluff, Crevecoeur, & Scott, 2015; Saunders & Knill, 2003), and this monitoring does not require many resources (Proteau et al., 2009; Reichenbach, Franklin, Zatka-Haas, & Diedrichsen, 2014).

In the present study, we first sought to determine the minimal amount of visual information needed by the CNS to detect that a movement is not progressing as planned and issue a correction. We used a cursor-jump paradigm to reach our goal. The cursor was unexpectedly translated by 15 mm 150 ms after movement initiation in a small proportion of the trials. A second cursor jump occurred 100 ms after the first jump in some of these trials, which moved the cursor back to its initial trajectory. The cursor remained visible after the second cursor jump until the movement was completed or occluded 16 ms, 40 ms, or 64 ms after the second cursor jump. We reasoned that the shortest visual sample for which participants were able to reduce or cancel the correction for the first cursor jump would reveal the minimum duration of a visual sample for the CNS to detect that the movement is not progressing as planned and how much information is required to perform a ‘complete’ correction.

Our second objective was to qualify the type of information used to detect the cursor jump(s) and trigger the associated correction processes. Specifically, in a series of complementary analyses we determined whether (a) the cursor jump could have been predicted by the participants and (b) the correction for the cursor jump was influenced by the duration or length of the cursor visibility after the jump. Then, we determined whether the corrections for the cursor jump represent ‘all or none’ processes (a correction sometimes occurs, but sometimes it does not) or whether they represent processes that accumulate information over time.

Method

Participants

Thirty-four participants aged between 20 and 30 years and who were students at the Université de Montréal took part in this experiment. The participants self-declared being right-handed and reported normal or corrected-to-normal vision. The Health Sciences Ethics Committee of the Université de Montréal approved this study.

Task and apparatus

The apparatus is illustrated in Figure 1. It consisted of a table, computer screen, headrest, mirror, and manipulandum with two degrees of freedom. The participants sat in front of the table, and they were asked to move a device similar to a computer mouse across the tabletop from a fixed starting position close to their body towards a target located further away from the body (see Figure 1B). The CRT computer screen (Mitsubishi, Color Pro Diamond, ~ 940 mm [37 inches], refresh rate of 60 Hz, resolution of 1024 x 768) was mounted on a ceiling support positioned directly over the table; the computer screen was oriented parallel to the surface of the table. The screen's image was reflected on a mirror placed directly beneath and parallel to the tabletop. The distance between the computer screen and the mirror was 200 mm. The distance between the mirror and the tabletop was also 200 mm, which permitted free displacement of the manipulandum on the tabletop. The information presented on the computer screen was reflected on the mirror and was visible to the participant (see Figure 1A). The mirror prevented participants from seeing their hand and lower arm during the experiment. A headrest was affixed to the side of the computer screen. It was aligned with the centre of the computer screen and was used to standardize the information displayed on the computer screen for all participants.

The tabletop was covered by a piece of Plexiglas to which a starting base and the manipulandum were affixed. The starting base consisted of a thin strip of Plexiglas glued to the tabletop. It was parallel to the leading edge of the table and had a small indentation on its distal face. This indentation was aligned with the centre of the headrest, directly in front of the participant's midline, and served as the starting base for the stylus. The indentation made it easy for the participant to position the stylus at the beginning of each trial.

The manipulandum consisted of two pieces of rigid Plexiglas (430 mm) joined at one end by an axle. One free end of the manipulandum was fitted with a second axle encased in a stationary base. The other free end of the manipulandum was fitted with a small vertical shaft (length: 30 mm; radius: 10 mm), i.e., the stylus, which could be gripped easily by the participant. Each axle of the manipulandum was fitted with a 13-bit optical shaft encoder (US Digital, model S2-2048, sampled at 500 Hz, angular accuracy of 0.0439°), which enabled us to track the displacement of the stylus online and to illustrate it with a 1:1 ratio on the computer screen. Moving the stylus away from the body resulted in an identical displacement of the cursor on the computer screen. The bottom of the stylus and the bottom of the optical encoder located at the junction of the two arms of the manipulandum were covered with a thin piece of Plexiglas. By lubricating the working surface at the beginning of each experimental session, displacement of the stylus was near frictionless.

Procedures

The participants were asked to try stopping the cursor (yellow; 3 mm in diameter) on a white, 5-mm diameter target presented on a black screen. The target was located 320 mm in front of the starting base and 86 mm to its right (15˚).

The participants performed the task with their right (dominant) hand. They were asked to initiate their movement as they pleased following the presentation of the target (i.e., not a reaction time task) and to perform smooth and continuous movements (i.e., not a stop-and-go strategy) towards the target. The participants were also required to gaze at the target during movement execution (their natural behaviour to ensure optimal accuracy; Neggers & Bekkering, 1999, 2000, 2001) and to complete their movements within a movement time ranging between 680 ms and 920 ms (800 ms +/- 15%). When movements were completed outside of this period, the experimenter reminded the participant of the target movement time. The target movement time and target location were as in previous work from our laboratory (Brière & Proteau, 2011; Veyrat-Masson et al., 2010).

At the beginning of each trial, the participant could see the cursor positioned on the starting base. Once the stylus was stabilized on the starting base for 500 ms, the target was presented on the screen. During data acquisition, movement initiation was detected when the cursor moved by at least 1 mm, whereas movement completion was detected when the cursor did not move more than 2 mm within a time frame of 100 ms. A preliminary study revealed that the procedure used to detect movement completion during data acquisition made it difficult for participants to use a stop-and-go strategy. When movement completion was detected, the position of the cursor endpoint and the target remained visible for 1 s.

The participants first took part in a familiarization phase consisting of 10 trials. This was followed by 200 experimental trials. A perturbation occurred in 20% of the experimental trials (40 trials). This perturbation could be a cursor jump and/or occlusion of the cursor. Perturbed trials were presented randomly with the restriction that one trial of each of the five types (8/40 trials per type) described below occurred once within each successive block of 25 trials. The participants were not informed that the cursor could jump on some trials. Informing the participants in this way could have interfered with their natural behavior during the task (i.e., gazing at the target). The experimenter noted any comments made by the participants regarding their performance or anything that the participant considered strange or peculiar during a trial. Details concerning the different types of perturbed trials are summarized in Figure 2.

Occluded conditions. For the double-jump occluded condition, the cursor jumped 15 mm perpendicularly and to the right of a straight line connecting the starting base and the target. The cursor jump occurred 150 ms after movement onset (see Figure 1B; Figure 2 leftmost column), and the cursor returned to its initial trajectory (i.e., 15 mm to the left) 100 ms later. For the participants in the first group (+16, *n* = 12), the cursor was then occluded 16 ms after the second cursor jump (i.e., 266 ms after movement onset). For the participants in the second (+40, *n* = 11) and third (+64, *n* = 11) groups, the cursor was occluded 40 ms and 64 ms after the second cursor jump, respectively (290 ms and 314 ms after movement onset, respectively). The single-jump occluded condition was designed to meet two criteria (Figure 2, second panel to the left). Within each group, we wanted (a) the cursor occlusion to occur at the same time as the double-jump condition and (b) the cursor jump to occur 100 ms prior to cursor occlusion. Therefore, the cursor jump occurred 166, 190 and 214 ms after movement onset for groups +16, +40, and +64, respectively. The difference among groups for the occurrence of the cursor jump should not influence the efficiency of the correction as it has been shown that the latency (Brière & Proteau, 2011; Saunders & Knill, 2003) and the accuracy of a correction (Brière & Proteau, 2011) is independent of when or where the perturbation occurred, if it occurs early in the movement trajectory. Finally, the no-jump condition (control, Figure 2, third panel to the left) was designed so that the cursor occlusion occurred at the same time as the single-jump and double-jump conditions. The cursor was occluded 266, 290 and 314 ms after movement onset for groups +16, +40, and +64, respectively.

Non-occluded conditions. Within each group (+16, +40, and +64), the single-jump and double-jump conditions were similar in all points to the occluded conditions described above but with the restriction that the cursor remained visible for the entire duration of a trial (see right panels of Figure 2). Finally, one no-jump (control) trial was picked randomly in each successive set of 25 trials with the restriction that it did not follow a perturbed trial.

Data reduction

The tangential displacement data of the stylus over time were first smoothed using a second order recursive Butterworth filter with a cut-off frequency of 10 Hz. The filtered data were then numerically differentiated once using a central finite technique to obtain the velocity profile of the aiming movement, a second time to obtain the acceleration profile, and a third time to obtain a jerk profile. From the kinematic profiles, we determined the end of the movement's primary impulse (Meyer, Abrams, Kornblum, Wright, & Smith, 1988). This occurred when one of the following events was detected on the kinematic profiles: (a) movement velocity fell below 20 mm/s, (b) movement reversal (velocity going from positive to negative), (c) movement lengthening (presence of a secondary movement impulse as indexed by the acceleration profile crossing the zero value for a second time) or (d) a significant disruption in the deceleration profile as indexed by a zero-crossing on the jerk profile. For a secondary movement impulse to be considered a discrete correction, its duration had to be at least 80 ms and its extent had to be at least 2 mm. Less than 5% of the trials in all conditions showed a secondary corrective impulse. These trials were withdrawn from all analyses.

To provide quick feedback to the participant during data acquisition, movement initiation was detected once the stylus had been moved 1 mm. For the main analyses, however, movement initiation was defined as the moment at which the tangential velocity of the cursor reached 10 mm/s and was maintained above this value for at least 20 ms. Visual inspection of the data revealed that once a velocity of 10 mm/s had been reached, movement was clearly underway. The movement endpoint was defined as the end of the movement's primary impulse using the parsing algorithm defined above. The difference between the procedure used for detecting movement initiation during acquisition and the procedure used in the main analyses explains why the movement times reported below were longer than the target movement time used during data acquisition.

To determine the efficacy of the correction for the cursor jumps, we determined the end of the movement's primary impulse for all trials (hereafter called the 'endpoint'). Endpoint frontal errors (in mm) were computed in Cartesian (x, y) coordinates (see Figure 1C). They refer to the position of the stylus in relation to the center of the target. A positive value indicates a movement ending to the right of the target, and a negative value indicates a movement ending to the left of the target. We also computed the within-participant movement endpoint variability (hereafter called the 'variable error') for each condition.

The dependent variables of interest were individually submitted to an analysis of variance (ANOVA) contrasting the experimental groups and conditions. The degrees of freedom were adjusted as suggested by Greenhouse and Geisser (1959) when Mauchly's test of sphericity was significant. However, the original degrees of freedom are presented when the effects were significant following Greenhouse–Geisser correction. All significant main effects involving more than two means were broken down using Tukey's HSD technique. Significant interactions were broken down by computing simple main effects that were followed by *post hoc* comparisons (Tukey HSD) when they involved more than two means. All effects are reported at p < 05.

Results

Participants were not aware of cursor jumps

Participants reported that they were not aware that the cursor had jumped on some trials, even after a debriefing. This result replicates previous observations (Bédard & Proteau, 2003; Brière & Proteau, 2011; Proteau et al., 2009; Saunders & Knill, 2003, 2004; Veyrat-Masson et al., 2010), even when a cursor jump occurred in a high proportion of the trials (although during saccadic visual suppression, Sarlegna et al., 2003, 2004).

Movement time

Movement time data were individually submitted to an ANOVA that contrasted 3 groups (+16, +40, +64) x 3 types of perturbation (no-jump, single-jump, double-jump) x 2 occlusion conditions (occluded, non-occluded). The ANOVA revealed a significant main effect of the occlusion condition (F[1, 31] = 9.18, p = 0.005). Movement time was 15 ms longer when the cursor remained visible throughout movement execution than when the cursor was occluded during movement execution (889 ms and 874 ms, for the non-occluded and occluded conditions, respectively). The ANOVA also revealed a significant group main effect (F[2, 31] = 6.01, p = 0.006). *Post hoc* comparisons revealed that movement time was significantly longer for the +16 ($p = 0.006$) group than for the + 64 group (917 ms, 893 ms, and 833 ms, for the +16, +40, and +64 groups, respectively).[4]

Endpoint location and variability

Figure 3 illustrates the mean movement trajectories for the single- and double-jump trials in the occluded and non-occluded conditions. The endpoint error and variability (variable error) data were submitted individually to the same type of analysis as the movement time data. For the endpoint error, the ANOVA revealed a significant group x type x occlusion interaction ($F[4, 62] = 5.38$, $p = 0.001$). The three-way ANOVA was decomposed by computing separate analyses for the no-jump, single-jump, and the double-jump trials. For the no-jump trials, the ANOVA revealed a significant main effect of the group ($F[2, 31] = 3.63$, $p = 0.038$), indicating significantly different endpoint locations between the +16 and the +64 groups. Whereas mean movement endpoint was slightly to the left of the target for the +16 group, mean movement endpoint was slightly to the right of the target for the + 64 group (-1.74 mm, -0.23 mm, and 0.47 mm for the +16, +40, and +64 groups, respectively). For the single-jump trials, the ANOVA only revealed a significant main effect of the group ($F[2, 31] = 4.14$, $p = 0.026$), indicating significantly different endpoint locations between the +16 and the +64 groups. Mean movement endpoint was significantly more to the left of the target for the +16 group than for the + 64 group (-14.06 mm, -11.73 mm, and -9.95 mm for the +16, +40, and +64 groups, respectively). For the double-jump trials, the ANOVA revealed a significant group x occlusion interaction ($F[2, 31] = 21.87$, $p < 0.001$). The breakdown of the

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[4] The longer movement time noted for the +16 group does not indicate the movement amplitude was longer for this group than for the other two groups. A supplementary analysis revealed that the length of the movement vector (distance between the starting base and the movement endpoint) was somewhat shorter for the +16 group (328.2 mm) than for the +40 (331.0 mm) and + 64 (330.2 mm) groups.

interaction revealed no difference in endpoint location for the non occluded and occluded conditions for the +64 group (-1.27 mm and -2.46 mm, respectively) (*F*[1, 31] = 1.57, p = 0.21). However, there was a significant main effect of the occlusion conditions for the +16 group (*F*[1, 31] = 114.69, $p < 0.001$) and for the +40 group (*F*[1, 31] = 19.89, $p < 0.001$). For both groups, movements were more accurate in the non occluded than in the occluded condition (group +16: -1.62 mm vs. -11.37 mm; group +40: -0.83 mm vs. -5.07 mm, respectively).

Concerning the variable error, the ANOVA revealed a significant main effect of the occlusion condition (*F*[1, 31] = 42.17, $p < 0.001$). Endpoint frontal variability was significantly smaller when the cursor remained visible throughout movement execution (3.5 mm) than when the cursor was occluded during movement execution (5.3 mm), $p < 0.001$.

Modulation of perturbed trials

In the present section, we evaluated the accuracy of the corrections that followed a cursor jump. This correction for the trials completed with vision of the cursor was the difference in the frontal position of the stylus at the movement endpoint between the no-jump non-occluded trials and the jump trials (single and double; see Figure 1C) completed with normal vision. This correction for the trials in which the cursor was occluded during movement execution was the difference in the frontal position of the stylus at the movement endpoint between the no-jump occluded trials and the jump trials (single and double) completed without vision of the cursor. A positive value indicated that the frontal position of the stylus at the movement endpoint was opposite to the direction of the cursor jump, which indicated that a correction occurred.

Movement correction data were analyzed using an ANOVA that contrasted the 3 groups (+16, +40 and +64) x 2 types of perturbations (single-jump vs. double-jump) x 2 conditions of cursor occlusion (occluded vs. non-occluded). The ANOVA revealed a significant group x type x occlusion interaction (*F*[2, 31] = 5.7, *p* = 0.01) (Figure 4). The three-way ANOVA was decomposed by computing separate analyses for the single-jump and the double-jump trials.

The ANOVA of the single-jump trials did not reveal any significant main effect or interaction (*p* > 0.085 in all cases). On average, participants corrected their movements to compensate for 76% of the single cursor jumps regardless of whether vision of the cursor was occluded soon after the perturbation (12.5 mm and 12.0 mm for the +16 group, 12.4 mm and 10.6 mm for the +40 group, and 11.2 mm and 9.7 mm for the +64 group for single-jump non-occluded and occluded, respectively; see the white [single-jump, non-occluded] and black [single-jump, occluded] markers in Figure 4). This similarity in results between the single-jump non-occluded and single-jump occluded conditions confirms previous observations from our laboratory that demonstrated the CNS requires only a short visual sample to detect that one's movement is not progressing as planned and initiate an efficient correction (Brière & Proteau, 2011; Proteau et al., 2009; Veyrat-Masson et al., 2010).

The ANOVA of the double-jump trials revealed a significant group x occlusion interaction (*F*[2, 31] = 15.8, *p* < 0.001). The breakdown of this interaction revealed a significant difference between the non-occluded and occluded trials for all three groups (*F*[1, 31] = 94.4 (*p* < 0.001), 10.4 *(p* = 0.003), and 4.6 (*p* = 0.04) for groups +16, +40, and +64, respectively). The data illustrated in Figure 4 (grey markers) show that all three groups aborted/cancelled the correction for the first cursor jump in the double-jump non-occluded condition (correction of 0.7 mm [+16], 1.33 mm [+40], and 1.47 mm [+64]) compared to corrections of 12.6 mm ([+16], 12.4 mm [+40], and 11.2 mm for the single-jump non-occluded trials). This finding replicates previous findings by Brière and Proteau (2011; see also Oostwoud-Wijdenes, Brenner, & Smeets, 2011) that indicated the processes responsible for the detection and eventual correction for a cursor jump do not interfere with the processing of incoming visual information.

The significant interaction was caused by the results of the double-jump occluded condition (Figure 4, slanted markers). Specifically, the size of the inappropriate correction for this condition significantly decreased as the period of visibility of the cursor following the second cursor jump increased, which was expected because the cursor jumped back to its initial trajectory. What we did not expect was the finding that seeing the cursor for only 16 ms following the second cursor jump (leftmost panel of Figure 4) was sufficient for the correction noted for the double-jump occluded trials to be significantly smaller than that noted for the single-jump non-occluded and occluded trials.[5] This result indicates that viewing the cursor trajectory for only 16 ms after the second jump was sufficient for participants to significantly reduce their correction for the first cursor jump. Conversely, viewing the cursor for 64 ms after it had jumped back to its initial trajectory was not entirely sufficient to completely eliminate the correction for the initial cursor jump.

Correcting for the cursor jump is not learned

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[5] A complementary ANOVA contrasting the corrections observed for the 4 types of perturbed trials for group +16 revealed a significant main effect of types ($F[3, 33] = 72.3$, $p < 0.001$). *Post hoc* comparisons revealed no significant difference between the single-jump non-occluded and the single-jump occluded conditions (12.6 mm vs. 12.0 mm, $p > 0.2$). The corrections noted for the single-jump non-occluded and the single-jump occluded conditions were significantly larger than that noted for the double-jump occluded conditions (8.7 mm), which was significantly larger than that noted for the double-jump non-occluded condition (0.7 mm).

Participants reported that they did not detect the cursor jumps. However, one could argue that their correction was learned or that participants somehow adapted the planning of their movements in anticipation of a cursor jump. We computed two supplementary analyses to investigate this issue. In the first analysis, we computed an ANOVA that contrasted the movement endpoint as a function of the 3 groups (+16, +40 and +64) x 2 types of perturbations (single-jump vs. double-jump) x 2 conditions of occlusion (non-occluded vs. occluded) x 8 perturbed trials (1^{st}, 2^{nd}, … 8^{th} perturbed trial) using repeated measurements on the last 3 factors. The results revealed no main effect of trial number ($F[7, 217] = 1.13$, $p = 0.34$) or any interaction involving this factor ($p > 0.30$ in all cases). Therefore, the corrections for the cursor jumps were not learned (for a similar observation, see Proteau et al., 2009).

In the second analysis, we examined whether the participants somehow anticipated the occurrence of a cursor jump. We compared the frontal position of the cursor 150 ms after movement initiation and at the moment of visual occlusion (see Figure 5). The data of interest were analyzed in an ANOVA that contrasted the 3 groups (+16, +40 and +64) x 3 types of trials (no-jump, single-jump and double-jump) x 2 conditions of occlusion (non-occluded vs. occluded) x 2 temporal landmarks (150 ms vs. moment of visual occlusion) using repeated measurements on the last 3 factors. The results revealed significant interactions for group x temporal landmarks ($F[2, 31] = 15.4$, $p < 0.01$) and types of trials x temporal landmarks ($F[2, 62] = 3.66$, $p = 0.03$). The breakdown of the former interaction into its simple main effects followed by *post hoc* comparisons did not reveal any significant difference across the type of trial at the 150-ms landmark ($p > 0.08$ in all cases). However, the frontal displacement of the stylus at the moment of visual occlusion was significantly larger in the +64 group than the + 40 and +16 groups, which did not differ significantly from each other (31.9 mm, 24.1 mm and

21.4 mm, respectively). These differences were expected because visual occlusion occurred 314 ms, 290 ms, and 266 ms after movement initiation in the +64, +40 and +16 ms groups, respectively. Therefore, we found no evidence that a correction for a cursor jump was preplanned (for supporting evidence, see also Brière and Proteau, 2011; Proteau et al., 2009).

Endpoint accuracy of cursor-jump trials is determined by the period of visibility of the cursor after the second cursor jump

Our findings suggest that seeing the cursor for a longer period of time after the second cursor permitted participants to better adapt the trajectory of their movement for the second jump. An alternative interpretation of our data is that it is not the duration that the cursor is seen after the second cursor jump that matters, but it is the amplitude of the movement trajectory that remained visible after the cursor jump that explains our findings. Specifically, the cursor remained visible after the second cursor jump for 9.7 mm (*sd*: 1.3 mm), 26.2 mm (*sd*: 3.2 mm), and 42.4 mm *(sd*: 4.7 mm) for conditions +16 ms, +40 ms, and +64 ms, respectively. Potential support for this alternative interpretation comes from our observation that, although participants were asked to complete their movements in a predetermined movement time, the movement time increased as the time for which the cursor remained visible after the second cursor jump decreased (833 ms, 893 ms, and 917 ms for groups +64, +40 and, +16, respectively). Therefore, considering that the participants did not consciously perceive the cursor jumps, it could be that they may have unconsciously slowed their movements as the period of cursor visibility after the second jump decreased to increase the amplitude of the visible trajectory.

We completed an analysis to determine whether the endpoint accuracy of the cursor-jump trials for the +64 group was related to the length of cursor visibility after the second cursor jump. The visible trajectory of the cursor after the second cursor jump varied between a minimum of 31.4 mm (*sd* = 6.1 mm) and a maximum of 52.2 mm (*sd* = 8.8 mm) in this group, and we observed no significant correlation between endpoint accuracy and the length of the visible trajectory after the second cursor jump, *r* = 0.05 (*sd* = 0.4). These results clearly indicate that the perceived position of the cursor in the present study depended on the duration of visibility and not the amplitude of the visible trajectory (see also Studenka & Newell, 2013; Whitaker, Levi, & Kennedy, 2008).

Continuous monitoring of visual feedback

We have demonstrated that a larger proportion of the correction for the first cursor jump was eliminated as the period of cursor visibility increased after the second cursor jump. The results reported in the preceding sections revealed that the size of the correction did not differ as practice increased nor with the length of cursor visibility after the second cursor jump. However, one might still argue that participants may have completely cancelled their correction for the first cursor jump in some trials, but they did not cancel their correction in other trials. This hypothesis could suggest an 'all or none' type of process, with the likelihood of a complete cancellation increasing with the duration of cursor visibility following the second cursor jump. Conversely, it could be that the correction cancellation process took place for all trials, but that this process is time dependent.

The first hypothesis suggested above would result in a bimodal distribution of the double-jump occluded trials, with one peak located near the mean frontal endpoint location in trials that did not require a correction (no-jump occluded; -0.9 mm). The second peak of the distribution would be located near the mean frontal endpoint location in the single-jump occluded condition (-14.6 mm) in which the single-jump (i.e., group +16, see Figure 2) occurred at the same time as the first jump in the double-jump occluded trials. The higher mode of this distribution would move towards the no correction point as the period of cursor visibility following the second cursor jump decreased. The second hypothesis described above suggests a unimodal distribution centered around the mean endpoint frontal error for this condition. A bimodal distribution of the results would indicate that the CNS sometimes detected the second cursor jump, but sometimes it did not. These results would indicate an intermittent visual monitoring of goal-directed movements. However, a unimodal distribution of the results for each group could suggest that visual information accumulates over time to better define the location of the cursor.

Figure 6 illustrates the frontal endpoint distribution of the single-jump occluded trials (upper panel) and the double-jump occluded trials for all participants. Each category represents the number of trials included in successive bins of 3 mm. For the three double-jump occluded conditions (+16 ms, +40 ms, and +64 ms), the data were fit by a unimodal distribution that explained between 81% and 92% of the total variance (coefficient of determination, R^2), which is consistent with the expected unimodal fit observed for the single-jump occluded trials (upper panel, $R^2 = 0.901$). These results strongly support that visual information accumulates over time to better define the location of the cursor.

Spatial integration over time

The data previously presented support a continuous monitoring of visual feedback and indicate that a very brief period of cursor visibility is sufficient to trigger error correction processes. If the perceived location of the cursor was determined by its last visible position, and if this perception was an instantaneous process, then we should have observed a complete cancellation of the correction for the first cursor jump for the +16, +40, and +64 groups.

However, this result was not observed. Rather, the size of the correction for the second cursor jump increased as a function of the time that the cursor remained visible after the second jump, which suggests that the visual information was integrated over time to determine the cursor's perceived position. We postulated that the frontal endpoint of the stylus for the double-jump non-occluded condition represented a complete correction for the second jump (see Figure 4, grey markers). This hypothesis was supported by our results, which demonstrated no significant difference in the frontal endpoint between this condition and the non-occluded no-jump condition (-1.6 mm and -0.9 mm, respectively, $F[1, 11] = 1.86$, $p = 0.20$). We then postulated that if no correction for the second jump had occurred for the double-jump occluded trials, then the stylus frontal endpoint would be similar to the frontal position of the single-jump occluded condition, in which a second cursor jump did not occur (-14.6 mm relative to the center of the target for group +16). We plotted these data and the frontal endpoint position of the stylus for the double-jump occluded trials for the +16, +40, and +64 groups (Figure 7) against the duration of the cursor visibility after the second cursor jump. The relationship between the position of the stylus at movement endpoint and the period of cursor visibility following the second cursor jump was well accounted for by a linear regression (endpoint bias = 0.1871*[period of cursor visibility after the second cursor jump] – 14.126, $R^2 = 0.972$), which enabled us to predict that seeing the cursor for 70 ms was the shortest integration period for which a complete correction for the second cursor jump would have appeared.

Discussion

The results of many studies using a target jump (Bridgeman, Lewis, Heit, & Martha, 1979; Day & Lyon, 2000; Desmurget, Epstein, Turner, Prablanc, Alexander, & Grafton, 1999;

Franklin et al., 2012; Goodale, Pélisson & Prablanc, 1986; Gritsenko & Kalaska, 2010; Prablanc & Martin, 1992; Sarlegna et al., 2003) or cursor jump (Brière & Proteau, 2011; Franklin & Wolpert, 2008; Proteau et al., 2009; Sarlegna et al., 2003, 2004, Saunders & Knill, 2003, 2004; Veyrat-Masson et al., 2010) paradigm suggest that goal-directed movements are monitored almost continuously to ensure endpoint accuracy (for a review see Gaveau, Pisella, Priot, Fukui, Rossetti, Pélissson, & Prablanc, 2014). A sudden and unexpected change in either the target location or cursor trajectory triggers a correction mechanism that is qualified as 'reflex-like' (Franklin & Wolpert, 2008). In the present study, we sought to determine the minimal amount of visual information needed by the CNS to detect that a movement is not progressing as planned and issue a correction. We used a double-cursor-jump paradigm in our investigation. The delay between the first and second cursor jump was sufficient for the participants to detect the first cursor jump (Brière & Proteau, 2011; Proteau et al., 2009), which was supported by the observation of large and equivalent corrections for a single cursor jump, regardless of whether vision of the cursor was permitted for the entire trial or was occluded 100 ms after the jump. The second jump cancelled the need for a correction for the first cursor jump. Our results replicate previous finding demonstrating that participants quickly cancelled the correction processes elicited by the first cursor jump (Brière & Proteau, 2011; Oostwoud-Wijdenes et al., 2011). Our specific goal was to determine the duration that one should view the cursor following the second cursor jump to cancel or modify the correction process triggered by the first cursor jump.

Goal-directed movements are continuously monitored visually

The results of previous reports suggest that vision continuously monitors the execution of goal-directed movements. This position was based on the observation that the time to initiate a correction for a cursor jump remained fixed regardless of where the visual perturbation was introduced in the movement trajectory (Brière & Proteau, 2011; Saunders & Knill, 2003). A second line of evidence arose from previous work from our laboratory in which we demonstrated that viewing the cursor for as little as 60 ms after a jump provided enough information to trigger an accurate correction (Proteau et al., 2009). An important new finding of the present study supports and extends this position. Specifically, we demonstrated that viewing the cursor for as little as 16 ms following the second cursor jump was sufficient to trigger error correction processes that resulted in a significant decrease in the correction for the first cursor jump by 23.1%. The correction cancellation for the first cursor jump also reached 93.1% when the cursor was viewed once it returned to its initial trajectory for as little as 64 ms.

The perceived position of the effector is averaged over time

Our data indicate that the perceived position of the cursor is not determined by its position at any point in time but rather by its integrated position over a fixed period of approximately 70 ms. This observation is another important new finding of the present study that contradicts previous observations reported by Shabbott and Sainburg (2009). These authors used a task and an apparatus similar to ours, but they unexpectedly induced a visuomotor rotation of the cursor to dissociate its position/trajectory from that of the participant's finger for some trials, instead of using a cursor-jump protocol. The cursor was visible on the starting base and during movement execution. Therefore, the rotation resulted in the cursor not progressing as expected, which was eventually detected and corrected by the participant. The authors manipulated the size of the induced error (i.e., smaller or larger rotation) and occluded the cursor after it had progressed different distances from the starting base to manipulate the duration of the cursor visibility and the lateral distance between the target and the cursor to determine which aspects of the error information mediated the correction for the rotation. Their results demonstrate that the size of the correction is determined by the lateral gap between the last visible cursor position and the location of the target and not by the duration of the cursor visibility. Shabbott and Sainburg (2009) concluded that the correction implemented was solely a function of the last visible difference between the cursor and the target. However, the cursor remained visible for at least 125 ms in that study (experiment 2; see their Figure 7). Our results demonstrated that 64 ms of cursor visibility was sufficient for the participant to obtain the information necessary to implement an efficient correction.

Integration of visual and proprioceptive sensory information in forward models

In its simplest form, movement planning of a manual aiming movement consists of computing a vector that links one's hand to the target. An inverse model transforms this vector in motor commands. An efference copy of these motor commands is sent to a forward model that anticipates their sensorimotor consequences, predicts the movement endpoint, and when necessary, issues corrective motor commands. The forward model is updated/fine-tuned during movement execution by incoming proprioceptive and visual inputs (for a review, see Desmurget & Grafton, 2000; Shadmehr, Smith, & Krakauer, 2010). The results of the present study concur with previous research using a cursor-jump paradigm (Brière & Proteau, 2011; Proteau et al., 2009; Sarlegna et al., 2004; Saunders & Knill, 2003, 2004) in suggesting a preponderant but not exclusive role of visual feedback for the updating of forward models.

A recurrent finding in studies that used a cursor-jump paradigm is that there is a limit to the size of the correction issued to counteract a cursor jump. For instance, when movement time is relatively long, as in the present study, the correction for a single cursor jump compensated for between 65% (Veyrat-Masson et al., 2010) and 75%-80% (the present study; Brière & Proteau, 2011) of the imposed bias. It could be that asking participants to complete their movement in a single motion (present study; Brière & Proteau, 2011; Proteau et al., 2009) prevented them from completing their corrections. However, this proposition is hard to reconcile with our observation that an almost complete correction for a double-jump was observed for group +64 in the present study (see also Brière & Proteau, 2011), which had the same 'single motion' requirement as in our previous work (Brière & Proteau, 2011; Proteau et al., 2009). A more likely explanation is that a cursor jump creates a conflict between the viewed position of the cursor and the felt position of the hand, which may have limited the participants' ability to estimate the current position of their hand, predict the movement endpoint, and plan their correction. This conflict underlines that both visual and proprioceptive feedback are fed back to the forward model. However, because the correction for the single cursor jump approximated 80% of the imposed perturbation, one must conclude that the weight given to vision was larger than the weight given to proprioception. This could result from the perceived lower reliability of the proprioceptive signal (Körding & Wolpert, 2004). Specifically, because of the cursor jump, the anticipated and felt position of the hand did not match its observed position for 16% of the trials, which likely decreased the perceived reliability of the proprioceptive feedback.

Conclusions

The visual system continuously monitors goal-directed movements, and a very brief sample of information is sufficient to trigger a correction mechanism. This correction did not differ significantly between conditions in which the effector remained visible until the movement endpoint and conditions in which it was occluded 64 ms after a cursor jump, which suggests that the visual information extracted during this period appears sufficient for the CNS to plan and execute an accurate correction. Thus, it appears that the visual information that is extracted during this short period of time is sufficient for a forward model to control the last 500 ms of the movement as accurately as if vision had been available until the movement endpoint.

References

Bédard, P., & Proteau, L. (2003). On the role of peripheral visual afferent information for the control of rapid video-aiming movements. *Acta Psychologica, 113*, 99–117.

Bridgeman, B., Lewis, S., Heit, G., & Martha, N. (1979). Relation between cognitive and motor-oriented systems of visual position perception. *Journal of Experimental Psychology: Human Perception and Performance, 5*, 692–700.

Brière, J., & Proteau, L. (2011). Automatic movement error detection and correction processes in reaching movements. *Experimental Brain Research, 208*, 39-50.

Cluff, T., Crevecoeur, F., & Scott, S.H. (2015). A perspective on multisensory integration and rapid perturbation responses. *Vision Research, 110,* 215-222.

Day, B.L., & Lyon, I.N. (2000). Voluntary modification of automatic arm movements evoked by motion of a visual target. *Experimental Brain Research, 130*,159–168.

Desmurget, M., Epstein, C.M., Turner, R.S., Prablanc, C., Alexander, G.E., & Grafton, S.T. (1999.) Role of the posterior parietal cortex in updating reaching movements to a visual target. *Nature Neuroscience, 2*, 563–567.

Desmurget, M., & Grafton, S.T. (2000). Forward modeling allows feedback control for fast reaching movements. *Trends in Cognitive Sciences, 4,* 423-431.

Franklin, S., & Wolpert, D.M. (2008). Specificity of reflex adaptation for task-relevant variability. *Journal of Neuroscience, 28,* 14165–14175.

Franklin, S., Wolpert, D.M., & Franklin, D.W. (2012). Visuomotor feedback gains upregulate during the learning of novel dynamics. *Journal of Neurophysiology, 108*, 467–478.

Gaveau, V., Pisella, L., Priot, A.-E., Fukui, T., Rossetti, Y., Pélisson, D., & Prablanc, C. (2014). Automatic online control of motor adjustments in reaching and grasping. *Neuropsychologia, 55*, 25-44.

Goodale, M.A., Pélisson, D., & Prablanc, C. (1986). Large adjustments in visually guided reaching do not depend on vision of the hand or perception of target displacement. *Nature, 320,* 748–750.

Greenhouse, S.W., & Geisser, S. (1959). On methods in the analysis of profile data. *Psychometrika, 24,* 95-112.

Gritsenko, V., & Kalaska, J.F. (2010). Rapid online correction is selectively suppressed during movement with a visuomotor transformation. *Journal of Neurophysiology, 104*, 3084-3104.

Körding, P.K., & Wolpert, D.M. (2004). Bayesian integration in sensorimotor learning. *Nature, 427*, 244-247.

Meyer, D.E., Abrams, R.A., Kornblum, S., Wright, C.E., & Smith, J.E. (1988). Optimality in human motor performance: ideal control of rapid aimed movements. *Psychological Review, 95,* 340–370.

Neggers, S.F.W., & Bekkering, H. (1999). Integration of visual and somatosensory target information in goal-directed eye and arm movements. *Experimental Brain Research, 125,* 97–107.

Neggers, S.F.W., & Bekkering, H. (2000). Ocular gaze is anchored to the target of an ongoing pointing movement. *Journal of Neurophysiology, 83*, 639–651.

Neggers, S.F.W., & Bekkering, H. (2001.) Gaze anchoring to a pointing target is present during the entire pointing movement and is driven by a non-visual signal. *Journal of Neurophysiology, 86,* 961–970.

Oostwoud-Wijdenes, L., Brenner, E., & Smeets, J.B.J. (2011). Fast and fine-tuned corrections when the target of a hand movement is displaced. *Experimental Brain Research, 214*, 453–462.

Prablanc, C., & Martin, O. (1992). Automatic control during hand reaching at undetected two-dimensional target displacements. *Journal of Neurophysiology, 67*, 455–469.

Proteau, L., Roujoula, A., & Messier. J. (2009). Evidence for continuous processing of visual information in a manual video-aiming task. *Journal of Motor Behavior, 41,* 219-231.

Reichenbach, A., Franklin, D.W., Zatka-Haas, P., & Fiedrichsen, J. (2014). A dedicated binding mechanism for the visual control of movement. *Current Biology, 24*, 780-785.

Sarlegna, F., Blouin, J., Bresciani, J.-P., Bourdin, C., Vercher, J.-L., & Gauthier, G.M. (2003). Target and hand position information in the online control of goal-directed arm movements. *Experimental Brain Research, 151*, 524-535.

Sarlegna, F., Blouin, J., Vercher, J.-L., Bresciani, J.-P., Bourdin, C., & Gauthier, G.M. (2004). Online control of the direction of rapid reaching movements. *Experimental Brain Research, 157*, 468-471.

Saunders, J.A., & Knill, D.C. (2003). Humans use continuous visual feedback from the hand to control fast reaching movements. *Experimental Brain Research, 152*, 341-352.

Saunders, J.A., & Knill, D.C. (2004). Visual feedback control of hand movements. *Journal of Neuroscience, 24*, 3223-3234.

Shabbott, B.A., & Sainburg, R.L. (2009). On-line corrections for visuomotor errors. *Experimental Brain Research, 195,* 59-72.

Shadmehr, R., Smith, M.A., & Krakauer, J.W. (2010). *Annual Review of Neuroscience, 33*, 89-108.

Studenka, B.E., & Newell, K.M. (2013). Visual information for prospective control of tracking irregular target paths with isometric force production. *Journal of Experimental Psychology: Human Perception and Performance, 39*, 1557-1567.

Vesia, M., Yan, X., Henriques, D.Y., Sergio, L.E., & Crawford, J.D. (2008). Transcranial magnetic stimulation over human dorsal–lateral posterior parietal cortex disrupts integration of hand position signals into the reach plan. *Journal of Neurophysiology, 100,* 2005-2014.

Veyrat-Masson, M., Brière, J., & Proteau, L. (2010). Automaticity of online control processes in manual aiming. *Journal of Vision, 10(14):27,* 1–14.

Whitaker, T.A., Levi, D.M., & Kennedy, G.J. (2008). Integration across time determines path deviation discrimination for moving objects. *PloS ONE, 3 (4)*: e1930 doi:101371/journalpone0001930.

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Figure captions

Figure 1. A: view of the experimental set-up. B: The manipulandum and the location of the target in relation to the participant. A single-jump (red) translated the trajectory of the cursor by 15 mm to the right. C: Target location in relation to the target. The dashed lines indicate potential endpoint errors for the no-jump and single-jump endpoint locations. The correction for the single jump is illustrated by the full line.

Figure 2. Illustration of the different experimental conditions. Left panels: within each group, the cursor occlusion occurred at the same moment (266 ms, 290 ms, or 314 ms after movement onset). Right panels: for all conditions, the cursor remained visible until movement completion. Double-jump: the first, second and third numbers indicate the moment of occurrence (in ms) of the first and second cursor jump, and of the cursor occlusion, respectively. The cursor was never occluded in the non-occluded condition. Single-jump: the first and second numbers indicate the moment of occurrence of the single-jump and of the cursor occlusion, respectively. The cursor was never occluded in the non-occluded condition. No-jump: the occurrence of cursor occlusion is indicated for the occluded condition.

Figure 3. Movement trajectories averaged over all trials of all participants in each group for the single- and double-jump trials completed in the non-occluded and occluded conditions. The black round marker illustrates the initial target, and the red round marker illustrates movement endpoint of the stylus if a complete correction for a single-jump trial was observed. Note that movement endpoints of the single- and double-jump trials completed in in the non-occluded condition indicate large and efficient corrections for the cursor jump(s). The cancellation of the correction for the first cursor jump progressively increases as the period of cursor visibility after the second cursor jump increases.

Figure 4. Amplitude (mm) and proportion (%) of the correction for the single- and double-jump trials as a function of the duration of cursor visibility after the last jump. Note the large corrections for the single-jump trials completed in the occluded and non-occluded conditions and the cancellation of the correction for the double-jump not occluded trials. Note also that 16 ms of cursor visibility after the second cursor jump permitted participants to eliminate 23% of the corrections normally observed for the single-jump trials (Group +16).

Figure 5. Frontal position of the stylus 150 ms after movement initiation at the occurrence of visual occlusion for the occluded trials and at movement endpoint. Note that for all three groups there is no evidence of corrections for the single- and double-cursor jump trials, at least up to the occurrence of visual occlusion.

Figure 6. Movement endpoint distribution for the different types of trials completed with an occluded cursor after the first (single-jump occluded) and second cursor jumps (conditions +16 ms, +40 ms and +64 ms). Note the unimodal distribution of movement endpoints for all conditions.

Figure 7. Movement endpoint error for the double-jump condition as a function of the period of cursor visibility (ms) after the second cursor jump. Note that the linear decrease in cursor endpoint bias is a function of the duration of the cursor visibility after the second cursor jump.

Figure 1

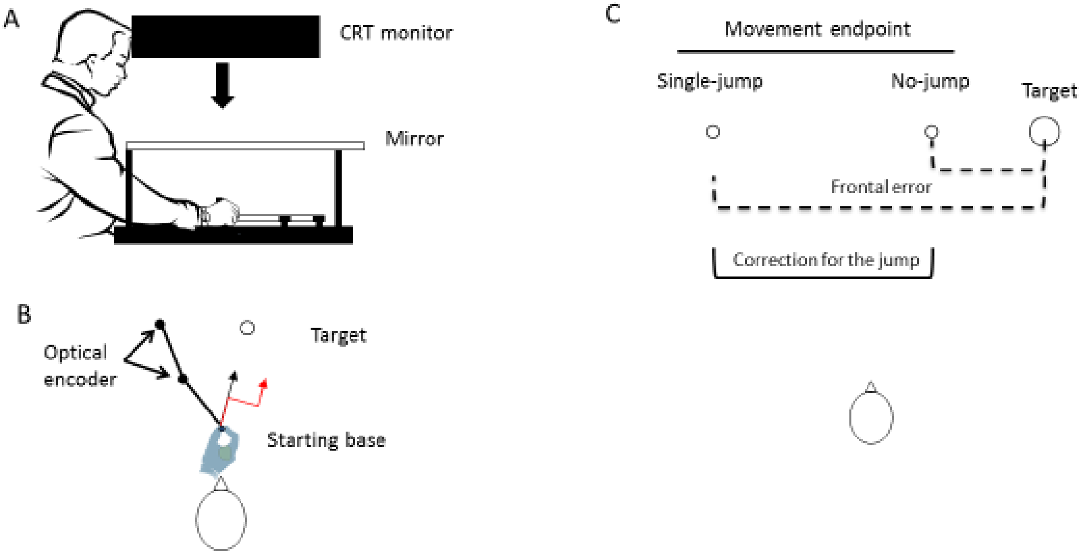

A
CRT monitor
Mirror
B
Optical encoder
Target
Starting base
C
Movement endpoint
Single-jump
No-jump
Target
Frontal error
Correction for the jump

Figure 2

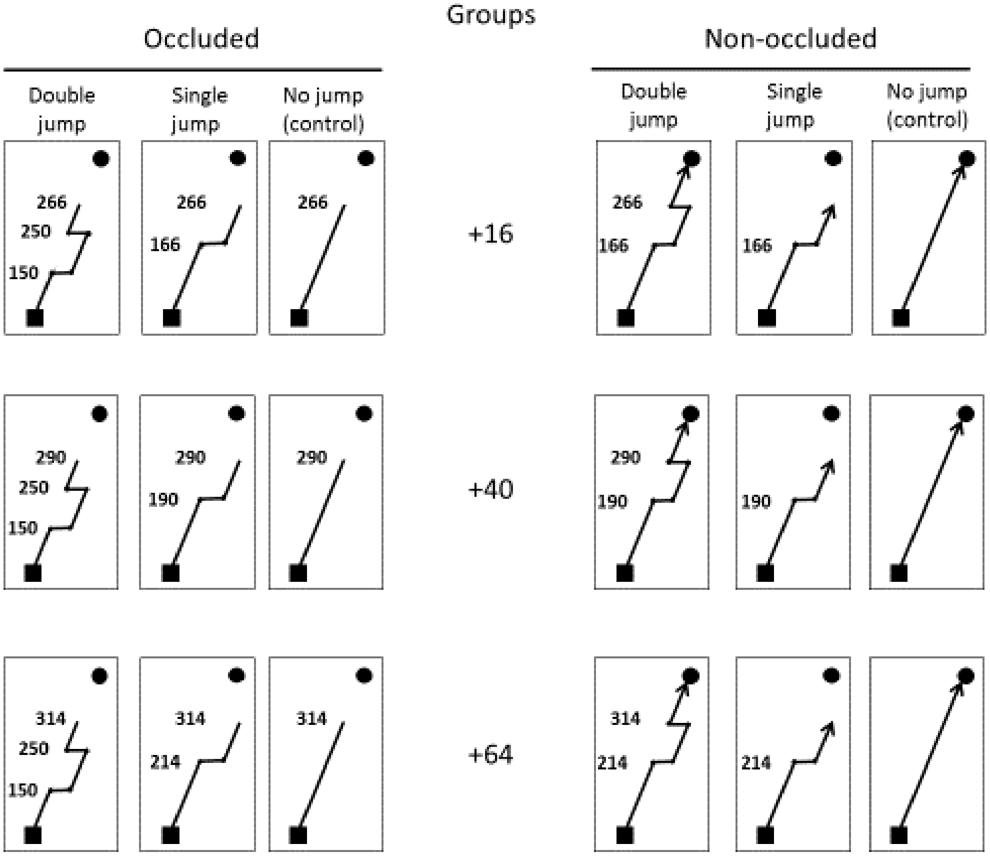
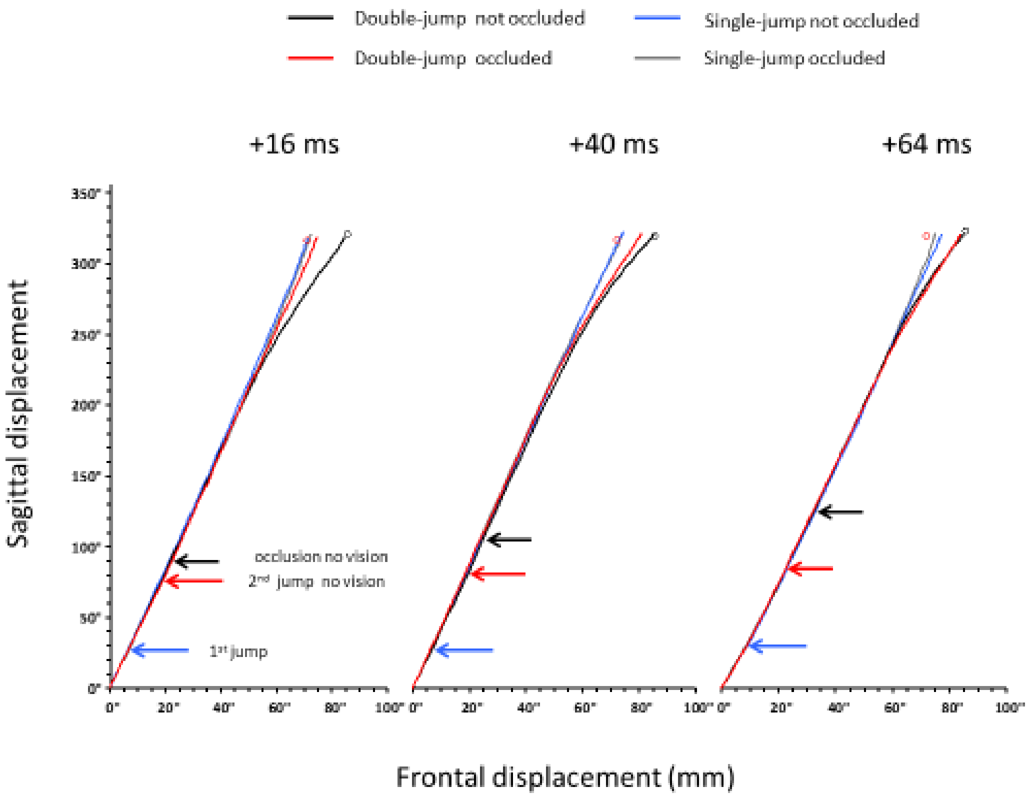
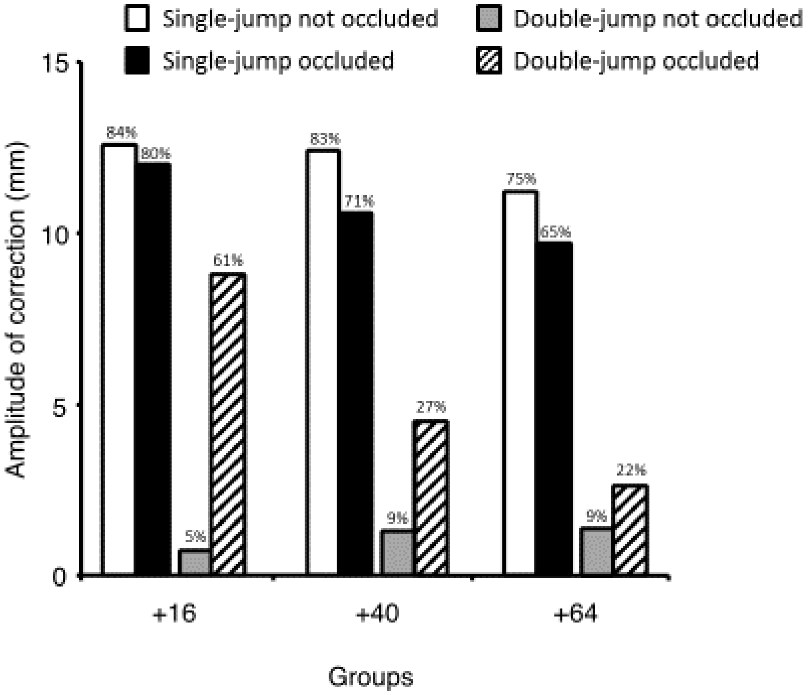

Groups
Occluded
Non-occluded
Double jump
Single jump
No jump (control)
Double jump
Single jump
No jump (control)
266
250
150
266
166
266
+16
266
166
166
290
250
150
290
190
290
+40
290
190
190
314
250
150
314
214
314
+64
314
214
214

Figure 3



Double-jump not occluded
Double-jump occluded
Single-jump not occluded
Single-jump occluded
+16 ms
+40 ms
+64 ms
Sagittal displacement
350
300
250
200
150
100
50
0
occlusion no vision
2nd jump no vision
1st jump
0
20
40
60
80
100
Frontal displacement (mm)

Figure 4



□ Single-jump not occluded
■ Single-jump occluded
▨ Double-jump not occluded
▨ Double-jump occluded
15
10
5
0
Amplitude of correction (mm)
84%
80%
5%
61%
83%
71%
9%
27%
75%
65%
9%
22%
+16
+40
+64
Groups

Figure 5

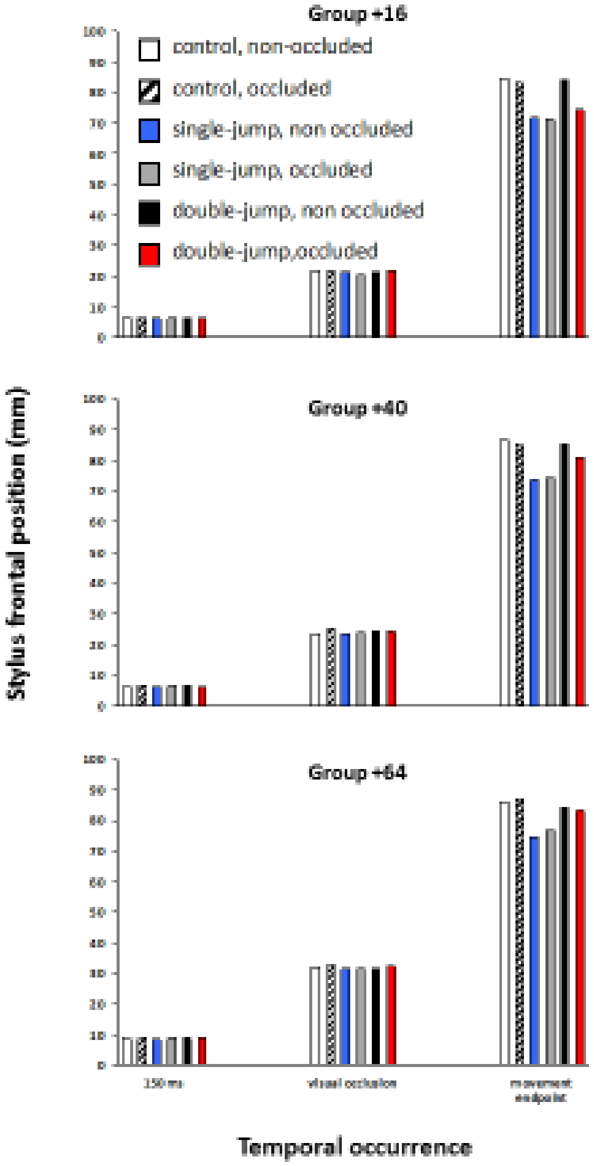

Group +16
control, non-occluded
control, occluded
single-jump, non occluded
single-jump, occluded
double-jump, non occluded
double-jump,occluded
Group +40
Group +64
Stylus frontal position (mm)
0
10
20
30
40
50
60
70
80
90
100
150 ms
visual occlusion
movement endpoint
Temporal occurrence

Figure 6

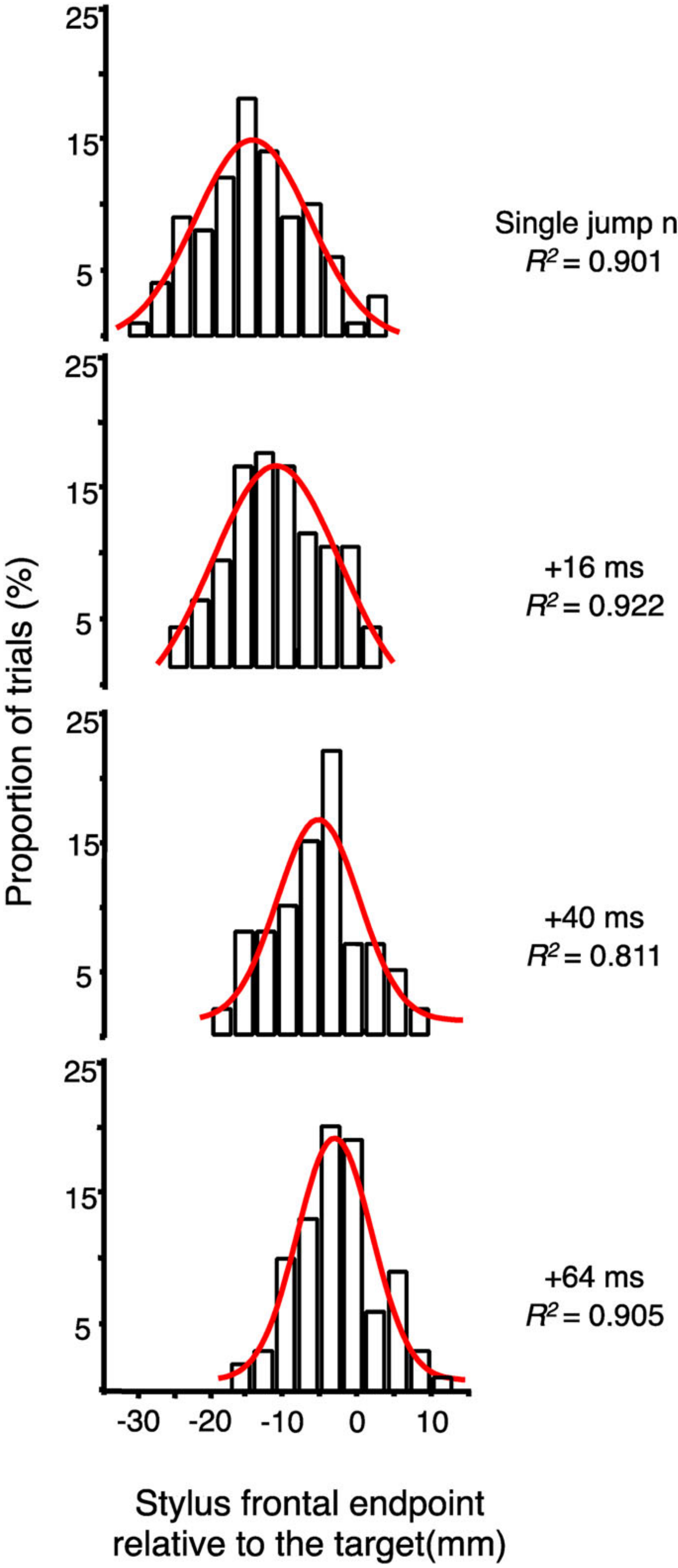
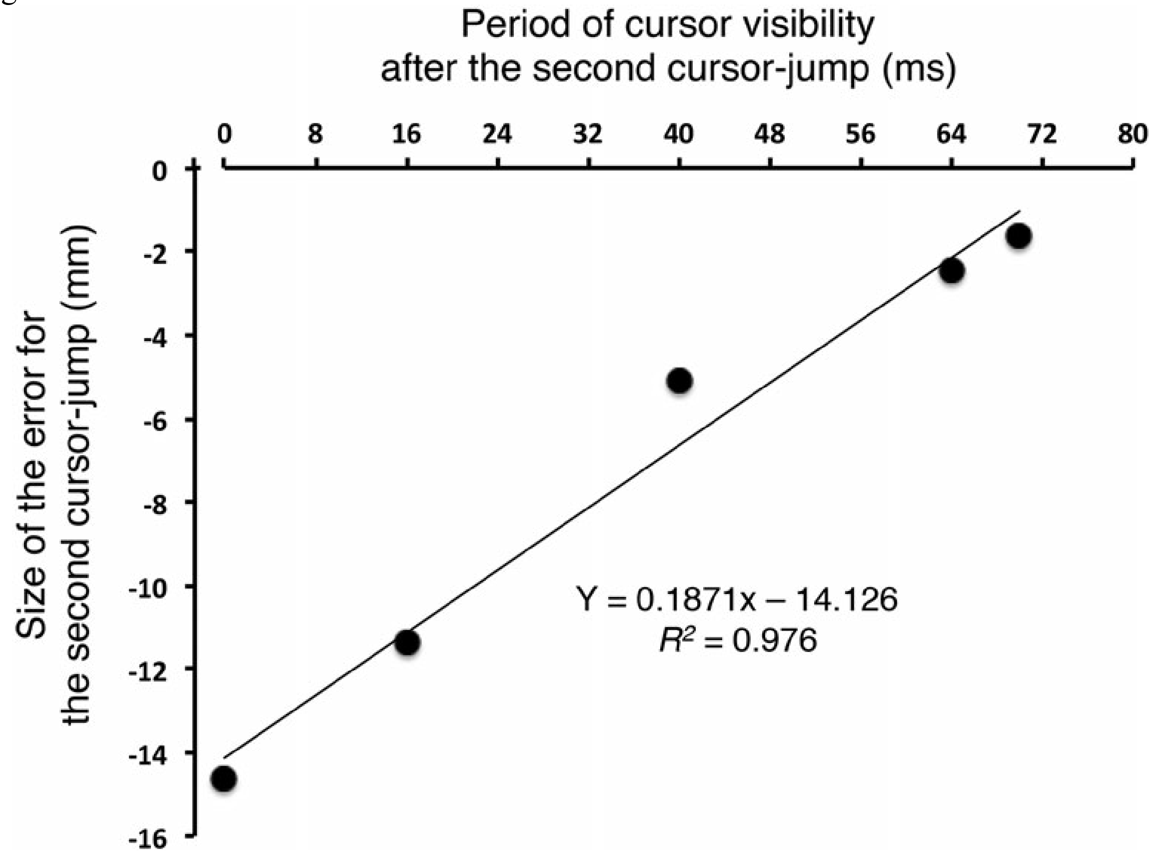

25
15
5
Single jump nv
$R^2 = 0.901$
25
15
5
+16 ms
$R^2 = 0.922$
25
15
5
+40 ms
$R^2 = 0.811$
25
15
5
+64 ms
$R^2 = 0.905$
Proportion of trials (%)
-30
-20
-10
0
10
Stylus frontal endpoint
relative to the target(mm)

Figure 7


Period of cursor visibility
after the second cursor-jump (ms)
0
8
16
24
32
40
48
56
64
72
80
0
-2
-4
-6
-8
-10
-12
-14
-16
Size of the error for
the second cursor-jump (mm)
Y = 0.1871x – 14.126
R2 = 0.976

Chapitre 4 : Article 3

Goal directed movements are continuously visually monitored: Modulation of movement execution for successive cursor jumps

Julien Brière and Luc Proteau[1]
Département de kinésiologie
Université de Montréal
Montréal, Canada

[1]Corresponding author:
Luc Proteau, Département de kinésiologie, Université de Montréal, P.O. Box 6128,
Downtown Station, Montréal, Canada, H3C 3J7.
Tel: (514) 343-2039
Fax: (514) 343-2181
Email: luc.proteau@umontreal.ca

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Abstract

The results of double-step experiments have revealed that goal-directed movements are closely monitored by the visual system. A sudden and unexpected translation of the target or of a cursor manually controlled by a participant leads to a quick and efficient correction. Moreover, in a cursor-jump study, seeing the cursor for only 64 ms after it has jumped back to its initial trajectory 100 ms after the first cursor jump results in the near complete cancellation of the correction initiated for the first cursor jump (Brière and Proteau, 2017). In the present study, we sought to determine whether the error detection and correction processes revealed in Brière and Proteau initiated only a cancellation/abortion process for the correction for the first cursor jump or whether this process accumulates information over time and therefore calibrates the correction as a function of the second cursor jump. We used a double cursor jump paradigm. The second cursor jump was in the direction opposite from that of the first cursor-jump, with an amplitude 50%, 100% or 150% that of the first cursor jump. In some conditions, the cursor was occluded 64 ms after the second cursor jump. A key finding of the present study is that participants corrected their movement as a function of the net perturbation after the second cursor-jump. This correction did not result in an increase in movement time. The results indicate that the visual information extracted during the 64 ms of cursor visibility after the second cursor jump is sufficient for a forward model to control the last 500 ms of the movement as accurately as if vision had been available until the movement endpoint.

Keywords: cursor-jump, online visual control, goal-directed movements, motor control, feedback processes, forward processes.

Goal directed movements are continuously visually monitored: Modulation of movement execution for successive cursor jumps

The intrinsic variability present in all human processes requires that the central nervous system (CNS) closely monitor our movements to allow us to quickly update movement planning and amend movement execution (Cluff, Crevecoeur and Scott 2015; Desmurget and Grafton 2000; Franklin and Wolpert 2008; Franklin, Wolpert and Franklin 2012; Vesia, Yan, Henriques, Sergio and Crawford 2008). We sought to determine the characteristics of the correction process when a planning or execution error is detected by the visual system in a goal-directed movement.

How the visual system monitors movement is often studied with a perturbation paradigm. In goal-directed aiming movements, the perturbation often takes the form of either a target jump or a cursor jump. In target jump experiments (Bridgeman, Lewis, Heit and Martha 1979; Day and Lyon 2000; Desmurget et al. 1999; Franklin et al. 2012; Goodale, Pélisson and Prablanc 1986; Gritsenko and Kalaska 2010; Prablanc and Martin 1992; Sarlegna et al., 2003), the location of the target is modified just before or soon after movement initiation (i.e., during the saccadic suppression period). In cursor jump experiments, the participants move a cursor toward a target on a visual display (Brière and Proteau 2011, 2016; Franklin and Wolpert 2008; Proteau, Roujoula and Messier 2009; Reichenbach, Franklin, Zatka-Haas and Diedrichsen 2014; Sarlegna et al. 2003, 2004, Saunders and Knill 2003, 2004; Veyrat-Masson, Brière and Proteau 2010). For some unexpected trials, the location of the cursor representing the participant's hand is translated, for example, by 2 cm, 150 ms after the movement initiation. Because the perturbations are both infrequent and unexpected, participants need to correct the movement that they had planned and initiated to counteract the perturbation; this opens a window on error detection and correction processes.

In cursor jump experiments, previous results have shown that participants correct their movements quickly and accurately to counteract the perturbation (Brière and Proteau 2011, 2016; Franklin et al. 2012; Proteau et al. 2009; Veyrat-Masson et al. 2010; Sarlegna et al. 2003, 2004; Knill and Saunders 2003, 2004), even when they were not aware of the perturbation. Moreover, efficient corrections for a cursor jump are apparent, even in the first perturbed trial to which participants are exposed (Brière and Proteau 2017; Proteau et al. 2009), regardless of when or where the perturbation takes place in the movement trajectory (Brière and Proteau 2011; Saunders and Knill, 2003). These observations suggest that goal-directed movements are under continuous visual monitoring, which put into play "automatic/attention free" error detection and correction processes. This position is supported by further observations revealing that when the participants are able to consciously detect the perturbation, they are not able to refrain from initiating a correction even when asked not to do so (Day and Lyon 2000; Franklin and Wolpert 2008; Johnson, Van Beers and Haggard 2002; Pisella et al. 2000).

We have further tested this idea and have shown that the detection of a cursor jump and the planning of a correction do not interfere in any way with the processing of online visual feedback (Brière and Proteau 2011, 2017). In addition, we have recently shown that a very brief sample of visual information is sufficient to trigger a correction process (Brière and Proteau 2017). Specifically, the cursor is unexpectedly translated by 15 mm, 150 ms after movement initiation. In some of these trials, a second cursor jump occurred 100 ms after the first one and moved the cursor back to its initial trajectory. After the second cursor jump, the cursor remained visible until movement completion or was occluded 16 ms, 40 ms, or 64 ms after the second cursor jump. The results showed that seeing the cursor back on its initial trajectory for only 16 ms was sufficient to cancel 23.1% of the corrections for the cursor jump; seeing the cursor back on its initial trajectory for 64 ms resulted in a 93.1% cancellation of the correction for the first cursor jump. These data have strongly suggested that goal-directed movements are almost continuously visually monitored to ensure endpoint accuracy. They further have indicated that the perceived position of the cursor is not determined by its exact position at any point in time but instead is determined by its integrated position over a fixed period of approximately 70 ms.

In the present study, we sought to determine whether the very quick and efficient error detection and correction processes revealed in Brière and Proteau (2017) put into play only a cancellation/abortion process for the correction for the first cursor jump or whether this process accumulates information over time and therefore calibrates the correction as a function of the second cursor jump. We used a double-jump paradigm as in Brière and Proteau (2011, 2017) and manipulated the size of the second jump. The second jump canceled the need for a correction for the first jump by 50%, 100%, or 150%, and the cursor remained visible for only 64 ms after the second jump occurred. If the visual system continually monitors the progression of one's movement and if the visual information used to detect and size the perturbation is averaged over a short period of time, then the cancellation of the correction for the first jump would be a function of the size of the second jump.

Method

Participants

Twelve participants aged between 20 and 30 years old and who were undergraduate students at the Université de Montréal took part in this experiment. The participants were all self-declared right-handed and reported normal or corrected-to-normal vision. All participants signed an informed consent form before taking part in the present study. The Health Sciences Ethics Committee of the Université de Montréal approved this study.

Task and apparatus

The task was to move a computer-mouse-like device from a fixed starting position located close to participant's body toward a target located further away from the body. The apparatus is illustrated in Figure 1. It consisted of a table, a computer screen, a headrest, a mirror, and a two-degree-of-freedom manipulandum. Participants sat in front of the table. The CRT computer screen (Mitsubishi, Color Pro Diamond, 37 inches, refresh rate of 60 Hz, resolution of 1024 x 768) was mounted on a ceiling support positioned directly over the table; the computer screen was oriented parallel to the surface of the table. The screen's image was reflected on a mirror placed directly beneath and parallel to the tabletop. The distance between the computer screen and the mirror was 20 cm; the distance between the mirror and the tabletop was also 20 cm, which permitted free displacement of the manipulandum on the tabletop. The information presented on the computer screen was reflected on the mirror and was visible to the participant. The mirror prevented participants from seeing their hands and lower arms during the experiment. A headrest was affixed to the side of the computer screen, aligned with the lateral center of the computer screen, and used to standardize the information displayed on the computer screen for all participants.

The tabletop was covered by a piece of Plexiglas over which a starting base and the manipulandum were affixed. The starting base consisted of a thin strip of Plexiglas glued to the tabletop. The starting base was parallel to the leading edge of the table and had a small indentation on its distal face. This indentation was aligned laterally and sagittally with the headrest. This indentation was also aligned laterally with the participant's midline and served as the starting base for the stylus (see below). The indentation made it easy for the participant to position the stylus at the beginning of each trial.

The manipulandum consisted of two pieces of rigid Plexiglas (43 cm) joined at one end by an axle. One free end of the manipulandum was fitted with a second axle encased in a stationary base. The other free end of the manipulandum was fitted with a small vertical shaft (length: 3 cm; radius: 1 cm), i.e., the stylus, which could be gripped easily by the participant. Each axle of the manipulandum was fitted with a 13-bit optical shaft encoder (U.S. Digital, model S2-2048, sampled at 500 Hz, angular accuracy of 0.0439°), which enabled us to track the displacement of the stylus online and to illustrate it with a 1:1 ratio on the computer screen. Moving the stylus away from the body in the frontal and sagittal planes resulted in an identical displacement of the cursor on the computer screen. The bottom of the stylus and the bottom of the optical encoder located at the junction of the two arms of the manipulandum were covered with a thin piece of Plexiglas. By lubrication of the working surface at the beginning of each experimental session, the displacement of the stylus was near frictionless.

Procedures

The participants were asked to try stopping the cursor (yellow; 3 mm in diameter) on a target with a diameter of 5 mm. The target was white and presented on a black screen. The target was located 320 mm in front of the starting base and 86 mm to its right (15°).

The participants used their right, dominant hands and were asked to initiate their movements as they wished after the presentation of the target (i.e., this was not a reaction time task) and to perform smooth and continuous movements (i.e., not a stop-and-go strategy) toward the target. The participants were also required to gaze at the target during movement execution (their natural behavior to ensure optimal accuracy; Neggers and Bekkering 1999, 2000, 2001) and to complete their movements in a movement time ranging between 680 ms and 920 ms (800 ms +/- 15%). When movements were completed outside this movement time bandwidth, the experimenter reminded the participants of the target movement time. The target movement time and target location were as in previous work from our laboratory (Brière and Proteau 2011, 2017).

At the beginning of each trial, all participants could see the cursor that they had to move resting on the starting base. Once the stylus was stabilized on the starting base for 500 ms, the target was presented on the screen. During data acquisition, movement initiation was detected when the cursor had been moved by 1 mm, whereas movement completion was detected when the cursor did not move more than 2 mm in a time frame of 100 ms. A preliminary study revealed that the procedure used to detect movement completion during data acquisition made it difficult for participants to use a stop-and-go strategy. When movement completion was detected, the position of the cursor endpoint and the target remained visible for 1 s.

The participants first took part in a familiarization phase consisting of 10 trials, and this was followed by 280 experimental trials. The unperturbed trials were completed in the normal vision condition. A perturbation occurred for 20% of the experimental trials (56 trials). This perturbation could be a cursor jump and/or masking of the cursor. Perturbed trials were presented randomly with the restriction that one trial of each of the seven types (8/56 trials per type) described below occurred once within each successive block of 35 trials.

The participants were not informed that the cursor could jump on some trials. Informing the participants in this way could have interfered with their natural behavior during the task (i.e., gazing at the target). The experimenter noted any comments made by the participants regarding their performance or about anything strange happening during a trial. The details of the different types of perturbed trials are summarized in Figure 2.

Occluded conditions. For the double-jump occluded condition, the cursor jumped 15 mm perpendicularly and to the right of a straight line connecting the starting base and the target 150 ms after movement onset (see Figure 2); the cursor jumped back 100 ms later. For the 15-7.5 mm condition, the cursor jumped 7.5 mm back toward its initial trajectory, whereas for the 15-15 and the 15-22.5 conditions, the cursor jumped back toward its initial trajectory by 15 mm and 22.5 mm, respectively. Therefore, in relation to the first cursor jump, the second jump required a correction of -7.5 mm, -15 mm, and -22.5 mm, respectively. For all three conditions, in keeping with Brière and Proteau (2017), the cursor was occluded 64 ms after the second cursor jump. The no jump occluded condition was designed so that the cursor occlusion occurred at the same time as for the double-jump conditions, that is, 314 ms after the movement initiation.

Normal vision conditions. The double-jump normal vision trials were similar in all points to the occluded conditions described above but with the restriction that the cursor remained visible for the whole duration of a trial. Finally, one no-jump (control) trial was picked randomly in each successive set of 35 trials with the restriction that it did not follow a perturbed trial.

Data reduction

The tangential displacement data of the stylus over time were first smoothed using a second order recursive Butterworth filter with a cut-off frequency of 10 Hz. The filtered data were then numerically differentiated once using a central finite technique to obtain the velocity profile of the aiming movement, a second time to obtain the acceleration profile, and a third time to obtain a jerk profile. From the kinematic profiles, we determined the end of the movement's primary impulse (Meyer, Abrams, Kornblum, Wright and Smith 1988). This occurred when one of the following events was detected on the kinematic profiles: (a) movement velocity decrease below 20 mm/s, (b) movement reversal (velocity going from positive to negative), (c) movement lengthening (presence of a secondary movement impulse as indexed by the acceleration profile crossing the zero value for a second time) or (d) a significant disruption in the deceleration profile as indexed by zero-crossing on the jerk profile. For a secondary movement impulse to be considered a discrete correction, its duration had to be at least 80 ms, and its extent had to be at least 2 mm. Less than 5% of the trials in all conditions showed a secondary corrective impulse. These trials were withdrawn from all analyses.

To provide quick feedback to the participant during data acquisition, movement initiation was detected once the stylus had been moved by 1 mm. For the main analyses, however, movement initiation was defined as the moment at which the tangential velocity of the cursor reached 10 mm/s and was maintained above this value for at least 20 ms. Visual inspection of the data revealed that once a velocity of 10 mm/s had been reached, movement had clearly begun. The movement endpoint was defined as the end of the movement's primary impulse using the parsing algorithm defined above. The difference between the procedure used for detecting movement initiation during acquisition and the procedure used in the main analyses explains why the movement times reported below were longer than the target movement time used during data acquisition.

We determined the end of the movement's primary impulse for all trials (hereafter called the "endpoint"). The endpoint frontal errors (in mm) were computed in Cartesian coordinates and refer to the position of the stylus in relation to the center of the target. A positive value indicates a movement ending to the right of the target, whereas a negative value indicates a movement ending to the left of the target. We also computed the within-participant movement endpoint variability (hereafter called the "variable error") for each condition, as well as movement time.

The dependent variables of interest (movement time, frontal constant error, and frontal variable error) were individually subjected to an analysis of variance (ANOVA) contrasting 2 conditions of cursor visibility (normal vision vs. occluded) x 4 types of trials (no cursor jump, 15-7.5, 15-15, and 15-22.5) using repeated measurements on both factors. The degrees of freedom were adjusted as suggested by Greenhouse and Geisser (1959) when Mauchly's test of sphericity was significant. However, the original degrees of freedom were presented when the effects were significant following the Greenhouse–Geisser correction. All significant main effects involving more than two means were broken down using Bonferroni's technique. Significant interactions were broken down by computing simple main effects that were followed by post hoc comparisons (Bonferroni's) when they involved more than two means. All effects are reported at $p < .05$.

Results

Participants were not aware of cursor jumps

Even after having been debriefed, the participants reported that they were not aware that the cursor had jumped on some trials. This aspect of the results replicates previous observations (Brière and Proteau 2011, 2016; Proteau et al. 2009; Saunders and Knill 2003, 2004; Veyrat-Masson et al. 2010).

Movement endpoint

The ANOVA computed on the frontal constant error (Figure 3, left panel) revealed significant main effects of the vision condition, F (1, 11) = 17.2, $p = 0.002$, $\eta^2 = 0.69$, and of the types of trials, F (3, 33) = 70.63, $p < 0.001$, $\eta^2 = 0.865$. The vision x type of trials interaction was not significant, F (3, 33) = 2.02, $p = 0.13$. The vision main effect revealed a significantly smaller constant error in the normal vision than in the occluded condition (-1.22 m and -3.53 mm, respectively). The post hoc comparison of the types of trials revealed that the control and the 15-15 conditions did not differ significantly from one another (p = 0.28, -0.93 mm and -2.63 mm, respectively). However, the endpoint frontal bias differed significantly across the cursor jump conditions (-7.65 mm, -2.63 mm, and 1.73 mm for the 15-7.5, 15-15 and 15-22.5 conditions, respectively, $p < 0.05$ for all comparisons).

The ANOVA computed on the frontal endpoint variable error (Figure 3, right panel) revealed a significant main effect of the types of trials, F (3, 33) = 6.61, $p = 0.001$, $\eta^2 = 0.38$. The post hoc comparisons revealed that endpoint frontal variability was significantly larger ($p < 0.05$) for the 15-22.5 condition (5.5 mm) than for the remaining three conditions, which did not differ significantly from one another (4.1 mm, 4.3 mm, and 4.5 mm for the no perturbation, 15-15 and 15-7.5 conditions, respectively, $p > 0.05$). The ANOVA also revealed a significant main effect of vision, $F(1, 11) = 24.54$, $p < 0.001$, $\eta^2 = 0.69$, indicating a smaller variability for the trials completed with visibility of the cursor rather than in the occluded condition (3.6 mm vs. 5.5 mm, respectively).

Movement time

The ANOVA did not reveal any significant main effect or interaction ($p > 0.1$). The mean movement time fluctuated between 829 and 866 ms.

Correction for the cursor jumps

In this section, we sought to evaluate the accuracy of the correction that followed a cursor jump. For the trials completed with vision of the cursor, this correction was the difference in the frontal position of the stylus at the movement endpoint between the control vision trials and the double-jump vision trials (see Figure 1C). For the trials for which the cursor was occluded during movement execution, this correction was the difference in the frontal position of the stylus at the movement endpoint between the control occluded trials (i.e., no jump) and the occluded, double-jump trials. The movement correction data were subjected to an ANOVA contrasting 2 conditions of cursor visibility (normal vision vs. occluded) x 3 types of trials (15-7.5, 15-15, and 15-22.5), using repeated measurements on both factors. The results are illustrated in Figure 4. The ANOVA revealed that main effect of cursor visibility and the cursor visibility x types of trials interaction were not significant, with $p > 0.14$ in both cases. Thus, regardless of whether the cursor remained visible throughout movement execution or was occluded 64 ms after the second cursor jump, participants similarly corrected their movements for the successive cursor jumps. However, the ANOVA revealed a significant effect of the types of trials, $F(2, 22) = 95.74$, $p < 0.001$, $\eta^2 = 0.89$. The post hoc comparisons of the type of trials revealed that the sizes of the corrections significantly differed from one condition to the next, $p < 0.01$ for all comparisons.

Specifically, Figure 4 illustrates that participants almost completely corrected their movements for the second cursor jump in the 15-15 condition (a complete correction is illustrated by a red line). More interestingly, Figure 4 also illustrates that participants corrected their movement for the second cursor jump in conditions 15-7.5 and 15-22.5, with corrections that are significantly different from those observed for the 15-15 condition. These results indicate that the participants were not simply aborting/canceling their correction for the 1st cursor jump in double jump trials. Instead, they modulated their correction for the first cursor jump as a function of the amplitude of the second jump, thus suggesting continuous processing of visual information for the control of goal-directed movements.

Spatial integration over time

Finally, Brière and Proteau (2017) have shown that the size of the correction for the second jump in a double-jump paradigm increases from 23.1% when the cursor is occluded only 16 ms after the second jump to 93.1% when the cursor is occluded 64 ms after the second jump. They have argued that their results indicate that the “perceived” location of the cursor corresponding to the visible position of the cursor is averaged over a fixed period of approximately 70 ms. We sought to determine whether such a constant integration interval would explain the size of the correction for the double-jump trials in the present study.

For the double-jump, normal-vision trials, the participants had more than 500 ms after the second cursor jump to correct their movements. We assumed that they had sufficient time to process the visual information relative to the cursor after the second jump. Thus, the stylus endpoint for the 15-7.5, 15-15, 15-22.5 conditions completed in the normal vision condition was achieved after a complete processing of the visual signal. Any remaining errors would result from transformation errors between the visual signal and the motor commands, a conflict between the observed and felt position of the hand, or mechanical factors. Therefore, the difference in the stylus endpoint for the control trials completed in the normal vision condition and the stylus endpoint for each one of these conditions indicates the amplitude of a complete correction for the second cursor jump. The correction for the second cursor jump was 8.5 mm, 14.4 mm, and 18.9 mm for the second jump in the 15-7.5, 15-15, and 15-22.5 conditions, respectively.

The next step was to determine the size of the correction for the second cursor jump for the 15-7.5 occluded, 15-15 occluded, and 15-22.5 occluded conditions; these corrections were of 8.0 mm, 12.2 mm and 16.4 mm, respectively. Overall, seeing the cursor for only 64 ms after the second jump permitted the participants to perform a correction for the second jump, which represented 88.5% of the correction noted when the cursor remained visible for the entire movement duration (94,1%, 84,7%, and 86.8% for the 15-7.5 occluded, 15-15 occluded, and 15-22.5 occluded conditions, respectively). The size of this correction is close to the 93.1% value reported by Brière and Proteau. This result suggests that the perceived position of the cursor corresponds to its position averaged over a time period of approximately 70 ms.

Discussion

The results of many recent studies using a target jump (Bridgeman et al. 1979; Day and Lyon 2000; Desmurget et al. 1999; Franklin et al. 2012; Goodale et al. 1986; Gritsenko and Kalaska 2010; Prablanc an d Martin 1992; Sarlegna et al. 2003) or a cursor jump (Brière and Proteau 2011; Franklin and Wolpert 2008; Proteau et al. 2009; Sarlegna et al. 2003, 2004, Saunders and Knill 2003, 2004; Veyrat-Masson et al. 2010) paradigm suggest that goal-directed movements are monitored almost continuously to ensure endpoint accuracy. A sudden and unexpected change in either the target location or the cursor trajectory triggers a correction mechanism that has been qualified as “reflex-like” (Franklin and Wolpert 2008). In the present study, we were interested in the adaptability of this correction mechanism in the case of successive “errors” in movement execution.

To reach our goal, we used a double cursor jump paradigm as in Brière and Proteau (2011, 2017). In that previous work, the second jump canceled (condition 15-15) the need for a correction for the first cursor jump. It has been shown that participants are able to cancel or abort their correction for the first cursor-jump and that seeing the cursor for as little as 64 ms after the second cursor jump is sufficient to be as accurate as in a control no jump condition. The specific goal of the present study was to determine whether the very quick and efficient error detection and correction processes revealed in Brière and Proteau (2011, 2017) put into play only a cancellation/abortion process for the correction for the first cursor jump or whether this process accumulates information over time and therefore calibrates the correction as a function of the second cursor jump.

Goal-directed movements are continuously visually monitored

The results of the present study are unequivocal. A key finding of the present study is that participants corrected their movement as a function of the net perturbation after the second cursor-jump. Moreover, this correction did not result in an increase in the movement time for the perturbed trials. Therefore, the correction mechanisms revealed in cursor jump experiments are both efficient and apparently do not require substantial resources or attention (see also Reichenbach et al. 2014 for a similar conclusion). One could argue that participants did not detect the first cursor jump and simply corrected their movement for the sum of the two perturbations or from its last observed position relative to the target. Concerning the first alternative interpretation of our findings, previous work from our laboratory has clearly indicated that this is not the case (Brière and Proteau 2011, 2017; see also Proteau et al. 2009). Specifically, participants in these studies showed large and equivalent corrections for a single cursor jump regardless of whether vision of the cursor was permitted for the whole trial or was occluded 100 ms after the jump. Therefore, the 100 ms delay between the 1st and the 2nd cursor jump in the present study was sufficient for the participants to detect the first cursor jump and even initiate a correction (Proteau and Brière 2011).

The second alternative interpretation of our findings is in line with previous observations reported by Shabbott and Sainburg (2009). These authors used a task and an apparatus similar to ours; however, instead of using a cursor jump protocol, they unexpectedly induced a visuomotor rotation of the cursor to dissociate its position/trajectory from that of the participant's finger for some trials. The cursor was visible on the starting base and during movement execution. Therefore, the rotation resulted in the cursor not progressing as expected, which eventually would be detected and corrected by the participant. To determine which aspects of the error information mediated the correction for the rotation, the authors manipulated the size of the induced error (i.e., smaller or larger rotation) and occluded the cursor after it had progressed different distances from the starting base to manipulate the duration of the cursor visibility and the lateral distance between the target and the cursor. In that study, the size of the correction was determined by the lateral gap between the last observed position of the cursor and the location of the target, rather than by the duration of the cursor visibility. However, in that study (experiment 2), the cursor remained visible for at least 125 ms (see their Figure 7). In view of the results of the present study and that of Brière and Proteau (2017), even the shortest period of cursor visibility in Shabbott and Sainburg was sufficient for the participant to have had all the information necessary to implement an efficient correction. Instead, our data concur with Brière and Proteau (2017) and indicate that the perceived position of the cursor is not determined by its position at any point in time but instead is determined by its integrated position over a fixed period of approximately 70 ms.

Conclusion

Goal-directed movements are continuously monitored by the visual system, which can result in successive corrections at apparently no attention cost. When the planned movement deviated from its intended path, the visual information extracted during a brief period of 64 ms was sufficient for the CNS to cancel the correction for a first cursor jump, plan and execute an accurate correction for the second cursor jump. Moreover, this error detection and correction mechanism was as efficient as when vision remained available for as much as 500 ms after the second cursor jump. This result indicates that the visual information extracted during the 64 ms of cursor visibility after the second cursor jump is sufficient for a forward model to control the last 500 ms of the movement as accurately as if vision had been available until the movement endpoint.

Acknowledgements, ethical standards and conflict of interest

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Informed consent was obtained from all individual participants included in the study. All procedures were in accordance with the ethical standards of the Health Sciences Ethics Committee of the Université de Montréal and with the 1964 Helsinki declaration and its later amendments.

Julien Brière declares that he has no conflict of interest. Luc Proteau declares that he has no conflict of interest.

References

Bédard, P., & Proteau, L. (2003). On the role of peripheral visual afferent information for the control of rapid video-aiming movements. *Acta Psychologica, 113*, 99–117.

Bridgeman, B., Lewis, S., Heit, G., & Martha, N. (1979). Relation between cognitive and motor-oriented systems of visual position perception. *Journal of Experimental Psychology: Human Perception and Performance, 5*, 692–700.

Brière, J., & Proteau, L. (2011). Automatic movement error detection and correction processes in reaching movements. *Experimental Brain Research, 208*, 39-50.

Brière, J., & Proteau, L. (2017). Visual monitoring of goal-directed aiming movements. *Quarterly Journal of Experimental Psychology. 70*, 736-749.

Cluff, T., Crevecoeur, F., & Scott, S.H. (2015). A perspective on multisensory integration and rapid perturbation responses. *Vision Research, 110,* 215-222.

Day, B.L., & Lyon, I.N. (2000). Voluntary modification of automatic arm movements evoked by motion of a visual target. *Experimental Brain Research, 130*,159–168.

Desmurget, M., Epstein, C.M., Turner, R.S., Prablanc, C., Alexander, G.E., & Grafton, S.T. (1999). Role of the posterior parietal cortex in updating reaching movements to a visual target. *Nature Neuroscience, 2*, 563–567.

Desmurget, M., & Grafton, S.T. (2000). Forward modeling allows feedback control for fast reaching movements. *Trends in Cognitive Sciences, 4,* 423-431.

Franklin, S., & Wolpert, D.M. (2008.) Specificity of reflex adaptation for task-relevant variability. *Journal of Neuroscience, 28,*14165–14175.

Franklin, S., Wolpert, D.M., & Franklin, D.W. (2012). Visuomotor feedback gains upregulate during the learning of novel dynamics. *Journal of Neurophysiology, 108*, 467–478.

Goodale, M.A., Pélisson, D., & Prablanc, C. (1986). Large adjustments in visually guided reaching do not depend on vision of the hand or perception of target displacement. *Nature 320,* 748–750.

Greenhouse, S.W., & Geisser, S. (1959). On methods in the analysis of profile data. *Psychometrika, 24,* 95-112.

Gritsenko, V., & Kalaska, J.F. (2010). Rapid online correction is selectively suppressed during movement with a visuomotor transformation. *Journal of Neurophysiology, 104*, 3084-3104.

Johnson, H., Van Beers, R.J., & Haggard, P. (2002). Action and awareness in pointing tasks. *Experimental Brain Research, 146*, 451–459.

Meyer, D.E., Abrams, R.A., Kornblum, S., Wright, C.E., & Smith, J.E. (1988). Optimality in human motor performance: ideal control of rapid aimed movements. *Psychological Review, 95,* 340–370.

Neggers, S.F.W., & Bekkering, H. (1999). Integration of visual and somatosensory target information in goal-directed eye and arm movements. *Experimental Brain Research, 125,* 97–107.

Neggers, S.F.W., & Bekkering, H. (2000). Ocular gaze is anchored to the target of an ongoing pointing movement. *Journal of Neurophysiology, 83*, 639–651.

Neggers, S.F.W., & Bekkering, H. (2001) Gaze anchoring to a pointing target is present during the entire pointing movement and is driven by a non-visual signal. *Journal of Neurophysiology, 86,* 961–970.

Pisella, L., Gréa, H., Tilikete, C., Vighetto, A., Desmurget, M., Rode, G., Boisson, D., & Rossetti, Y. (2000). An 'automatic pilot' for the hand in human posterior parietal cortex: toward reinterpreting optic ataxia. *Nature Neuroscience, 3,* 729–736.

Prablanc, C., & Martin, O. (1992) Automatic control during hand reaching at undetected two-dimensional target displacements. *Journal of Neurophysiology, 67*, 455–469.

Proteau, L., Roujoula, A., & Messier, J. (2009). Evidence for continuous processing of visual information in a manual video-aiming task. *Journal of Motor Behavior, 41,* 219-231.

Reichenbach, A., Franklin, D.W., Zatka-Haas, P., & Fiedrichsen, J. (2014). A dedicated binding mechanism for the visual control of movement. *Current Biology, 24*, 780-785.

Sarlegna, F., Blouin, J., Bresciani, J.P., Bourdin, C., Vercher, J.L., & Gauthier, G.M. (2003). Target and hand position information in the online control of goal-directed arm movements. *Experimental Brain Research, 151*, 524-535.

Sarlegna, F., Blouin, J., Vercher, J.L., Bresciani, J.P., Bourdin, C., & Gauthier, G.M. (2004) Online control of the direction of rapid reaching movements. *Experimental Brain Research, 157*, 468-471.

Saunders, J.A., & Knill, D.C. (2003). Humans use continuous visual feedback from the hand to control fast reaching movements. *Experimental Brain Research, 152*, 341-352.

Saunders, J.A., & Knill, D.C. (2004). Visual feedback control of hand movements. *Journal of Neuroscience, 24*, 3223-3234.

Shabbott, B.A., & Sainburg, R.L. (2009). On-line corrections for visuomotor errors. *Experimental Brain Research, 195,* 59-72.

Vesia, M., Yan, X., Henriques D.Y., Sergio, L.E., & Crawford, J.D. (2008). Transcranial magnetic stimulation over human dorsal–lateral posterior parietal cortex disrupts integration of hand position signals into the reach plan. *Journal of Neurophysiology, 100,* 2005-2014.

Veyrat-Masson, M., Brière, J., & Proteau, L. (2010). Automaticity of online control processes in manual aiming. *Journal of Vision, 10(14):27,* 1–14.

Figure captions

Figure 1. A: view of the experimental set-up. B: The manipulandum and the location of the target in relation to the participant. A single-jump (red) translated the trajectory of the cursor by 15 mm to the right. C: Target location in relation to the target. The dashed lines indicate potential endpoint errors for the no-jump and single-jump endpoint locations. The correction for the single jump is illustrated by the full line.

Figure 2. Illustration of the experimental conditions. For all double-jump trials, the first cursor jump (15 mm) occurred 150 ms after movement initiation. The second jump occurred 100 ms later and differed in size: 7.5, 15 or 22.5 mm. For the occluded trials, the cursor was occluded 64 ms after the second jump. For the control occluded no jump trials, the cursor was occluded 314 ms after movement initiation. For the normal vision trials (double-jump and control), the cursor remained visible until movement completion.

Figure 3. Frontal constant error (left panel) and variable error (right panel) as a function of the cursor jump conditions and the conditions of cursor visibility. Note that the frontal movement endpoints for the double jump trials suggest that participants adapted their movements for successive cursor jumps.

Figure 4. Corrections for the successive cursor jumps as a function of the cursor jump conditions and the conditions of cursor visibility. A complete correction for the successive cursor jumps is indicated by a red line. A complete correction for a single 15 mm cursor jump performed in either the occluded or the normal vision condition is illustrated by the blue line.

Figure 1

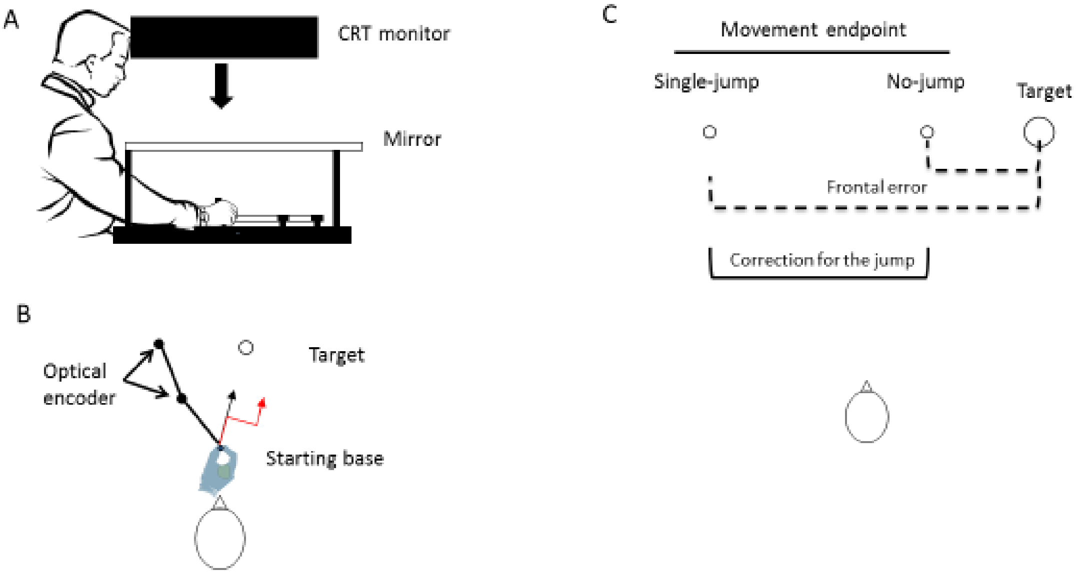

A
CRT monitor
Mirror
B
Optical encoder
Target
Starting base
C
Movement endpoint
Single-jump
No-jump
Target
Frontal error
Correction for the jump

Figure 2

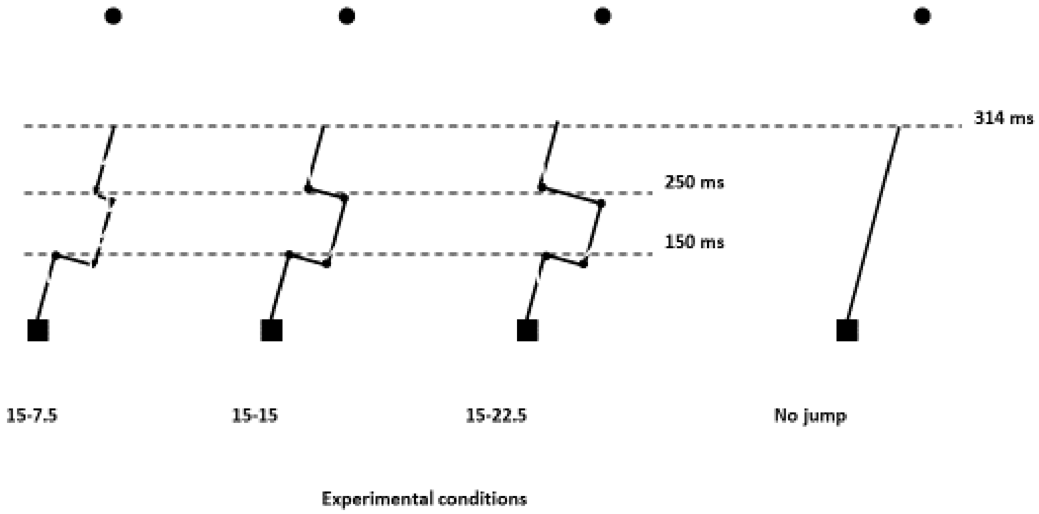
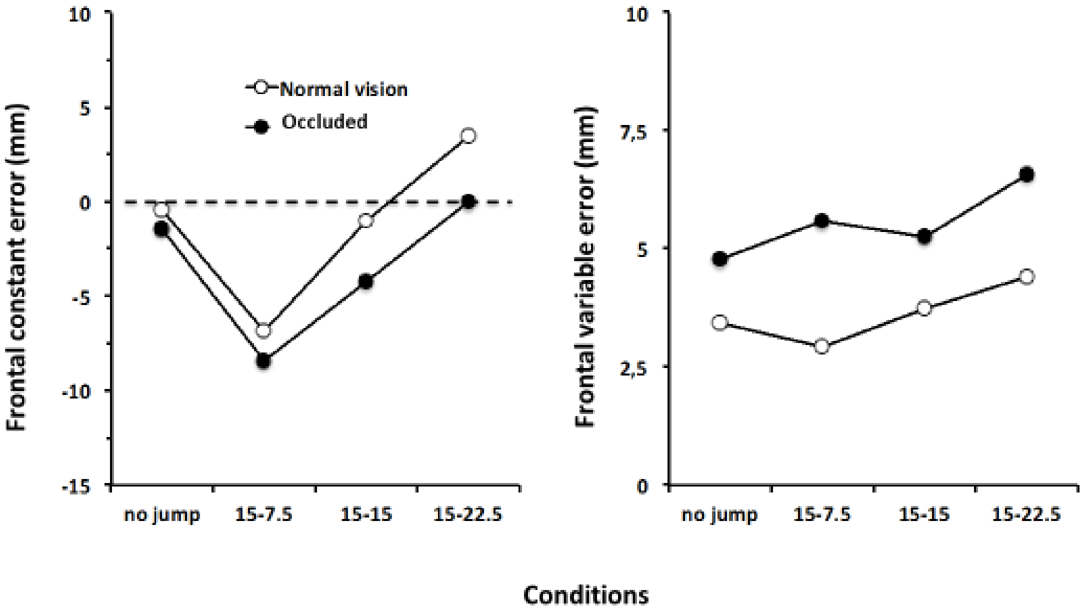
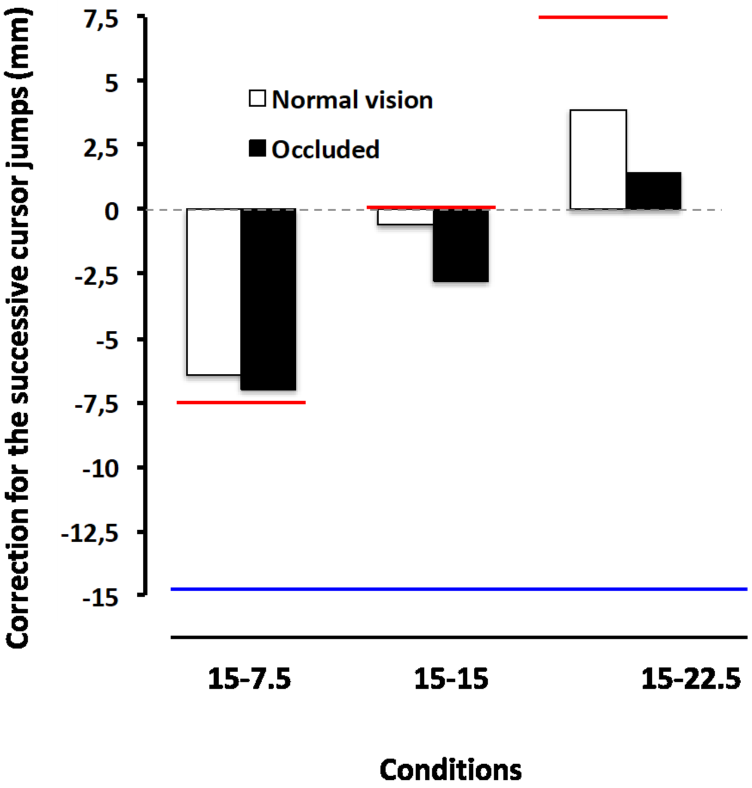

314 ms
250 ms
150 ms
15-7.5
15-15
15-22.5
No jump
Experimental conditions

Figure 3



10
5
0
-5
-10
-15
Frontal constant error (mm)
Normal vision
Occluded
no jump
15-7.5
15-15
15-22.5
10
7,5
5
2,5
0
Frontal variable error (mm)
no jump
15-7.5
15-15
15-22.5
Conditions

Figure 4


Correction for the successive cursor jumps (mm)
7,5
5
2,5
0
-2,5
-5
-7,5
-10
-12,5
-15
☐ Normal vision
■ Occluded
15-7.5
15-15
15-22.5
Conditions

Chapitre 5 : Article 4

Automaticity of online control processes in manual aiming

Marie Veyrat-Masson, Julien Brière, and Luc Proteau[1]
Département de kinésiologie
Université de Montréal

[1]Corresponding author:
Luc Proteau, Département de kinésiologie, Université de Montréal, P.O. Box 6128,
Downtown Station, Montréal, Canada, H3C 3J7.
Tel: (514) 343-2039
Fax: (514) 343-2181
Email: luc.proteau@umontreal.ca

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Abstract

Cursor-jump experiments have suggested the existence of efficient, automatic, and even reflexive online correction processes in manual aiming movements. We wanted to determine whether the latency/gain of the correction for a cursor jump are only influenced by the size of the cursor jump or whether they are also influenced by the need of a correction for the target to be reached. In Experiment 1, we used two target sizes (5 and 30 mm) and three cursor-jump amplitudes (5, 15, and 25 mm), so that for some target size / cursor-jump combinations, no correction would be needed to reach the target. Participants were not aware of the cursor jump, but we observed a 65% correction regardless of target size. In Experiment 2, participants pointed at a large target for which a 15 mm cursor jump never impeded target attainment. Participants modified the trajectory of their movement in the direction opposite to the cursor jump. The corrections were smaller than that observed in Experiment 1 (42% of the cursor jump). Our results indicate that the latency of the correction for a cursor jump was not influenced by the size of the cursor jump or that of the target. However, the correction tailored the movement's initial impulse according to the target's characteristics.

Automaticity of online control processes in manual aiming

Reaching movements toward a visual target put into play a series of processes for identifying the target and its location and transforming this information into appropriate motor commands (for a review, see Desmurget et al., 1998; Elliott & Khan, 2010). The processes leading to movement planning and then to movement execution have intrinsic variability. Because of this variability inherent in all biological systems, and because of the high level of accuracy required in many of our daily activities, the CNS must quickly update movement planning and amend movement execution.

Error detection and correction processes have been at the center of many research efforts since the seminal work of Woodworth (1899). Although many research strategies have been used in the last century, many authors opted to use a perturbation paradigm. In this paradigm, some aspects of the task are changed just prior to, at, or soon after movement initiation. Because these perturbations occur unexpectedly and often for only a small proportion of the trials, it is expected that participants would plan their movements as if no perturbation would occur. Thus, to reach the target, participants need to correct the movement they have planned and initiated to counteract the perturbation, which opens a window on error detection and correction processes.

In many experiments, the perturbation changed the target location, its visually perceived location, or the velocity of the participant's hand. In target-jump experiments (Bridgeman et al., 1979; Desmurget et al., 1999; Goodale et al., 1986; Gritsenko, Yakovenko, & Kalaska, 2009; Prablanc & Martin, 1992) participants first gazed at a fixation point and, following a variable foreperiod, a target was lit in his or her peripheral visual field. Participants were asked to look and to aim at the target quickly and accurately. Once the eyes' movement reached peak velocity (i.e., during the saccadic suppression period), the location of the target was switched to a different one. Results revealed that, although participants were unaware of the target jump, they quickly and accurately modified the trajectory of their hand (or cursor) so that their movement ended close to the target. Because participants could not refrain from initiating a correction toward the new target location (Day & Lyon, 2000; Johnson et al., 2002; Pisella et al., 2000), it was concluded that an "automatic pilot" drives fast corrective arm movements (see as well, however, Cameron et al., 2007). Similar observations were reported in cursor-jump experiments (Brenner & Smeets, 2003; Franklin & Wolpert, 2008; Proteau et al., 2009; Sarlegna et al., 2003, 2004; Saunders & Knill, 2003, 2004, 2005).

Typically, in cursor-jump experiments, participants move a cursor shown on a visual display to a target illustrated on the same display. The location of the cursor representing the participant's hand could be translated, for example by 2 cm soon after movement initiation. Again, participants were unaware of the cursor jump (no participant reported having consciously perceived the jump) but nonetheless corrected their movement in the direction opposite to that of the cursor jump. Because efficient corrections were apparent even for the first—and not consciously perceived—perturbed trial to which participants were exposed (Proteau et al., 2009), it was concluded that these error detection and correction processes did not require learning or adaptation. Also, because participants could not refrain from initiating a correction in the direction opposite to that of the cursor jump (Franklin & Wolpert, 2008), even when asked to move their hand in the same direction as the cursor jump, it was proposed that the correction was reflexive.

In the present study, we were interested in the apparent automatic (and even reflex-like) nature of the correction process revealed by target-jump and cursor-jump studies. Recent research by Gritsenko et al. (2009) has revealed that latency of the correction for a target jump was not influenced by the size of the target jump, whereas the correction scaled linearly with the amplitude of the target jump throughout movement execution. Moreover, the gain of the correction process was scaled to the overall movement speed and movement duration of each participant. This indicated that the correction process was coordinated with the anticipated delay remaining until movement completion. What is still unknown is whether the latency and the gain of the correction are also influenced by the size of the target. To our knowledge, this is the first attempt at determining whether a correction will be initiated if the perturbation (here, a cursor jump) does not jeopardize target attainment, and if so, whether the gain of the correction would be affected by target size.

Experiment 1

Method

Participants

Thirty-six young adults (18-25 years old) took part in this experiment. They were all naïve regarding the goal of the study. All participants were self-declared right-handed and reported normal or corrected-to-normal vision. They took part in a single 40-minute experimental session and were paid CAN $10 for their time. The Health Sciences Ethics Committee of the Université de Montréal approved this study.

Task and apparatus

The task was to move a computer-mouse-like device from a fixed starting position located close to the body toward one of two possible targets located further away from the body. The apparatus is illustrated in Figure 1. It consisted of a table, a computer screen, a headrest, a mirror, and a two-degrees-of-freedom manipulandum.

Participants sat in front of the table. The computer screen (cathode ray tube, Mitsubishi, Color Pro Diamond 37 inches, refresh rate 60 Hz) was mounted face down on a ceiling-support positioned directly over the table; the computer screen was oriented parallel to the surface of the table. The image of the computer screen was reflected on a mirror placed directly beneath it and parallel to the tabletop, and was thus visible to the participant. The distance between the computer screen and the mirror was 20 cm, while the distance between the mirror and the tabletop was 20 cm, which permitted free displacement of the manipulandum on the tabletop. A headrest was affixed on the side of the computer screen. It was aligned with the lateral center of the computer screen, thus standardizing the information reflected in the mirror for all participants.

The tabletop was covered by a piece of Plexiglas over which a starting base and the manipulandum were affixed. The starting base consisted of a thin strip of Plexiglas glued to the tabletop. It was parallel to the leading edge of the table and had a small indentation on its distal face. This indentation was aligned with the headrest and the participant's midline and served as the starting base for the stylus (see below). The indentation made it easy for the participant to position the stylus at the beginning of each trial.

The manipulandum consisted of two pieces of rigid Plexiglas (43 cm) joined at one end by an axle. One free end of the manipulandum was fitted with a second axle encased in a stationary base. The other free end of the manipulandum, hereafter called the stylus, was fitted with a small vertical shaft (length: 3 cm, radius: 1 cm), which could be easily gripped by the participant. From the participant's perspective, the far end of the manipulandum was located 40 cm to the left of the starting base and 70 cm in the sagittal plane. Each axle of the manipulandum was fitted with a 13-bit optical shaft encoder (U.S. Digital, model S2-2048, sampled at 500 Hz, angular accuracy of 0.0439°), which enabled us to track the displacement of the stylus online and to illustrate it with a 1:1 ratio on the computer screen. Displacement of the stylus resulted in an identical and superimposed displacement of the cursor on the computer screen. The bottom of the stylus and the bottom of the optical encoder located at the junction of the two arms of the manipulandum were covered with a thin piece of Plexiglas. By lubricating the working surface at the beginning of each experimental session, displacement of the stylus was near frictionless.

Procedures

Participants used their right dominant hand to move a cursor shown on the computer screen toward targets illustrated on the same screen. Participants performed 10 familiarizing trials, followed by 160 experimental trials. For all trials, the yellow cursor (5 mm in diameter) and the white targets (see below) were illustrated on a black background. The cursor and target remained visible throughout movement execution.

For the familiarization trials, the targets (5 mm in diameter) were located at 320 mm from the starting base and located at every 10° to the right and left of the starting base (from -50° to -10° and from +10° to +50°). In this phase, one trial was performed toward each one of the 10 targets in random order. The experimental trials were equally divided among two new target locations (7.5° and 15° to the right of the participant's midline) and two target sizes (5 mm or 30 mm in diameter). In all cases, the distance between the starting base and the center of the target was 320 mm. For each target location / target size combination, a cursor jump occurred for 20% of the trials (8 out of 40 trials aimed at each target). Thus, there were 32 cursor-jump trials and 128 no-jump trials overall. Target (size and location) and cursor-jump trials were presented randomly (same order across participants), with one restriction being that cursor-jump trials be separated by at least two no-jump trials.

Participants were assigned randomly to one of three groups (n = 12). For the first group, the cursor jump was 5 mm, while for the two remaining groups, it was either 15 mm or 25 mm. The cursor jump occurred 100 ms after movement initiation (plus an additional random delay fluctuating between 14 and 21 ms due to equipment) and translated the position of the cursor perpendicularly to a straight line connecting the starting base and the center of the target. The cursor always jumped to the right. Thus, a correction for the cursor jump would be observed if the position of the stylus migrated closer to the participant's midline for the cursor-jump trials than it did for the no-jump trials.

At the beginning of each trial, all participants could see the cursor they had to move resting on the starting base. A target was presented once the stylus was stabilized on the starting base for 500 ms. Participants were first asked to gaze at the target and then to initiate a single straight and smooth movement (i.e., not a stop-and-go movement) as they pleased (i.e., not a reaction-time task). They were also required to complete their movement in a movement time ranging between 680 ms and 920 ms (800 ms +/- 15%). During data acquisition, movement initiation was detected when the cursor had been moved by 1 mm, whereas movement completion was detected when the cursor did not move by more than 2 mm in a time frame of 100 ms. A preliminary study revealed that the procedure we used to detect movement completion made it difficult for participants to use a stop-and-go strategy. When movements were completed outside the prescribed movement time bandwidth, the participant was reminded of the target movement time. A movement time bandwidth (Proteau et al., 2009;

Saunders & Knill, 2003, 2004, 2005) reduces the possibility of different speed-accuracy trade-offs between the different experimental conditions (Fitts, 1954).

Data reduction

The tangential displacement data of the stylus over time were first smoothed using a second order recursive Butterworth filter with a cut-off frequency of 10 Hz. The filtered data were then numerically differentiated once using a central finite technique to obtain the velocity profile of the aiming movement, a second time to obtain the acceleration profile, and a third time to obtain a jerk profile. From the kinematic profiles, we determined the end of the movement's primary impulse (Meyer et al., 1988). This occurred when one of the following events was first detected on the kinematic profiles: (a) movement reversal (velocity going from positive to negative), (b) movement lengthening (presence of a secondary movement impulse as indexed by the acceleration profile crossing the zero value for a second time) or (c) a significant disruption in the deceleration profile as indexed by zero-crossing on the jerk profile. For a secondary movement impulse to be considered a discrete correction, its duration had to be of at least 80 ms and its extent had to be of at least 2 mm. Note that less than 3.5% of the trials in all conditions showed a secondary corrective impulse. These trials were withdrawn from all analyses.

To provide a quick feedback to the participant during data acquisition, movement initiation was detected once the stylus had been moved by 1 mm. However, for the main analyses, movement initiation was defined as the moment at which the tangential velocity of the cursor reached 10 mm/s and was maintained above this value for at least 20 ms. Visual inspection of the data revealed that once the 10 mm/s had been reached, movements were clearly underway.

To determine the efficacy of the correction for the cursor jump, we determined the end of the movement's primary impulse for all trials (hereafter called movement endpoint). Note that the data reported concern the position of the stylus moved by the participants, not that of the cursor shown on the computer screen. Endpoint frontal and sagittal errors were computed in Cartesian coordinates. These refer to the position of the stylus in relation to the center of the target. The frontal error was the signed difference on the frontal axis (in mm) between the movement endpoint and the target. A positive value indicates a movement ending to the right of the target, and a negative value indicates a movement ending to the left of the target. The sagittal error of a trial was defined as the signed difference between movement endpoint and the target on the sagittal axis (in mm). A positive value indicates that the target had been overshot, and a negative value that it had been undershot. For all groups and conditions, data that differed by more than two standard deviations from the cell mean were excluded from all analyses; less than 3% of the trials were excluded. From these data, we computed the constant and variable aiming errors on the frontal and sagittal dimensions of the task. The constant error is the mean signed difference between the target and endpoint location. It indicates whether participants showed a bias in their movements (too long, too short, to the right, or to the left of the target). The variable error is the within-participant variability in endpoint location.

To avoid repetition and to facilitate reading of this article, details concerning the dependent variables of interest and the statistical analyses that were computed are defined at the beginning of each subsection of the results presentation. All significant main effects and interactions involving more than two means were broken down using Dunn's procedures. All effects are reported at $p < .05$ (adjusted for the number of comparisons using Bonferroni's technique). Data of one participant in the 25-mm cursor-jump group were excluded from all analyses because they differed by more than two standard deviations from the mean results of that group.

Results

Cursor-jump was not consciously detected

Even after having been debriefed, participants reported that they were not aware that the cursor jumped on some trials. This aspect of the results replicates previous observations (Bédard & Proteau, 2003; Brière & Proteau, 2010; Proteau et al., 2009), even when a cursor jump occurred for a high proportion of the trials (though during saccadic visual suppression, Sarlegna et al., 2003, 2004; see also Saunders & Knill, 2003, 2004, 2005). It should be noted that, on average, the cursor jump occurred at 38.7° (SD = 2.5°) of visual angle, which is quite far in the periphery of the retina and may explain why participants did not notice it.

Although participants were not aware of the cursor jump, the large corrections observed (see below) indicate that the participants reacted to compensate for it. Because the cursor jump was always to the right, one could argue that the participants might have adapted for the cursor jump by biasing movement planning/execution to the left of the target (direction of the needed correction for a cursor jump). If so, orientation planning for the no-jump trials should progressively migrate to the left of the target, whereas frontal velocity of the stylus for the no-jump trials should progressively decline. Moreover, the planning bias and declining frontal velocity for the no-jump trials should be a function of the cursor jump size.

To test for this possibility, we contrasted movement orientation and frontal velocity 200 ms after movement initiation had been detected for the first and last four no-jump trials. The data were submitted to a 3 Groups (5-, 15-, or 25-mm cursor jump) x 2 Phases (first vs.

last four no-jump trials) x 2 Targets (7.5° and 15°) x 4 Trials ANOVA using repeated measurements on the last three factors. The ANOVAs revealed a significant main effect of Target, F (1, 32) = 739.9 and 731.3, ps < .01, for movement orientation and frontal velocity, respectively. These main effects revealed that movements were initiated more to the right, resulting in larger frontal velocity for the 15° target than for the 7.5° target. The ANOVAs also revealed a significant Phase x Trial interaction, F (3, 96) = 4.2 and 7.1, ps < .01, for movement orientation and frontal velocity, respectively. The breakdown of these interactions revealed that for the first four no-jump trials, movement orientation and frontal velocity gradually decreased from Trial 1 to Trial 4 (from 10.3° to 9.2°, and from 148.3 mm/s to 120.1 mm/s, respectively), whereas movement orientation and frontal velocity did not significantly differ between the last four no-jump trials (means of 8.4° and 115.4 mm/s, respectively). Finally, for both movement orientation and frontal velocity, neither the Group main effect nor the Group x Phase interaction were significant, all p > 0.34. The results of these analyses revealed that movement planning/execution was not biased (consciously or unconsciously) by the occurrence of cursor-jump trials.

Correction for a cursor jump

In the present section, we wanted to determine whether participants corrected their movements for different sizes of cursor jumps and targets, and if so, how efficiently. Examples of stylus trajectories of control and cursor-jump trials aimed towards the different targets are illustrated in Figure 2. This figure clearly illustrates that these participants corrected their movements for the cursor jump. In addition, they show larger corrections for larger cursor jumps (Brière & Proteau, 2010; Sarlegna et al., 2004), regardless of target size. It should also be noted that movement endpoint of no-jump trials are located near the center of the target, regardless of the latter's size.

Mean movement endpoint of all participants are reported in Table 1. Because target location had no significant effect on endpoint accuracy or variability, data of the two target locations were collapsed in the following statistical analyses. Endpoint constant and variable frontal and sagittal errors and movement time data were submitted individually to an ANOVA contrasting 3 Groups (5, 15, or 25 mm cursor jump) X 2 Types of trials (no-jump vs. cursor-jump) and 2 Target sizes (5 mm and 30 mm in diameter) using repeated measurements on the last two factors.

Endpoint constant error. The ANOVA computed on the frontal constant error revealed a significant Group x Type interaction, $F(2, 32) = 66.4$, $p < .001$. The breakdown of this interaction revealed that endpoint of cursor-jump trials was significantly to the left of endpoint of no-jump trials for the 5-mm (3.3 mm, $p < .001$), 15-mm (9.9 mm, $p < .001$), and 25-mm groups (16.0 mm, $p < .001$). This indicates that participants corrected their movements even for the smallest cursor jump. The interaction revealed that the correction grew larger as cursor-jump size increased. However, in relative terms, participants corrected their movements for 66%, 66%, and 64% of the perturbation for the 5-, 15-, and 25-mm cursor jump, respectively. Neither the Target size main effect, $F(1, 32) = 1.60$, $p = .21$, nor any interaction involving that factor ($p > .13$ for all interactions) were significant. In addition, to determine whether the correction became larger with practice, we contrasted the frontal endpoint location of the cursor jump trials in a 3 Groups (5 mm, 15 mm, and 25 mm cursor jump) x 32 Trials (from the first 1st to the 32nd cursor jump) ANOVA using repeated measurements on the second factor. The ANOVA revealed a significant main effect of trial, F (31, 992) = 2.36, $p < .001$. Post-hoc comparisons revealed a smaller correction for Trial 1 (8.03 mm) than it did for Trials 6, 7, 11, 14, and 26 (14. 1 mm, SD = 0.19 mm), but not for the remaining 26 trials (11.5 mm, SD = 1.14 mm. As illustrated in Figure 3, we found no strong evidence that the size of the correction increased with practice. Therefore, it appears that the cursor jump elicited a strong correction from the very first cursor-jump trial. The ANOVA computed on the sagittal constant error did not reveal any significant main effect or interaction ($p > .16$ for all main effects and interactions).

Endpoint variable error. The ANOVAs computed on frontal and sagittal endpoint variable error did not reveal any significant main effect or interaction ($p > .30$ for all main effects and interactions). On average, endpoint variability for the cursor-jump and no-jump trials was 5.71 mm and 5.96 mm on the frontal component of the task and 7.37 mm and 7.76 mm on the sagittal component, respectively.

Movement time. The ANOVA computed on movement time revealed two significant interactions (see Table 1). First, the breakdown of the Type x Target size interaction, $F(2, 32) = 6.741$, $p = .014$, revealed significantly longer movement times for the cursor-jump trials than it did for the no-jump trials. This difference was significantly larger when participants aimed at the 5 mm (692 ms vs. 681 ms, $p < .001$) rather than at the 30 mm (688 ms vs. 680 ms, $p = .051$) target. Second, the breakdown of the Group x Type interaction, $F(2, 32) = 7.868$, $p = .002$, revealed significantly longer movement times for the cursor-jump trials than it did for the no-jump trials for the 25-mm (677 ms vs. 670 ms, $p = .001$) and 15-mm (708 ms vs. 692 ms, $p < .001$) cursor jumps, but not for the 5-mm cursor jump (686 ms vs. 680 ms, $p = .845$).

Characteristics of the correction

To determine when participants initiated a correction for a cursor jump, we used the unfiltered displacement data of the stylus on the frontal axis. As in previous work from our lab (Brière & Proteau, 2010; Proteau et al., 2009), we chose to analyze the frontal displacement of the stylus because the cursor jump, and thus the expected correction, largely occurred on this axis. For each participant, we computed a mean trajectory for jump and no-jump trials aimed at each target. Then, at every 20 ms, we computed the difference in location between these mean trajectories. A correction for the cursor jump was detected when (a) cursor-jump trials deviated from the no-jump trials by more than 1 mm in the direction opposite to the cursor jump compared with the position of the cursor at the occurrence of the cursor jump and (b) the deviation continued as movements progressed toward the targets. The 1-mm criterion was chosen arbitrarily. This technique was used by Proteau et al. (2009), who reported latency in the same range as reported by others (Brenner & Smeets, 2003; Saunders & Knill, 2003, 2005). Finally, and perhaps more importantly, it should be remembered that the absolute value of the latency is not our point of interest. What is important is to determine, using the same method, whether the latency differed across experimental conditions. Figure 4 illustrates the difference in the frontal location and velocity of the stylus between the no-jump and cursor-jump trials as a function of time.

The latency data were submitted to a 3 Groups (5, 15, or 25 mm cursor-jump) x 2 Target sizes (5 vs. 30 mm) ANOVA using repeated measurements on the second factor. Note that two participants from the 5-mm group were excluded from this analysis because they showed no evidence of a correction, and correction latency could therefore not be computed. The ANOVA did not reveal any significant main effect (Fs < 1, p > .64) or interaction, F(2, 30) = 1.374, p = .27. Mean latency data fluctuated between 137 ms and 172 ms (see Figure 4, upper right panel); these estimations of correction latency are reduced by approximately 40 ms when estimated from the velocity profiles (see Figure 4, lower left panel). The correction was initiated when the cursor reached 11.1° (SD = 6.2°) of visual angle.

Finally, to determine whether the initial portion of the correction was related to the size of the cursor jump, we computed the slope of this correction. Specifically, for each participant we determined by how much the mean trajectory of cursor jump trials deviated from that of no-jump trials 200 ms after a correction had been detected. The ANOVA computed on this dependent variable revealed a significant main effect of cursor-jump size, $F(2, 30) = 43.09$, $p < .001$. Post hoc comparisons revealed that participants initiated a more abrupt correction as the size of the cursor jump increased (17.15, 35.25, and 63.3 mm/s for the 5-, 15-, and 25-mm cursor jump, respectively; see also Figure 4). However, the slope of this correction did not differ significantly as a function of target size, $F(1, 30) < 1$.

Supplementary analyses. The results presented so far revealed slightly longer movement times for the cursor-jump trials than it did for the no-jump trials. A supplementary analysis revealed that this difference in movement time did not reflect a longer movement path for the former than for the latter trials. On the contrary, movement path was slightly longer for the no-jump (325.9 mm) trials than it was for the cursor jump trials (323.1 mm, 321.7 mm, and 321.4 mm for the 5-, 15-, and 25-mm cursor jump trials, respectively). We also wanted to determine whether larger corrections were associated with a longer correction latency, a longer movement time, or only with a steeper slope of correction, as suggested by the results illustrated in Figure 4. For this purpose, we computed a series of coefficients of correlation across participants ($n = 33$); data for each participant were averaged across target location and target size. The results revealed that a longer latency was not predictive of a larger correction for a cursor jump, a steeper slope of correction, or a shorter movement time, (r[31]= -0.03, 0.22, and -0.29, respectively, p >.05. However, the size of the correction was closely correlated with the initial slope of the correction (r[31]= 0.88, p < .001, and more modestly, albeit significantly, with movement time, (r[31]= 0.36, p < .05.

Discussion

The goal of this experiment was to determine whether the processes responsible for the detection and correction of unintentional deviations of one's movement aimed at a fixed target are solely based on the characteristics of the deviation or whether they are also adapted to the target's characteristics. We used a perturbation paradigm in which the cursor moved by the participants suddenly jumped between 5 mm and 25 mm to the right of a vector joining the starting base and the target, while the cursor was seen relatively far in the periphery of the retina (~39° of visual angle). Although participants were not aware of this cursor jump, they soon corrected their movement (130-170 ms) in the opposite direction of the cursor jump. Neither the size, the latency, nor the slope of the correction were modified by target-size.

Our observation that participants modified the trajectory of their movements to counteract the cursor jump concurs with previous observations (Brenner & Smeets, 2003; Brière & Proteau, 2010; Franklin & Wolpert, 2008; Proteau et al., 2009; Sarlegna et al., 2003, 2004; Saunders & Knill, 2003, 2004, 2005). Our results also concur with previous observations in that the corrections were initiated while the cursor was beyond 10° of visual angle (Proteau et al., 2009), its latency was not related to the size of the cursor jump (Sarlegna et al., 2004; Gritsenko et al., 2009, although for target jumps), and the correction did not fully compensate for the size of the cursor jump (Proteau et al., 2009; Sarlegna et al., 2003, 2004; Saunders & Knill, 2003, 2004, 2005). An important new finding of the present experiment is that only the slope of the correction for a cursor jump was a function of the size of the cursor jump. A similar observation was reported recently by Gritsenko et al. (2009) for target jumps of different amplitudes. This suggests that the error detection process put into play in the present study was sensitive enough not only to detect a deviation in the cursor trajectory but also to grade it.

Our results also concur in one important way with those reported by Brenner and Smeets (2003). These authors tested a condition in which both the cursor moved by the participants, and the target, jumped simultaneously and in the same direction. In this condition, the cursor and target jumps did not modify the relative position of the cursor and the target. Nonetheless, the authors noted that participants initiated a correction that apparently summed up the correction usually observed when only a target jump took place, as compared to that usually observed in reaction to a cursor jump. This suggests independent correction processes for the correction of the cursor jump and that of the target jump. In the present experiment, we observed the same correction for a cursor jump regardless of target size. Specifically, participants similarly corrected their movements for a 5-mm cursor jump that would have resulted in missing a 5-mm target or that was irrelevant for successfully reaching a 30-mm target. This observation strongly suggests that the correction for a cursor jump is solely related to the size of the induced error, without consideration for target size. This suggests that the correction is based on a comparison between a) expected sensory consequences that can be derived from a forward model of movement control and b) actual feedback ensuring that the movement is initiated/continued as planned. However, the correction process did not allow participants to complete their movement on the target. We will return to this point in the general discussion.

Before concluding that the error detection and correction processes triggered by the cursor jump have, as sole input, the size of the detected error regardless of movement goal, we must consider that, in the present experiment, participants apparently always aimed at the center of the target (see Figure 2). Endpoint location and variability of no-jump trials did not significantly differ when participants aimed at the 5-mm or 30-mm targets. Thus, it could be argued that the effective target size did not differ between these two experimental conditions, which would explain why participants behave similarly. We completed a second experiment to determine whether a cursor jump would still elicit a correction when participants were asked to plan and execute a movement that would end anywhere within the boundaries of a very large target and for which not correcting for a cursor jump would not jeopardize target attainment.

Experiment 2

Method

Participants

Eleven new participants took part in this experiment. They were aged between 18 and 22 years, and naïve regarding the goal of the study. All participants were self-declared right-handed and reported normal or corrected-to-normal vision. They took part in a single 40-minute experimental session and were paid CAN $10 for their time. The Health Sciences Ethics Committee of the Université de Montréal approved this study.

Task, apparatus, and procedures

We used the same task and apparatus as in Experiment 1. We also used the same procedures as for Group 15 mm in Experiment 1, but with a few exceptions. Participants completed 10 familiarization trials followed by 160 experimental trials. There were 128 no-jump trials and 32 cursor-jump trials (20% perturbation, as in Experiment 1). For all cursor-jump trials, the cursor jumped 100 ms after movement initiation. In all cases, the cursor jumped 15 mm to the right of its actual position. We used a single target. Its centre was located at 320 mm from the starting base. The target had an arc of 30° starting at 7.5° and ending at 37.5° to the right of the participants' midline. The target was 30 mm deep. Participants were asked to aim in the general direction of the target and to stop the cursor within its boundaries in approximately 800 ms. We opted not to use a larger circular target than that in Experiment 1 (for example a 50-mm target) because pilot data indicated that participants were still aiming at the center of the target, which was not the case when we used a wedge-like target.

Data reduction

As expected, the size of the target and our instructions to aim in its general direction introduced large inter-trial variability (see Figure 5A). This made it difficult to determine appropriate no-jump control trials. To circumvent this difficulty, we used a bootstrapping technique to estimate the properties of movement trajectories for no-jump trials as well as for cursor-jump trials (see Efron & Thibshirani, 1993, for details on the bootstrapping technique; see Georgopoulos et al., 1999; Merchant et al., 2008 for an application on neurophysiological data). Bootstrapping consists of building a series of independent samples from the data. Thus, for each participant, we built 100 samples of no-jump and cursor-jump trials. For each sample, we drew 32 control trials with replacement from our sample of 160 no-jump trials. Similarly, we drew 32 cursor-jump trials with replacement from our sample of 32 cursor-jump trials. For each participant, the mean results obtained for all 100 samples of no-jump and cursor-jump trials were averaged.

Results

Figure 5 (left panel) illustrates the trajectory of the first four no-jump and cursor-jump trials for one typical participant. These results and those illustrated in Figure 5A indicate that participants distributed their movements over a large portion of the target. The results of the frontal coordinates of endpoint location relative to the starting position were submitted to t-tests (two-tailed) contrasting 2 Types of trials (no jump vs. cursor jump). This analysis revealed that cursor-jump trials ended significantly to the left of no-jump trials (95.7 mm vs. 102.2 mm, respectively), t (10) = 4.036, p = .002, that is, in a direction opposite to the cursor jump. Thus, participants corrected their movements for the cursor jump (see also Figure 5, left panel). This correction did not result in a significant increase in movement time. On the contrary, cursor-jump trials had slightly shorter movement times than did no-jump trials (813 ms and 824 ms for cursor- jump and no-jump trials, respectively), t (10) = -1.961, p = .078.

To determine whether the characteristics of the correction for the cursor jump differed from those reported in Experiment 1, we contrasted the results of Group 15 mm when aiming at the 5- mm target in Experiment 1 (same cursor jump size as in the present experiment) with those of the present experiment (bootstrapped data). The results (see Figures 5B and 5C) revealed that the latency of the correction did not differ significantly across experiments (147 ms and 140 ms for Experiments 1 and 2, respectively), t (21) = .27, p =.79. However, the slope (35.9 mm/s vs. 24.4 mm/s), t (21) = 2.58, p =. 017, and ultimately the size (9.6 mm vs. 6.5 mm), t (21) = 2.07, p = .051, of this correction were significantly larger in Experiment 1 than they were in Experiment 2.

Discussion

The results of this second experiment are straightforward. Participants corrected their movements for the cursor jump, even though this correction was not needed to perform the task successfully. The latency of this correction did not differ from that reported in Experiment 1. This suggests that the error detection process engaged a corrective process, even if the correction was irrelevant considering the ultimate goal. However, the more gradual correction observed for the same cursor-jump size in the present experiment, as compared to that of Experiment 1, suggests that the correction process takes into consideration the "urgency" of the correction. In Experiment 1, this urgency was reflected by steeper corrections for the larger cursor jumps. In the present experiment, no correction was needed to reach the target; therefore, it was more gradual than and not as large as it was in Experiment 1.

General discussion

In the present study, we wanted to determine whether error detection and correction processes based on visual information and relative to the displacement of one's hand toward a fixed target were solely driven by the stimulus that elicited them or also by the target's characteristics. The results of the two experiments reported in the present paper revealed that the latency of the correction triggered by the cursor jump was not influenced by the target's characteristics. However, the execution of the correction was affected significantly by both the size of the cursor jump and the target's characteristics.

Correction latency

Our observation that correction latency was not influenced by the size of the cursor jump concurs with results previously reported by Sarlegna et al. (2004) for a cursor jump and by Gritsenko et al. (2009) for a target jump. Also, as in Proteau et al. (2009), it indicates that even small deviations of the cursor from its intended path were detected by a very efficient error detection process that acts outside the central visual field (> 10° of visual angle; see also Abahnini et al., 1997; Abahnini & Proteau, 1999; Bard et al., 1985, 1990; Bédard & Proteau, 2001, 2003; Blouin et al., 1993a, 1993b, 1996; Paillard, 1980; Paillard & Amblard, 1985; Proteau et al., 2000). The initiation of this correction does not appear to require attention from the participants because a correction was initiated while participants were not aware of the cursor jump. The slope of the correction was a function of the size of the cursor jump (see also Gritsenko et al., 2009; Sarlegna et al., 2004). This indicates that the error detection process put into play in the present study was sensitive enough not only to detect a difference between the expected and actual cursor position (Brenner & Smeets, 2003; Shabbott & Sainburg, 2009) and trajectory (Saunders & Knill, 2004) but also to grade it.

Correction execution

Although the correction that was initiated to counteract the cursor jump was graded for its size, the results of Experiment 2 indicated that the slope of this correction was also influenced by target size. Specifically, the slope of the correction for a 15-mm cursor-jump was significantly larger in Experiment 1 than it was in Experiment 2. It should be remembered that increasing the diameter of the target from 5 mm to 30 mm (Experiment 1) was not sufficient for observing this difference. This indicates that a difference in target size that has been shown to influence movement time (Fitts, 1954), movement variability, or the proportion of trials requiring a secondary corrective impulse (Tinjust & Proteau, 2009) when the cursor is located close to the target was not sufficient to influence the slope of the correction in Experiment 1. This suggests that the error correction process revealed in Experiment 2 has a different origin than that usually observed when the cursor and target are seen close to one another in central vision.

Because the latency of the correction was not influenced by target size, whereas target size modified the slope of the correction, this suggests that detection of an error and execution of a correction are based on distinct processes. This position concurs with recent observations reported by Glover et al. (2005). In that study, participants reached to grasp a small or large illuminated cylinder. During the reach, the cylinder could change from large to small or small to large. When repetitive transcranial magnetic stimulation (rTMS) was applied over the left intraparietal sulcus of the parietal cortex, Glover et al. observed a disruption in the online correction for a change in target size, but only when the rTMS was applied concurrent with the initiation of the adjustment and not when it was applied after the adjustment had already begun. This proposition fits well with the minimal intervention principle advocated by Todorov and Jordan (2002) and suggests that initiation of a correction is automatic but that its execution is functional.

An alternative interpretation of our finding could be that the gain of the error correction process triggered by the cursor jump could be modulated as a function of the task's constraints. When these constraints are relatively loose, as in Experiment 2, it could be that the gain of the error correction process is set relatively low. Again, this proposition is in agreement with the minimal intervention principle advocated by Todorov and Jordan (2002). Specifically, effective target size was relatively small in Experiment 1, whereas it was quite large in Experiment 2, which explains why steeper corrections were observed in the former experiment than they were in the latter experiment. In turn, this suggests that one has some control over which component(s) of the movement to more loosely or strictly control.

Partial corrections for cursor jumps

The results of this study concur with all previous research using a cursor-jump paradigm (Brière & Proteau, 2010; Proteau et al., 2009; Sarlegna et al., 2004; Saunders & Knill, 2003, 2004, 2005) in indicating that there is a limit to the size of the correction that can be performed by this apparently attention-free online corrective process. For instance, the correction for the cursor jump compensated for only between 45% (Sarlegna et al., 2004) and 80% (Saunders & Knill, 2003) of the imposed bias. In the present study, this correction was approximately 65%. Proteau et al. (2009) have suggested that the limits of the correction process could be exceeded when the error falls outside the normal variability of one's movement. Although this could be the case with relatively large cursor jumps, this explanation does not fit well with the partial correction observed in Experiment 1 for a 5-mm cursor jump. Rather, it could be that asking participants to complete their movement in a single motion (present study; Brière & Proteau, 2010; Proteau et al., 2009), considering the movement completed when their hand was still traveling at a relatively high velocity (100 mm/s; Saunders & Knill, 2003), or asking participants to produce very fast movements (Bédard & Proteau, 2003; Sarlegna et al., 2003, 2004) prevented them from completing their corrections. These results all contrast with those reported by Gritsenko et al. (2009), who showed that the gain of the correction for a target jump was set for movements to end up on the target. This difference might indicate that the correction processes revealed in cursor-jump and target-jump experiments differ in some important ways. However, a cursor jump—but not a target jump—creates a conflict between the seen position of the cursor and the felt position of the hand, which may have limited the participant's ability to produce a complete correction.

Conclusion

When a reaching movement deviates from its intended path, quick and graded corrections are initiated while one’s hand (or a cursor) is seen in peripheral vision. This correction occurs even when it is not required to complete the task successfully. This suggests that the initiation of the correction is based on a comparison between the intended and actual movement trajectory, without much consideration for the ultimate movement goal. On the contrary, the execution of the correction takes into consideration not only the size of the error that has been detected but also the task’s constraints. These constraints likely influence the gain of the correction processes put into play early after movement initiation, when one’s movement deviates from its intended trajectory.

References

Abahnini, K., Proteau, L., & Temprado, J.J. (1997). Evidence supporting the importance of peripheral visual information for the directional control of aiming movement. *Journal of Motor Behavior, 29*, 230-242.

Abhanini, K., & Proteau, L. (1999). The role of peripheral and central visual information for the directional control of manual aiming movements. *Canadian Journal of Experimental Psychology, 53*, 160-175.

Bard, C., Hay, L., & Fleury, M. (1985). Role of peripheral-vision in the directional control of rapid aiming movements. *Canadian Journal of Psychology, 39*, 151-161.

Bard, C., Hay, L., & Fleury, M. (1990). Timing and accuracy of visually directed movements in children – control of direction and amplitude components. *Journal of Experimental Child Psychology, 50*, 102-118.

Bédard, P., & Proteau, L. (2001). On the role of static and dynamic visual afferent information in goal-directed aiming movements. *Experimental Brain Research, 138,* 419-431.

Bédard, P., & Proteau, L. (2003). On the role of peripheral visual afferent information for the control of rapid video-aiming movements. *Acta Psychologica, 113,* 99-117.

Blouin, J., Bard, C., Teasdale, N., & Fleury, M. (1993a). On-line versus off-line control of rapid aiming movements. *Journal of Motor Behavior, 25,* 275-279.

Blouin, J., Teasdale, N., Bard, C., & Fleury, M. (1993b). Directional control of rapid aiming movements: The role of the kinetic visual feedback system. *Canadian Journal of Experimental Psychology, 47,* 678-696.

Blouin, J., Gauthier, G. M., Vercher, J.-L. & Cole, J. (1996). The relative contribution of retinal and extraretinal signals in determining the accuracy of reaching movements in normal subjects and a deafferented patient. *Experimental Brain Research, 109,* 148-153.

Brenner, E., & Smeets, J.B. (2003). Fast corrections of movements with a computer mouse. *Spatial Vision, 16,* 365-76.

Bridgeman, B., Lewis, S., Heit, G., & Martha, N. (1979). Relation between cognitive and motor-oriented systems of visual position perception. *Journal of Experimental Psychology: Human Perception and Performance, 5,* 692-700.

Brière, J., & Proteau, L. (2010). Movement error detection and correction based on automatic and attention-free processes. *Experimental Brain Research (in press).*

Cameron, B.D., Franks, I.M., Enns, J.T., & Chua, R. (2007). Dual-target interference for the 'automatic pilot' in the dorsal stream. *Experimental Brain Research, 182,* 297-305.

Day, B.L., & Lyon, I.N. (2000). Voluntary modification of automatic arm movements evoked by motion of a visual target. *Experimental Brain Research, 130,* 159-168.

Desmurget, M., Epstein, C.M., Turner, R.S., Prablanc, C., Alexander, G.E., & Grafton, S.T. (1999). Role of the posterior parietal cortex in updating reaching movements to a visual target. *Nature Neuroscience, 2,* 563-567.

Desmurget, M., Pélisson, D., Rossetti, Y. & Prablanc, C. (1998). From eye to hand: Planning goal-directed movements. *Neuroscience & Biobehavioral Reviews, 22,* 761-788.

Efron, B., & Tibshirani, R. (1993). *An introduction to the bootstrap*. New York: Chapman & Hall/CRC.

Elliott, D., & Khan, M.A. (2010). *Vision and goal-directed movements: A neurobehavioral perspective.* Champaign, IL: Human kinetics.

Fitts, P.M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology, 47,* 381-391.

Franklin, D.W., & Wolpert, D.M. (2008). Specificity of reflex adaptation for task-relevant variability. *Journal of Neuroscience, 28,* 14165-14175.

Georgopoulos, A.P., Pellizzer, G., Poliakov, A.V., & Schieber, M.H. (1999). Neural coding of finger and wrist movements. *Journal of Computational Neuroscience, 6,* 279-288.

Glover, S., Miall, R.C., & Rushworth, M.F.S. (2005). Parietal rTMS disrupts the initiation but not the execution of on-line adjustments to a perturbation of object size. *Journal of Cognitive Neuroscience, 17,* 124-136.

Goodale, M.A., Pélisson, D., & Prablanc, C. (1986). Large adjustements in visually guided reaching do not depend on vision of the hand or perception of target displacement. *Nature, 320,* 748-750.

Gritsenko, Y., Yakovenko, S., & Kalaska, J.F. (2009). Integration of predictive feedforward and sensory feedback signals for online control of visually guided movement. *Journal of Neurophysiology, 102*, 914-930.

Johnson, H., Van Beers, R.J., & Haggard, P. (2002). Action and awareness in pointing tasks. *Experimental Brain Research, 146,* 451-459.

Merchant, H., Naselaris, T., & Georgopoulos, A.P. (2008). Dynamic sculpting of directional tuning in the primate motor cortex during three-dimensional reaching. *Journal of Neuroscience, 28,* 9164-9172.

Meyer, D.E., Abrams, R.A., Kornblum, S., Wright, C.E., & Smith, J.E. (1988). Optimality in human motor performance: Ideal control of rapid aimed movements. *Psychological Review, 95,* 340-370.

Paillard, J. (1980). The multichanneling of visual cues and the organization of visually guided response. In G.E. Stelmach & J. Requin (Eds.), *Tutorial in motor behavior* (pp. 259-279). Amsterdam: North Holland.

Paillard, J., & Amblard, B. (1985). Static versus kinetic visual cues for the processing of spatial relationships. In D.J. Ingle, M. Jeannerod, & D.N. Lee (Eds), *NATO ASI Series: Brain mechanisms and spatial vision* (pp. 299-330). La Haye: Martinus Nijhoff.

Pisella, L., Grea, H., Tilikete, C., Vighetto, A., Desmurget, M., Rode, G., Boisson, D., & Rosetti, Y. (2000). An 'automatic pilot' for the hand in human posterior parietal cortex: toward reinterpreting optic ataxia. *Nature Neuroscience, 3,* 729-736.

Prablanc, C., & Martin, O. (1992). Automatic-control during hand reaching at undetected 2-dimensional target displacements. *Journal of Neurophysiology, 67,* 455-469.

Proteau, L., Boivin, K., Linossier, S., & Abahnini, K. (2000). Exploring the limits of peripheral vision for the control of movement. *Journal of Motor Behavior, 32,* 277-286.

Proteau, L., Roujoula, A., & Messier, J. (2009). Evidence for continuous processing of visual information in a manual video-aiming task. *Journal of Motor Behavior, 41,* 219-231.

Sarlegna, F., Blouin, J., Bresciani, J.P., Bourdin, C., Vercher, J.-L., & Gauthier, G.M. (2003). Target and hand position information in the online control of goal-directed arm movements. *Experimental Brain Research, 151,* 524-535.

Sarlegna, F., Blouin, J., Vercher, J.-L., Bresciani, J.P., Bourdin, C., & Gauthier, G.M. (2004). Online control of the direction of rapid reaching movements. *Experimental Brain Research, 157,* 468-471.

Saunders, J.A., & Knill, D.C. (2003). Humans use continuous visual feedback from the hand to control fast reaching movements. *Experimental Brain Research, 152,* 341-352.

Saunders, J.A., & Knill, D.C. (2004). Visual feedback control of hand movements. *Journal of Neuroscience, 24,* 3223-3234.

Saunders, J.A., & Knill, D.C. (2005). Humans use continuous visual feedback from the hand to control both the direction and distance of pointing movements. *Experimental Brain Research, 162,* 458-473.

Shabbott, B.A., & Sainburg, R.L. (2009). On-line corrections for visuomotor errors. *Experimental Brain Research, 195,* 59-72.

Tinjust, D., & Proteau, L. (2009). Modulation of the primary impulse of spatially-constrained video-aiming movements. *Human Movement Science, 28,* 155-168.

Todorov, E., & Jordan, M.I. (2002). Optimal feedback control as a theory of motor coordination. *Nature Neuroscience, 5,* 1226-1235.

Woodworth, R.S. (1899). The accuracy of voluntary movement. *Psychological Review, 3, (3, Suppl. 13),* 1-119.

Table 1. Mean (standard deviation) frontal and sagittal distance between the stylus and the center of the target at movement endpoint, and movement time as a function of the type of trials, target size, and cursor-jump amplitude. Frontal position: a negative value indicates that the stylus ended to the left of the target center. Sagittal position: a negative value indicates that the stylus ended short of the target center.

Type of trial	**Target size**	**Cursor-jump amplitude**		
		5 mm	**15 mm**	**25 mm**
		Frontal position (mm)		
No-jump	5 mm	-1.0 (2.3)	-1.9 (2.1)	-3.8 (2.7)
	30 mm	-1.1 (2.7)	-2.0 (3.2)	-2.9 (2.2)
Cursor-jump	5 mm	-4.7 (2.5)	-11.5 (1.6)	-20.2 (2.2)
	30 mm	-4.0 (1.6)	-12.1 (1.6)	-18.4 (2.9)
		Sagittal position (mm)		
No-jump	5 mm	0.8 (2.2)	0.9 (4.1)	2.2 (2.1)
	30 mm	-1.8 (2.2)	-0.2 (3.4)	3.0 (4.7)
Cursor-jump	5 mm	-0.1 (2.2)	-0.8 (6.6)	-1.2 (2.0)
	30 mm	-1.3 (1.9)	-2.1 (6.3)	0.8 (2.8)
		Movement time (ms)		
No-jump	5 mm	674 (50)	698 (51)	670 (42)
	30 mm	686 (49)	686 (43)	669 (49)
Cursor-jump	5 mm	679 (44)	716 (52)	681 (52)
	30 mm	692 (50)	700 (49)	673 (42)

Figure Captions

Figure 1. Top. View of the apparatus. Bottom**.** Illustration of 25-mm cursor jump for movements aimed at 30-mm (left) and 5-mm (right) targets.

Figure 2. Stylus trajectories for no-jump (dashed line) and cursor-jump (full line) trials aimed at 5-mm and 30-mm targets located at 7.5° to the right of the starting base. The results are from one participant in each cursor-jump condition.

Figure 3. Mean trial-by-trial correction for the 5-, 15-, and 25-mm cursor jumps. Note that the correction was present immediately from the first cursor-jump trial and remained largely unchanged across trials.

Figure 4. Difference in the frontal displacement (upper left panel) and velocity (lower left panel) of the stylus between no-jump and cursor-jump trials as a function of time. Note the similar correction latency for cursor-jump trials regardless of the size of the cursor jump and that of the target. Note that correction latency is reduced by approximately 40 ms when determined from the velocity rather than the displacement data. Note that the gain of the correction (slope) was significantly larger for larger cursor jumps, but did not differ across target size. Standard error of the mean is illustrated on the upper and lower right panels.

Figure 5. Left. Stylus trajectories for the first four no-jump (red) and cursor-jump (black) trials for one typical participant (A). Distribution of trials (and standard error for the mean) within the target. Difference in the frontal displacement (B) and velocity (C) of the stylus between no-jump and cursor-jump trials as a function of time. Note the similar correction latency for 15 mm cursor jump aimed at a 5 mm target in Experiment 1 and in Experiment 2. Note that correction latency is reduced by approximately 40 ms when determined from the velocity rather than the displacement data. Note the smaller gain of the correction in

Experiment 2 compared to Experiment 1.

Figure 1

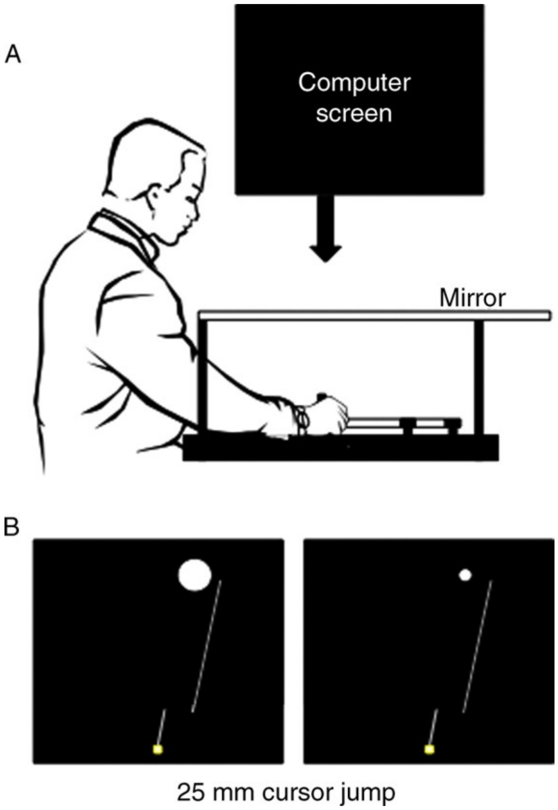
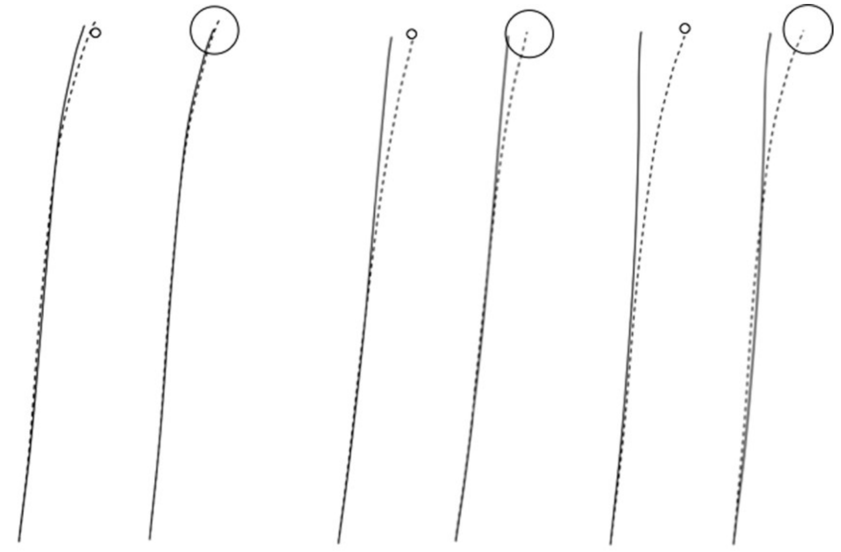
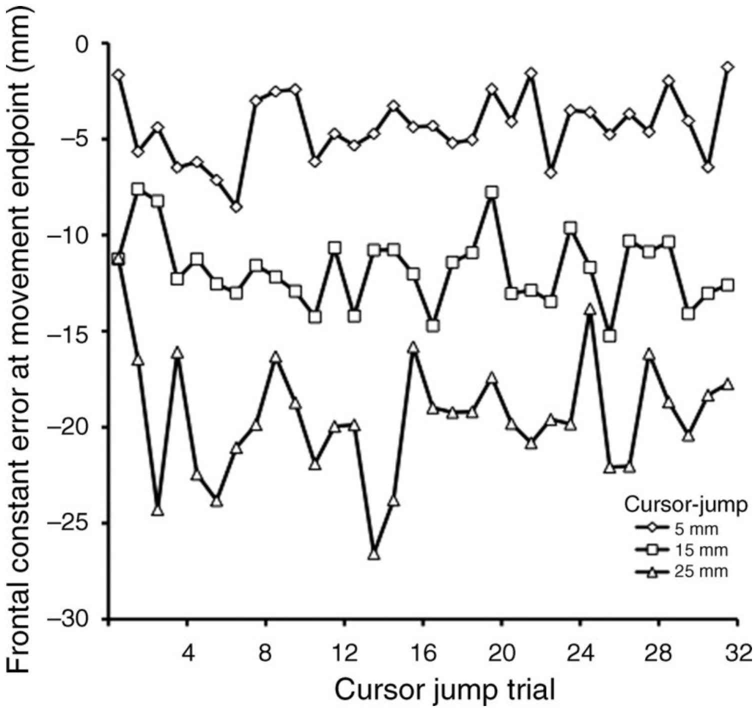


Figure 2



5 mm cursor jump 15 mm cursor jump 25 mm cursor jump

Figure 3



Frontal constant error at movement endpoint (mm)
0
−5
−10
−15
−20
−25
−30
4
8
12
16
20
24
28
32
Cursor jump trial
Cursor-jump
5 mm
15 mm
25 mm

Figure 4

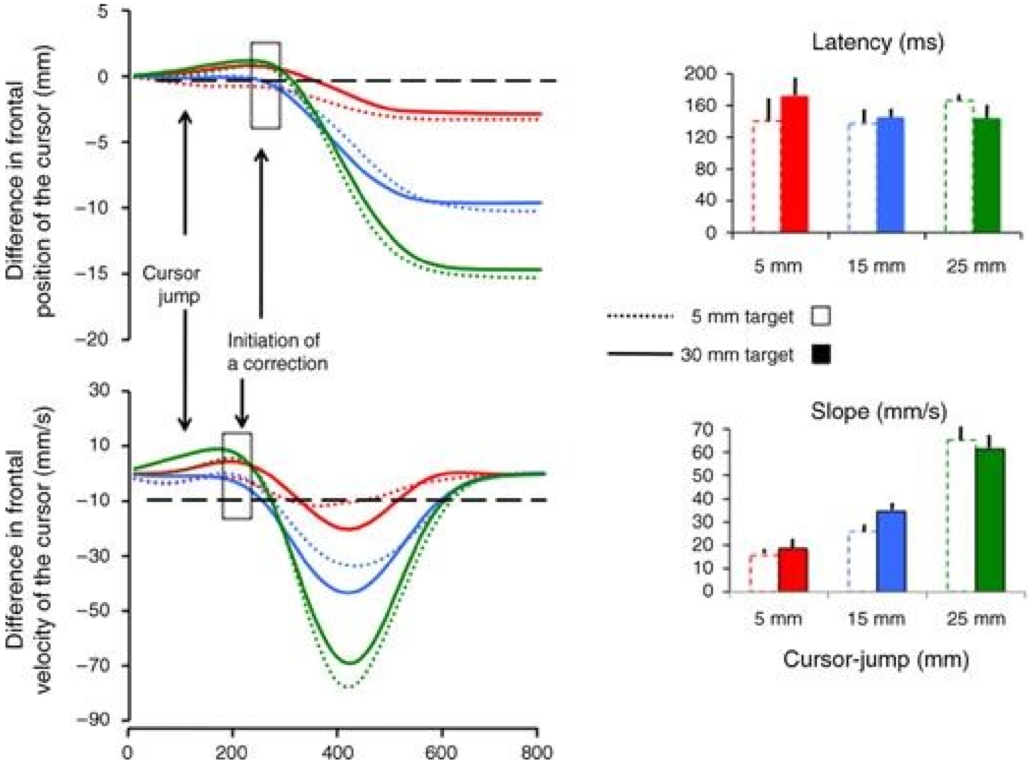
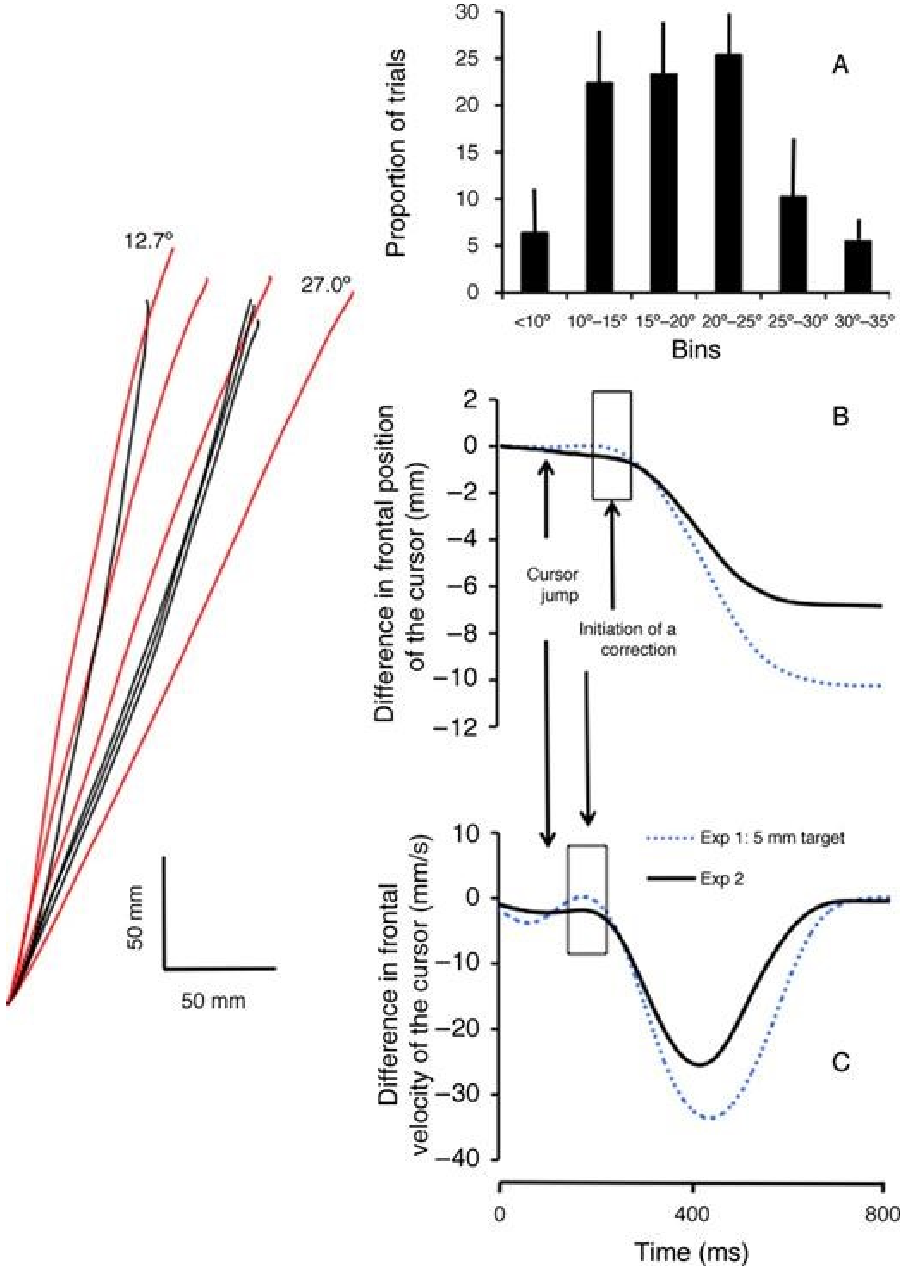

Difference in frontal position of the cursor (mm)
5
0
−5
−10
−15
−20
Cursor jump
Initiation of a correction
Difference in frontal velocity of the cursor (mm/s)
30
10
−10
−30
−50
−70
−90
0
200
400
600
800
Latency (ms)
200
160
120
80
40
0
5 mm
15 mm
25 mm
5 mm target
30 mm target
Slope (mm/s)
70
60
50
40
30
20
10
0
5 mm
15 mm
25 mm
Cursor-jump (mm)

Figure 5


12.7°
27.0°
50 mm
50 mm
A
Proportion of trials
30
25
20
15
10
5
0
<10°
10°–15°
15°–20°
20°–25°
25°–30°
30°–35°
Bins
B
Difference in frontal position of the cursor (mm)
2
0
−2
−4
−6
−8
−10
−12
Cursor jump
Initiation of a correction
C
Exp 1: 5 mm target
Exp 2
Difference in frontal velocity of the cursor (mm/s)
10
0
−10
−20
−30
−40
0
400
800
Time (ms)

Chapitre 6 : Article 5

Goal-directed movements:
Correction for an erroneous movement trajectory but not for a cursor jump

Julien Brière and Luc Proteau[1]
Département de kinésiologie
Université de Montréal
Montréal, Canada

[1]Corresponding author:
Luc Proteau, Département de kinésiologie, Université de Montréal, P.O. Box 6128,
Downtown Station, Montréal, Canada, H3C 3J7.
Tel: (514) 343-2039
Fax: (514) 343-2181
Email: luc.proteau@umontreal.ca

keywords: cursor jump, online visual control, goal-directed movements, motor control, feedback processes, forward model

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Abstract

Goal-directed movements are subject to intrinsic planning and execution variability, which require that the central nervous system (CNS) closely monitors our movements to ensure endpoint accuracy. The present study investigated whether seeing a sudden change in the direction of one's movement provided information that could be used by the CNS to plan and control an efficient correction in addition to seeing one's movement-displaced trajectory. We used a cursor jump paradigm in which a cursor moved by the participant was unexpectedly moved 150 ms after movement initiation. For one condition, the cursor remained visible throughout movement execution. For a second condition, the cursor was occluded 100 ms after the cursor jump, whereas for the last condition, the cursor was visible for only 100 ms beginning immediately after the jump occurred. Participants successfully corrected their movements for the cursor jump in all three conditions. However, the correction latency was significantly longer for the latter condition than for the former two conditions. Taken together, these results indicate that seeing the cursor jump per se did not provide information that could be used by the CNS to plan an appropriate correction. However, suddenly seeing the cursor at an unexpected location apparently increased the time required to evaluate the trajectory of one's movement and initiate a correction.

Goal-directed movements:

Correction for an erroneous movement trajectory but not a cursor jump

Goal-directed movements require a series of processes to identify the target and its location and to transform this information into appropriate motor commands (for a recent review, see Gaveau et al., 2014). Practice leads to accurate movement planning and movement execution processes, but the output of these processes remains subject to intrinsic variability (Fox, Snyder, Vincent, & Raichle, 2007; Osu, Morishige, Nakanishi, Miyamoto, & Kawato, 2015; van Beers, Haggard, & Wolpert, 2004). Therefore, it is imperative that the central nervous system (CNS) closely monitors our movements to quickly update movement execution (Desmurget and Grafton, 2000; Franklin, Wolpert & Franklin, 2012; Franklin and Wolpert, 2008; Vesia, Yan, Henriques, Sergio, & Crawford, 2008). It has been proposed that vision is processed almost continuously to ensure movement endpoint accuracy (Brière & Proteau, 2011, 2017; Cluff, Crevecoeur, & Scott, 2015; Saunders & Knill, 2003). The present paper investigated the nature of the visual information that is used by the CNS to detect that a goal-directed movement would miss a target and plan and execute an efficient correction.

Many authors have used a cursor jump paradigm to investigate visual error detection and online correction processes (Brière and Proteau, 2011, 2017; Franklin & Wolpert, 2008; Proteau, Roujoula, & Mesier, 2009; Sarlegna, Blouin, Bresciani, Bourdin, Vercher, & Gauthier 2003; Sarlegna, Blouin, Vercher, Bresciani, Bourdin, & Gauthier, 2004, Saunders & Knill, 2003, 2004; Veyrat-Masson, Brière & Proteau, 2010). Specifically, participants moved a cursor toward a target on a visual display. The location of the cursor that represented the participant's hand was "instantaneously" translated—for example, by 2 cm—100 ms after movement initiation. Participants likely planned their movements as if no perturbation would occur because cursor jumps were infrequent and unexpected. Therefore, participants needed to detect the experimentally induced error for the perturbed trials, evaluate its impact on the ongoing movement (i.e., quantify its size and direction), and plan and perform a correction to counteract the perturbation, which elucidates error detection and correction processes.

Participants in cursor jump experiments often report that they were not aware of the perturbation, but the results indicate that they corrected their movements quickly and accurately to counteract the perturbation (Brière & Proteau, 2011, 2017; Proteau et al., 2009; Sarlegna et al., 2003, 2004; Saunders & Knill, 2003, 2004; Veyrat-Masson et al., 2010). These corrections were apparent even in the first perturbed trial to which participants were exposed (Brière & Proteau, 2017; Proteau et al. 2009). Therefore, the authors concluded that the error detection and correction processes were “automatic/attention free” and did not require learning or adaptation. In the same vein, participants who consciously detected the perturbation could not refrain from initiating a correction in the direction opposite that of the cursor jump (Franklin and Wolpert 2008), even when asked to move their hand in the same direction as the cursor jump.

The cursor in most cursor jump experiments was instantaneously translated while progressing toward the target (Brière & Proteau, 2011, 2016; Proteau et al., 2009; Sarlegna et al., 2003, 2004; Veyrat-Masson et al., 2010). Therefore, the dynamic information of the cursor jump (i.e., the sudden change in location/trajectory) was available to the CNS. The present study investigated whether the cursor jump per se provided information that the CNS used to initiate a correction more quickly and/or more accurately than when the cursor jump was occluded. Recent results suggest that the cursor jump per se provides useful information for the planning and execution of an appropriate correction. Specifically, Brière and Proteau

(2017) demonstrated that seeing the cursor for only 16 ms after a jump occurred provided sufficient information for the participants to correct their movements for approximately 23% of the cursor jump amplitude. It is surprising that such a short period of cursor visibility after the jump resulted in a significant correction. This observation suggests that the cursor jump provided information that was used by the CNS in addition to the information provided by the displaced trajectory.

Methods

Participants

Ten participants between 20 and 30 years of age who were students at the Université de Montréal participated in this experiment. The participants self-declared right handedness and reported normal or corrected to normal vision. The Health Sciences Ethics Committee of the Université de Montréal approved this study.

Task and apparatus

Figure 1 illustrates the apparatus, which consisted of a table, computer screen, headrest, mirror, and manipulandum with two degrees of freedom (Figure 1A, B). The participants sat in front of the table and were asked to move a device similar to a computer mouse across the tabletop from a fixed starting position close to their body toward a target located further away from the body (see Figure 1B). The CRT computer screen (Mitsubishi, Color Pro Diamond, ~ 940 mm [37 inches], refresh rate of 60 Hz, resolution of 1024 x 768) was mounted on a ceiling support positioned directly over the table. The computer screen was oriented parallel to the surface of the table. The screen's image was reflected on a mirror placed directly beneath and parallel to the tabletop. The distance between the computer screen and the mirror was 200 mm. The distance between the mirror and the tabletop was also 200 mm, which permitted free displacement of the manipulandum on the tabletop. The information presented on the computer screen was reflected in the mirror, and it was visible to the participant (see Figure 1A). The mirror prevented participants from seeing their hand and lower arm during the experiment. A headrest was affixed to the side of the computer screen. It was aligned with the center of the computer screen and was used to standardize the information displayed on the computer screen for all participants.

A piece of Plexiglas covered the tabletop, and a starting base and the manipulandum were affixed to the Plexiglas. The starting base consisted of a thin strip of Plexiglas glued to the tabletop. It was parallel to the leading edge of the table and had a small indentation on its distal face. This indentation was aligned with the center of the headrest, directly in front of the participant's midline, and it was the starting base for the stylus. The indentation made it easy for the participant to position the stylus at the beginning of each trial.

The manipulandum consisted of two pieces of rigid Plexiglas (430 mm) joined at one end by an axle. One free end of the manipulandum was fitted with a second axle encased in a stationary base. The other free end of the manipulandum was fitted with a small vertical shaft (length: 30 mm; radius: 10 mm), i.e., the stylus, which was gripped easily by the participant. Each axle of the manipulandum was fitted with a 13-bit optical shaft encoder (US Digital, model S2-2048, sampled at 500 Hz, angular accuracy of 0.0439°), which enabled tracking of the displacement of the stylus online and its illustration at a 1:1 ratio on the computer screen. Movement of the stylus away from the body resulted in an identical displacement of the cursor on the computer screen. The bottom of the stylus and the bottom of the optical encoder located at the junction of the two arms of the manipulandum were covered with a thin piece of

Plexiglas. Lubrication of the working surface at the beginning of each experimental session allowed near frictionless displacement of the stylus.

Procedures

Participants were asked to stop the cursor (yellow; 3 mm in diameter) on a target (diameter of 5 mm). The target was white on a black screen. The target was located 320 mm in front of the starting base and 86 mm to its right (15˚).

Participants used their right (dominant) hand to initiate their movement following the presentation of the target (i.e., not a reaction time task), and they were asked to perform smooth and continuous movements (i.e., not a stop-and-go strategy) toward the target. Participants were also required to gaze at the target during movement execution (their natural behavior to ensure optimal accuracy; Neggers and Bekkering, 1999, 2000, 2001) and complete their movements in a movement time between 680 ms and 920 ms (800 ms +/- 15%). The experimenter reminded the participant of the target movement time when movements were completed outside of this time bandwidth. A movement time bandwidth (Proteau et al. 2009; Saunders & Knill 2003, 2005) reduces the possibility of different speed-accuracy trade-offs between different experimental conditions (Fitts 1954). The target movement time and the target location were as in previous work from our laboratory (Brière and Proteau 2011; 2016; Veyrat-Masson et al. 2010).

All participants could see the cursor resting on the starting base at the beginning of each trial. The stylus was stabilized on the starting base for 500 ms, and the target was presented on the screen. Movement initiation was detected during data acquisition when the cursor was moved 1 mm, and movement completion was detected when the cursor did not move more than 2 mm in a time frame of 100 ms. A preliminary study revealed that the use of this procedure to detect movement completion during data acquisition made it difficult for participants to use a stop and go strategy. The position of the cursor endpoint and the target remained visible for 1 s after the detection of movement completion.

Participants first took part in a familiarization phase consisting of 10 trials. This phase was followed by 250 experimental trials. A perturbation occurred for 20% of the experimental trials (50 trials). Two types of perturbations were used: a cursor jump and/or occlusion of the cursor (see below). The perturbed trials were presented randomly with the restriction that one trial of each of the five types described below occurred once within each successive block of 25 trials. One unperturbed trial (i.e., a control trial) was also randomly selected within each successive block of 25 trials, with the restriction that it did not immediately follow a perturbed trial. Participants were not informed that the cursor would jump on some trials because this information may have interfered with their natural behavior during the task (i.e., gazing at the target). The experimenter noted any comments of the participants regarding their performance or the occurrence of anything strange or peculiar during a trial.

Specifically, the trials were categorized by the inclusion of a cursor jump (cursor jump vs. no jump trial). The cursor was translated to the right, perpendicular to a straight line that connected the starting base and the target, 150 ms after movement onset for all cursor jump trials. Therefore, correction for a cursor jump would be observed if the endpoint location of the participants' hand/stylus was to the left relative to the no jump trials.

The cursor was visible from movement onset to movement completion (0-end), from movement onset until the 250-ms mark (0-250 ms), or between 150 ms and 250 ms following movement onset (150-250 ms) within each of these two categories (i.e., jump vs. no-jump) (see Figure 2). Therefore, a cursor jump in the *jump 0-end* trials occurred 150 ms after movement initiation, and the cursor was visible throughout movement execution. The *no-jump 0-end* trials were control trials. The cursor in the *jump 0-250 ms* trials was visible when the jump occurred (i.e., 150 ms after movement initiation) and it remained visible for 100 ms, after which it was occluded. The cursor in the *no-jump 0-250 ms* trials was occluded 250 ms after movement onset. The cursor in the *jump 150-250 ms* trials became visible only after the jump occurred, and it remained visible for 100 ms. Finally, the cursor in the *no-jump 150-250 ms* was visible only between 150 and 250 ms after movement onset. The primary difference between the last two conditions was that the cursor was visible when it jumped in the former condition and was not visible when it jumped in the latter condition.

Data reduction

The tangential displacement data of the stylus over time were first smoothed using a second order recursive Butterworth filter with a cut-off frequency of 10 Hz. The filtered data were numerically differentiated once using a central finite technique to obtain the velocity profile of the aiming movement, a second time to obtain the acceleration profile, and a third time to obtain a jerk profile. We determined the end of the movement's primary impulse from the kinematic profiles (Meyer, Abrams, Kornblum, Wright, & Smith, 1988). This occurred when one of the following events was detected on the kinematic profiles: (a) movement velocity falling below 20 mm/s, (b) movement reversal (velocity going from positive to negative), (c) movement lengthening (presence of a secondary movement impulse as indexed by the acceleration profile crossing the zero value for a second time) or (d) significant disruption in the deceleration profile as indexed by zero-crossing on the jerk profile. A secondary movement impulse was considered a discrete correction when its duration was at least 80 ms and its extent was at least 2 mm. Notably, less than 5% of the trials in all conditions exhibited a secondary corrective impulse. These trials were withdrawn from all analyses.

Movement initiation was detected when the stylus was moved 1 mm to provide quick feedback to the participant during data acquisition. However, movement initiation was defined as the moment at which the tangential velocity of the cursor reached 10 mm/s and was maintained above this value for at least 20 ms for the primary analyses. Visual inspection of the data revealed that movement was clearly underway once a velocity of 10 mm/s was reached. Movement endpoint was defined as the end of the movement's primary impulse using the parsing algorithm defined above.

We determined the end of the movement's primary impulse for all trials (hereafter called endpoint) to investigate the efficacy of the correction for the cursor jumps. Endpoint direction and extent errors were computed in Cartesian coordinates, which referred to the position of the stylus in relation to the center of the target. The direction error was the signed difference on the frontal axis (in mm) between the movement endpoint and the target. A positive value indicated a movement ending to the right of the target, and a negative value indicated a movement ending to the left of the target (see Figure 1C). The extent error of a trial was defined as the signed difference between the movement endpoint and the target on the sagittal axis (in mm). A positive value indicated that the target was overshot, and a negative value that the target was undershot. We computed the constant and variable aiming errors for the direction and extent dimensions of the task from these data. The constant error was the mean signed difference between the target and the endpoint location, and this value indicated whether participants exhibited bias in their movements (e.g., too long, too short, to the right, or to the left of the target). The variable error was the within-participant variability in endpoint location.

We also determined the latency of the correction for a cursor jump. We used the stylus frontal location data because the cursor jump and the expected correction primarily occurred on this axis. We computed the mean frontal location of the stylus for the 6 types of trials defined above for each participant. Then, we computed the difference in the location of the stylus between the no jump and the cursor jump trials every 20 ms. A correction for the cursor jump was detected within each condition of cursor visibility when the cursor jump condition deviated from the no jump condition by more than 1 mm in the direction opposite that of the cursor jump. The 1-mm criterion was chosen arbitrarily. Correction onset was also detected only when the change in direction continuously increased as movement unfolded and became significant to ensure that we did not obtain a false positive. This technique was used by Proteau et al. (2009), who reported latencies in the same range as previous reports (Brenner & Smeets, 2003; Saunders & Knill, 2003).

Results

Participants were not aware of cursor jumps

Even after having been debriefed, participants reported that they were not aware that the cursor had jumped during some trials. This aspect of the results replicates previous observations (Brière et Proteau, 2011, 2017; Proteau et al., 2009; Saunders & Knill, 2003; Veyrat-Masson et al., 2010), even when a cursor jump occurred in a high proportion of the trials (but during saccadic visual suppression, Sarlegna et al., 2003, 2004).

Movement endpoint, endpoint variability, and movement time

We investigated how participants reacted to the cursor jump during different conditions of cursor visibility. Figure 2 illustrates the visible portion of the *cursor* trajectory and movement endpoint in all experimental conditions averaged over all participants. Figure 3 illustrates *stylus* trajectories of one randomly selected participant for the 6 different trial types.

Movement endpoint bias, variability data and movement time data were individually submitted to an ANOVA to compare the 2 types of trials (no-jump vs. cursor jump) and the 3 periods of cursor visibility (0-end, 0-250 ms, 150-250 ms) using repeated measurements on both factors. Geisser-Greenhouse correction was applied when appropriate. All significant main effects involving more than two means were further examined using Bonferroni's technique. Significant interactions were identified by computing the simple main effects followed by post hoc comparisons (Bonferroni's technique) when the effects involved more than two means. All effects are reported at $p < 0.05$.

Frontal endpoint error and variability. The ANOVA computed on the stylus endpoint frontal bias revealed a significant main effect of trial type (F (1, 9) = 117.98, $p < 0.01$) and a significant period of cursor visibility x types of trials interaction (F (2, 18) = 4.96, $p < 0.05$). The breakdown of the interaction into its simple main effects (see Figures 3 and 4, upper panel) revealed a significant effect of the period of cursor visibility for the no jump trials (F (2, 8) = 12.78 $p < 0.01$), which indicates a significantly smaller bias for the normal vision condition (no-jump 0-end; -0.37 mm) than the vision 0-250 and vision 150-250 ms conditions (-2.45 mm and -3.15 mm, respectively), which did not differ significantly from each other. The biases noted for the latter three conditions were significantly smaller than those noted for the three cursor jump conditions, which did not significantly differ from one another (F (2, 8)

< 1.0) (-13.2 mm, -13.1 mm, and -13.1 mm for condition jumps 0-end, 0-250, and 150-250, respectively).

The ANOVA of the frontal endpoint variability revealed a significant main effect of the period of cursor variability (F (2, 18) = 8.36) (see Figure 4, lower panel). Post hoc comparisons revealed a significantly lower frontal endpoint variability for the 0-end condition (4.63 mm) than for the 0-250 ms and 150-250 ms conditions (5.3 mm and 6.7 mm, respectively, $p < 0.05$), which did not significantly differ from one another ($p > 0.15$).

Sagittal endpoint error and variability. ANOVA of the sagittal constant error revealed a significant main effect of trial type (F (1, 9) = 8.85, $p < 0.02$) and a significant period of cursor visibility x type of trials interaction (F (2, 18) = 3.88, $p = 0.04$). The breakdown of the interaction into its simple main effects (not illustrated) revealed a significant trial type effect for the 0-end period of cursor visibility (F (1, 9) = 18.29, $p < 0.01$); movements were longer for the jump than for the no jump trials (constant errors of 1.9 mm and -0.8 mm, respectively). No significant difference between the jump and the no jump trials was noted for the 0-250 ms (constant errors of 0.1 mm and 0.6 mm, respectively) or 150-250 ms conditions (constant errors of 0.5 mm and -1.5 mm, respectively, $p > 0.10$ for both comparisons).

ANOVA of the sagittal variable error (not illustrated) revealed a significant main effect of the period of cursor visibility (F (2, 18) = 18.91, $p < 0.001$). Post hoc comparisons revealed significantly smaller sagittal endpoint variability for the 0-end than for the 0-250 ms and 150-250 ms periods of cursor visibility, which did not differ significantly from one another (4.4 mm, 7.6 mm and 8.5 mm, respectively).

Movement time. ANOVA of movement time revealed a significant main effect of trial type (F (1, 9) = 5.48, $p < 0.05$), which indicates a shorter movement time for the no jump trials than for the jump trials (787 ms vs. 807 ms, respectively).

Correction for cursor jump. We also determined whether the size of the correction for the cursor jump (i.e., the difference in frontal endpoint position between the no jump and the cursor jump trials; see Figure 1C) differed for the three periods of cursor visibility. The results of the ANOVA contrasting this dependent variable across the three periods of cursor visibility revealed a significant main effect of the periods of cursor visibility (F (2, 18) = 4.96, $p < 0.05$). Post hoc comparisons revealed a significantly larger correction for the 0-end condition (12.8 mm, $p < 0.05$) than for the 0-250 ms and 150-250 ms conditions (10.6 mm and 9.9 mm, respectively), which did not significantly differ from one another ($p > 0.25$). These results clearly indicate that a correction occurred for all three types of cursor jump trials. This correction did not differ significantly regardless of cursor jump visibility on the computer screen for the first 250 ms of the movement.

Correction latency. ANOVA of the correction latency revealed a significant difference among the three periods of cursor visibility (F (2, 18) = 4.7, $p = 0.022$). Post hoc comparisons revealed that mean correction latency did not differ significantly between the 0-end and the 0-250 ms conditions (148 ms and 144 ms, respectively), but it was significantly shorter than that of the 150-250 ms condition (210 ms).

Discussion

Movement planning and execution processes are intrinsically variable, which makes it important for the CNS to closely monitor goal-directed movements to ensure endpoint accuracy. The questions of interest in our laboratory are to determine how closely goal-directed movements are monitored by the visual system and to identify the sources of information that ensure endpoint accuracy. We used a cursor jump paradigm in which the position of a cursor moved by the participant was rarely and unexpectedly translated after movement initiation. The results of many recent studies demonstrated that participants quickly and efficiently corrected their movement to counteract the cursor jump, even when they were not consciously aware of it (Brière & Proteau, 2011, 2017; Proteau et al., 2009; Sarlegna et al., 2003, 2004; Saunders & Knill, 2003; Veyrat-Masson et al., 2010). We recently demonstrated that seeing the displaced cursor for only 16 ms after the jump was sufficient time for participants to correct their movements for 23% of the cursor jump (Brière & Proteau, 2017). This important finding suggested that the visual system "continuously" monitors our movements. The present study investigated whether the observed correction for the cursor jump was based solely on the processing of the trajectory of the cursor displacement in relation to the target location or whether the sudden displacement/translation of the cursor also provided information that could be used by the CNS to quickly determine that the cursor would miss the target and be entered into movement correction processes. To the best of our knowledge, there are no data available on this subject.

The results of the present study are unequivocal. Participants corrected their movement to counteract the cursor jump even if they were not consciously aware of it, which is consistent with previous studies (Brière & Proteau, 2011, 2017; Proteau et al., 2009; Sarlegna et al., 2003, 2004; Saunders & Knill, 2003, 2004; Veyrat-Masson et al., 2010). This correction even occurred in the first cursor jump trial (Brière & Proteau, 2011, 2017), and it did not occur at the expense of a significant increase in movement variability, although movement time increased by 20 ms. The 20-ms increase in movement time in the jump trials is largely explained by the slightly longer movements noted for this condition. Therefore, the results of the present study replicate previous findings that the detection that the cursor deviates from its trajectory and that the planning of an appropriate correction is relatively "automatic" and does not require much resources (Brière & Proteau, 2011; Reichenbach, Franklin, Zatka-Haas, & Diedrichsen, 2014). This position coincides with recent data that participants cannot prevent the initiation of a correction process for a cursor jump even when asked to do so (Franklin & Wolpert 2008; see also Day and Lyon 2000; Johnson, van Beers and Haggard 2002; Pisella et al., 2000).

The results of the present study clearly indicated that the dynamic information relative to the cursor jump per se did not result in a larger movement correction than when this information was not available. This result is an important new finding of the present study. The observation of the displaced cursor for only 100 ms prior to its occlusion was sufficient to ensure correction for the cursor jump, which did not significantly differ from the results when the cursor is visible for the first 250 ms. These findings are consistent with our recent observation that the "perceived" direction of the cursor appears to reflect its position averaged over a time window of approximately 70 ms (Brière and Proteau, 2017), which minimizes the importance of minute changes in cursor location to evaluate its direction. This averaging procedure has one clear advantage; it filters the noise in the visual system.

Another new finding of the present study is that this observation remained true even when the actual and expected locations of the cursor were not identical. Specifically, participants in the jump 150-250 ms condition did not see the cursor jump; therefore, the cursor became visible at a location that differed from its expected location. When the cursor became visible, it was located outside the normal frontal variability of the no jump trials (a 15-

mm jump vs. a mean frontal variability of 3.5 mm for the control trials at the moment of occurrence of a cursor jump). Nonetheless, 100 ms of cursor visibility was sufficient to accurately evaluate the direction of the cursor and feed this information into the forward model. However, the correction latency data suggest that this input occurred at a temporal cost because seeing the first 150 ms of the cursor displacement (condition 0-250 ms vs. condition 150-250 ms) permitted participants to initiate a correction more quickly than when the cursor was visible only on the starting base prior to movement initiation. This result suggests additional processing time when the cursor suddenly appeared at a location that was relatively remote from its expected location. Future studies should address this issue.

Notably, participants in the present study and previous research never fully completed the correction for the cursor jump, even in the 0-end condition. Specifically, the correction for a single cursor jump compensated for 65% (Veyrat-Masson et al., 2010) and 75-80% (the present study; Brière & Proteau, 2011, 2017) of the imposed bias when the movement time was relatively long, as in the present study. Brière and Proteau (2017; see also Sarlegna et al., 2003) suggested a more likely explanation that a cursor jump creates a conflict between the viewed position of the cursor and the felt position of the hand, which may have limited the participants' ability to estimate the current position of their hand, predict the movement endpoint, and plan their correction. This conflict underlines that visual and proprioceptive feedback are fed back into the forward model, but that the weight given to vision was larger than the weight given to proprioception because the correction for the single cursor jump approximated 80% of the imposed visual perturbation. The lower weight given to proprioception may result from the perceived lower reliability of the proprioceptive signal (Körding & Wolpert, 2004). Specifically, the anticipated and felt position of the hand did not match its observed position for the cursor jump trials, which likely decreased the perceived reliability of the proprioceptive feedback.

Conclusion

The visual system closely monitors goal-directed movements, and a very brief sample of information is sufficient to trigger an efficient correction mechanism. The information that is fed to the correction mechanism concerns the movement trajectory at the exclusion of the cursor jump per se.

References

Brenner, E., & Smeets, J.B. J. (2003). Fast corrections of movements with a computer mouse. *Spatial Vision, 16*, 365-376.

Brière, J., & Proteau, L. (2011). Automatic movement error detection and correction processes in reaching movements. *Experimental Brain Research, 208*, 39-50.

Brière, J., & Proteau, L. (2017). Visual monitoring of goal-directed aiming movements. *Quarterly Journal of Experimental Psychology. 70*, 736-749

Cluff, T., Crevecoeur, F., & Scott, S.H. (2015). A perspective on multisensory integration and rapid perturbation responses. *Vision Research, 110,* 215-222.

Day, B.L., & Lyon, I.N. (2000). Voluntary modification of automatic arm movements evoked by motion of a visual target. *Experimental Brain Research, 130*,159–168.

Desmurget, M., & Grafton, S.T. (2000). Forward modeling allows feedback control for fast reaching movements. *Trends in Cognitive Sciences, 4,* 423-431.

Fitts, P.M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. Journal of Experimental Psychology, 47, 381-391.

Fox, M.D., Snyder, A.Z., Vincent, J.L., & Raichle, M.E. (2007). Intrinsic fluctuations within cortical systems account for intertrial variability in human behaviour. *Neuron, 56*, 171-184.

Franklin, S., & Wolpert, D.M. (2008). Specificity of reflex adaptation for task-relevant variability. *Journal of Neuroscience, 28,* 14165–14175.

Franklin, S., Wolpert, D.M., & Franklin, D.W. (2012). Visuomotor feedback gains upregulate during the learning of novel dynamics. *Journal of Neurophysiology, 108*, 467–478.

Gaveau, V., Pisella, L., Priot, A.-E., Fukui, T., Rossetti, Y., Pélisson, D., & Prablanc, C. (2014). Automatic online control of motor adjustments in reaching and grasping. *Neuropsychologia, 55*, 25-44.

Greenhouse, S.W., & Geisser, S. (1959). On methods in the analysis of profile data. *Psychometrika, 24,* 95-112.

Gritsenko, V., & Kalaska, J.F. (2010). Rapid online correction is selectively suppressed during movement with a visuomotor transformation. *Journal of Neurophysiology, 104*, 3084-3104.

Johnson, H., van Beers, R.J., & Haggard, P. (2002). Action and awareness in pointing tasks. *Experimental Brain Research, 146*, 451–459.

Körding, P.K., & Wolpert, D.M. (2004). Bayesian integration in sensorimotor learning. *Nature, 427*, 244-247.

Meyer, D.E., Abrams, R.A., Kornblum, S., Wright, C.E., & Smith, J.E. (1988). Optimality in human motor performance: ideal control of rapid aimed movements. *Psychological Review, 95,* 340–370.

Neggers, S.F.W., & Bekkering, H. (1999). Integration of visual and somatosensory target information in goal-directed eye and arm movements. *Experimental Brain Research, 125,* 97–107.

Neggers, S.F.W., & Bekkering, H. (2000). Ocular gaze is anchored to the target of an ongoing pointing movement. *Journal of Neurophysiology, 83*, 639–651.

Neggers, S.F.W., & Bekkering, H. (2001.) Gaze anchoring to a pointing target is present during the entire pointing movement and is driven by a non-visual signal. *Journal of Neurophysiology, 86,* 961–970.

Osu, R., Morishige, K., Nakanishi, J., Miyamoto, H., & Kawato, M. (2015). Practice reduces task relevant variance modulation and forms nominal trajectory. Scientific Reports, 5: 17659. DOI: 10.1038/srep17659

Pisella, L., Gréa, H., Tilikete, C., Vighetto, A., Desmurget, M., Rode, G., Boisson, D., & Rossetti, Y. (2000). An 'automatic pilot' for the hand in human posterior parietal cortex: toward reinterpreting optic ataxia. *Nature Neuroscience, 3,* 729–736.

Proteau, L., Roujoula, A., & Messier. J. (2009). Evidence for continuous processing of visual information in a manual video-aiming task. *Journal of Motor Behavior, 41,* 219-231.

Reichenbach, A., Franklin, D.W., Zatka-Haas, P., & Fiedrichsen, J. (2014). A dedicated binding mechanism for the visual control of movement. *Current Biology, 24*, 780-785.

Sarlegna, F., Blouin, J., Bresciani, J.-P., Bourdin, C., Vercher, J.-L., & Gauthier, G.M. (2003). Target and hand position information in the online control of goal-directed arm movements. *Experimental Brain Research, 151*, 524-535.

Sarlegna, F., Blouin, J., Vercher, J.-L., Bresciani, J.-P., Bourdin, C., & Gauthier, G.M. (2004). Online control of the direction of rapid reaching movements. *Experimental Brain Research, 157*, 468-471.

Saunders, J.A., & Knill, D.C. (2003). Humans use continuous visual feedback from the hand to control fast reaching movements. *Experimental Brain Research, 152*, 341-352.

Saunders, J.A., & Knill, D.C. (2004). Visual feedback control of hand movements. *Journal of Neuroscience, 24*, 3223-3234.

Saunders, J.A., & Knill, D.C. (2005). Humans use continuous visual feedback from the hand to control both the direction and distance of pointing movements. *Experimental Brain Research, 162,* 458-473.

Shabbott, B.A., & Sainburg, R.L. (2009). On-line corrections for visuomotor errors. *Experimental Brain Research, 195,* 59-72.

Van beers, R.J., Haggard, P., & Wolpert, D.M. (2004). The role of execution noise in movement variability. *Journal of Neurophysiology, 91*, 1050-1063.

Vesia, M., Yan, X., Henriques, D.Y., Sergio, L.E., & Crawford, J.D. (2008). Transcranial magnetic stimulation over human dorsal–lateral posterior parietal cortex disrupts integration of hand position signals into the reach plan. *Journal of Neurophysiology, 100,* 2005-2014.

Veyrat-Masson, M., Brière, J., & Proteau, L. (2010). Automaticity of online control processes in manual aiming. *Journal of Vision, 10(14):27,* 1–14.

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Figures

Figure 1. A: View of the experimental set-up. B: The manipulandum and the location of the target in relation to the participant. A cursor jump (red) translated the trajectory of the cursor by 15 mm to the right. C: Target location in relation to the target. The dashed lines indicate potential endpoint errors for the no-jump and jump endpoint locations. The full line illustrates the frontal correction for the single jump.

Figure 2. Cursor trajectory for cursor-jump (red lines) and no-jump (black line) trials averaged across all participants for the three conditions of cursor visibility. The target is illustrated by a round black marker at the top of the illustration. Movement endpoints are illustrated by round open markers (red: cursor trials, black: no jump trials).

Figure 3. Stylus/hand trajectories for the cursor-jump (dashed lines) and no-jump (full line) trials for the three conditions of cursor visibility. Data from one randomly picked participant.

Figure 4. Mean frontal stylus endpoint location (top) and variability (bottom) for the cursor-jump (filled) and no-jump (unfilled) trials for the three conditions of cursor visibility.

Figure 1

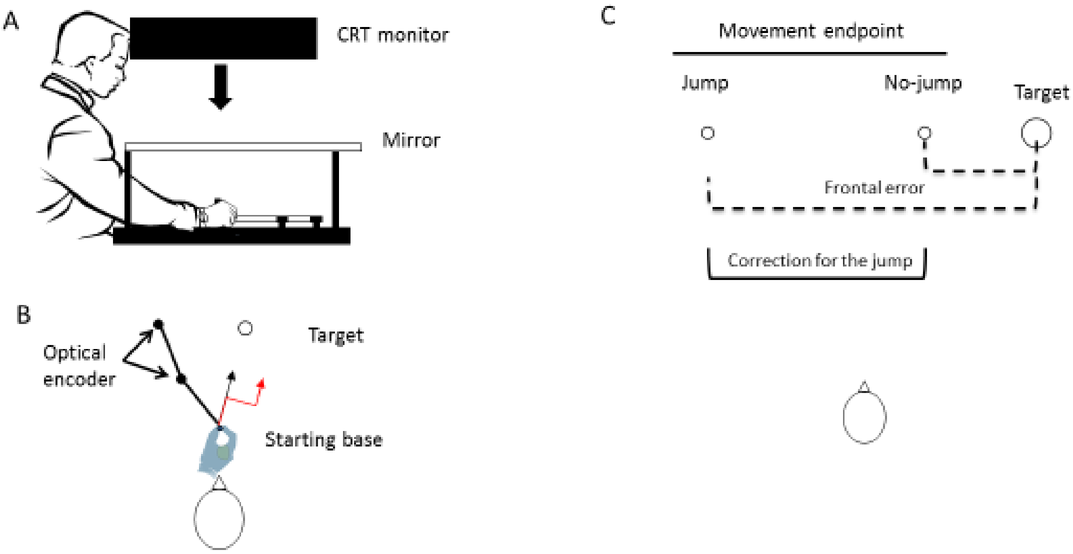

A
CRT monitor
Mirror
B
Optical encoder
Target
Starting base
C
Movement endpoint
Jump
No-jump
Target
Frontal error
Correction for the jump

Figure 2

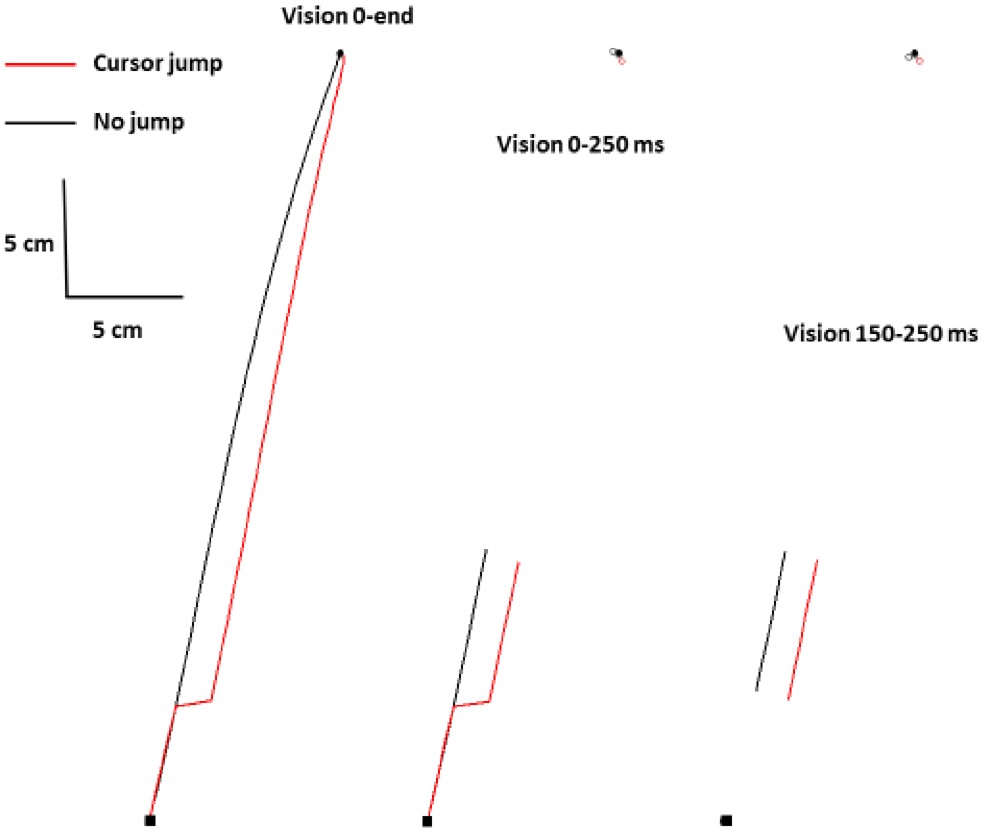

Vision 0-end
Cursor jump
No jump
5 cm
5 cm
Vision 0-250 ms
Vision 150-250 ms

Figure 3

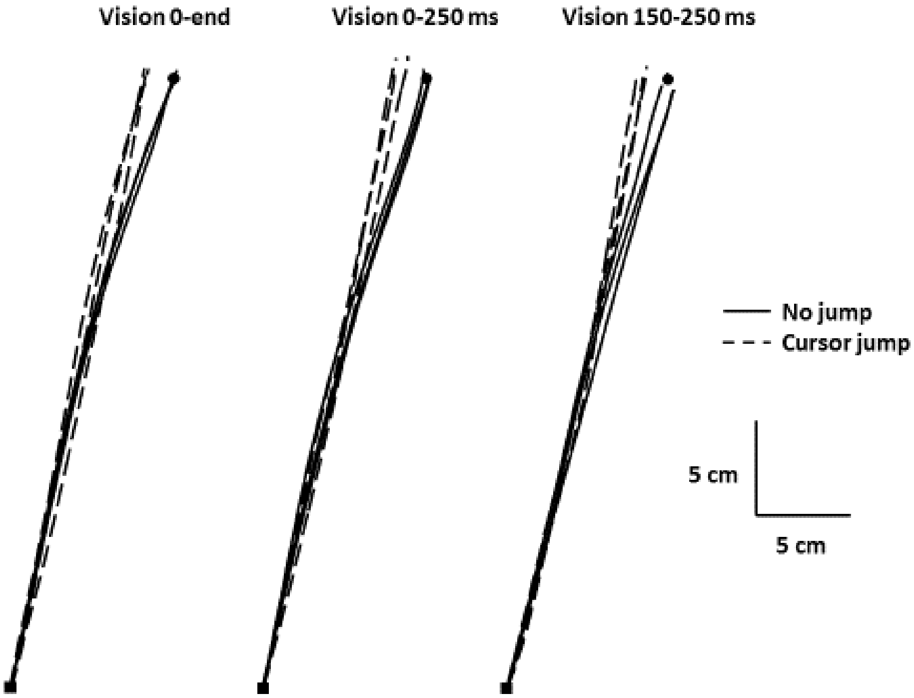
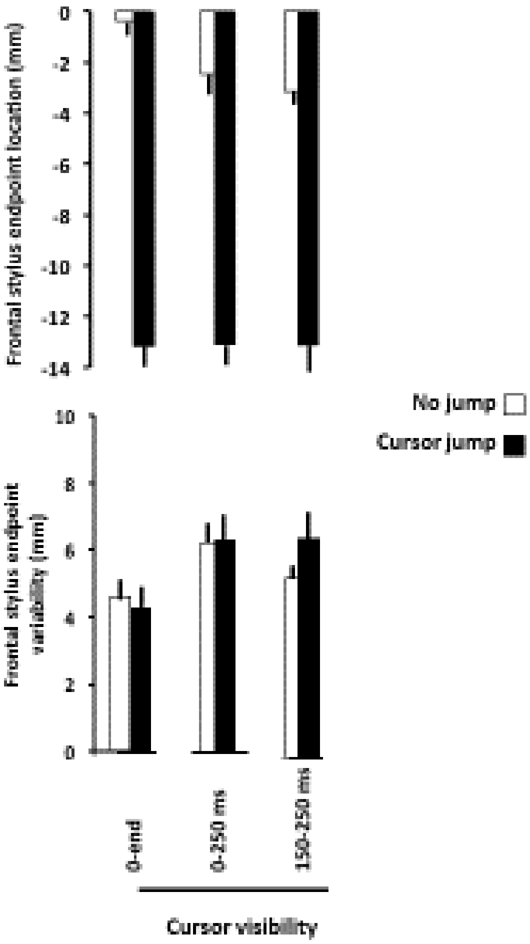

Vision 0-end
Vision 0-250 ms
Vision 150-250 ms
No jump
Cursor jump
5 cm
5 cm

Figure 4


Frontal stylus endpoint location (mm)
0
-2
-4
-6
-8
-10
-12
-14
Frontal stylus endpoint variability (mm)
10
8
6
4
2
0
0-end
0-250 ms
150-250 ms
Cursor visibility
No jump ☐
Cursor jump ■

Chapitre 7 : Discussion générale

L'objectif général de cette thèse était de déterminer le rôle des afférences visuelles dans le contrôle en temps réel du mouvement dans une tâche d'atteinte manuelle. Les caractéristiques des corrections qui peuvent être apportées en cours de mouvement ont été au centre des analyses. Il s'agissait de déterminer la nature, la précision et la latence de ces corrections en plus de la charge attentionnelle requise par ces dernières. Pour atteindre nos objectifs, nous avons conçu différentes manipulations expérimentales impliquant des perturbations qui modifiaient la trajectoire des mouvements.

1-État de la question

1.1 Sur le traitement continu de l'informations visuelle

Les dernières années ont été caractérisées par plusieurs découvertes concernant l'importance des afférences visuelles pour le contrôle du mouvement. D'abord, les études ayant utilisé un paradigme de saut de curseur (Sarlegna et al., 2003 ; Sarlegna et al., 2004 ; Saunders et Knill, 2003, 2004, 2005 ; Proteau et al., 2009) ont permis d'établir que la vision pouvait être utilisée rapidement pour moduler la première impulsion d'un mouvement d'atteinte. Concrètement, alors que la main se dirige vers une cible, le système nerveux central continue de traiter l'information visuelle relative à ce déplacement; cette information est utilisée pour détecter une erreur de planification et/ou d'exécution, et planifier puis réaliser une correction appropriée. Ces modulations se font de façon fluide et progressive. De surcroît, Saunders et Knill (2003) ont montré que la latence requise pour amorcer une correction est indépendante de l'endroit où survient la perturbation. Ceci supportait la proposition qui voulait que l'information visuelle relative à la main soit traitée de façon continue tout au long de la trajectoire d'un mouvement d'atteinte.

Plus tard, d'autres auteurs ont poussé l'idée plus loin et ont tenté d'évaluer la robustesse de ce processus de détection/correction des erreurs. Pour ce faire, lorsqu'une perturbation survenait, Franklin et Wolpert (2008) ont demandé aux participants de réagir dans la direction opposée à une correction efficace. Les participants devaient donc ajuster leur mouvement dans la même direction que le saut de curseur. Les résultats montrent que les participants amorçaient d'abord une réponse de correction dans la direction opposée au saut de curseur avant de produire une réponse qui correspondait aux instructions qu'ils avaient reçues. Ainsi, il semble que cette réaction naturelle à corriger un mouvement dans la direction inverse à l'erreur détectée soit difficile à inhiber. Ces auteurs évoquent même que cette réponse serait de nature réflexive. Dans le même sens, d'autres chercheurs ont montré que ces corrections surviennent dès le premier essai perturbé et, par conséquent, ne sont pas la conséquence d'un apprentissage quelconque (Proteau et al., 2009).

1.2 Sur la fréquence d'échantillonnage

Au cours des dernières années, certains auteurs ont voulu déterminer la quantité minimale d'information visuelle nécessaire pour le système nerveux central afin de détecter et de corriger un mouvement imprécis. Pour ce faire, le curseur/stylet déplacé par le participant devenait invisible après un certain délai suivant l'amorce du mouvement. En modifiant la période de visibilité du curseur, ces auteurs ont proposé des durées minimales de visibilité du curseur/stylet qui sont passées de 250 ms, (Woodworth, 1899) à 150 ms (Zelaznik et al., 1983) puis à aussi peu que 100 ms (Carlton, 1992 ; Elliott et al., 2001).

D’autres auteurs ont plutôt utilisé un protocole de saut de curseur. Ainsi, les essais pour lesquels un saut de curseur avait pris place pouvaient se dérouler alors que la trajectoire du mouvement demeurait permise ou dans un contexte où le curseur ne demeurait visible que pour une courte période de temps suite au saut de curseur. Proteau et al., (2009) ont démontré que si le curseur demeurait visible pour aussi peu que 60 ms suite à la perturbation visuelle, les mouvements de correction étaient aussi précis que si le curseur était visible jusqu’à la fin du mouvement. Les corrections observées étaient de l’ordre de 70-80% de la perturbation imposée. Une période de visibilité plus brève serait-elle suffisante pour détecter une erreur et planifier une réponse de correction efficace?

Peu importe la réponse à la question précédente, quelle est la nature de l’information visuelle utilisée pour planifier et réaliser une correction efficace? Ce pourrait être la dernière position perçue du curseur qui est utilisée par le processus de détection et de correction de l’erreur (Shabbott et Sainburg, 2009). Cependant, considérant le bruit inhérent dans chacun des systèmes mis en jeu, la dernière position perçue ne représenterait qu’un estimé très approximatif de la position réelle du curseur. Un estimé basé sur une plus longue période d’échantillonnage serait susceptible de donner un estimé plus précis de la position réelle du curseur.

1.3 Sur la fonctionnalité des corrections

Les auteurs (Franklin et Wolpert, 2008 ; Franklin et al., 2014 ; Franklin et al., 2012 ; Dimitriou et al., 2013) comparant la correction de mouvements d’atteinte manuelle suite à un saut de curseur à des activités de type réflexe semblent oublier la fluidité du mouvement chez l’être humain. À première vue, il semblerait inefficace que le système nerveux central tente de corriger chacune des déviations perçues dans nos mouvements. Un système de correction plus efficace permettrait de ne corriger que les mouvements qui doivent être corrigées pour que l'objectif visé soit atteint; on parle ici de correction fonctionnelle. Todorov et Jordan (2002 ; voir aussi Sarlegna et Blouin, 2010) suggèrent que la correction se fait en deux phases distinctes : l'amorce de la correction serait automatique alors que son exécution serait, elle, plus fonctionnelle. Ainsi, le gain de cette correction (i.e., la vitesse d'exécution de la correction) serait modulable en fonction de la situation. Les travaux de Knill et al. (2011) ont supporté cette interprétation puisqu'on y remarqua que la grandeur d'une correction amorcée pour contrecarrer un saut de curseur était calibrée en fonction de la grandeur de la cible. Dans cette perspective, une correction pour un saut de curseur survient-elle dès que le saut de cible est détecté ou ne survient-elle que si la perturbation empêche l'individu d'atteindre l'objectif désiré?

1.4 Sur l'apport de l'élément dynamique du saut

Les auteurs cités précédemment ont utilisé différentes méthodes pour déplacer le curseur en cours de mouvement. Certains l'ont fait de façon graduelle sur une brève période de temps (Saunders et Knill, 2003, 2004, 2005) alors que d'autres ont utilisé des perturbations « instantanées » (Sarlegna et al., 2003 ; Sarlegna et al., 2004 ; Proteau et al., 2009). Les résultats de ces deux protocoles, et plus particulièrement la qualité de la correction apportée suite au saut de curseur, n'ont jamais été contrastés. L'information visuelle dynamique relative au saut de curseur permet-elle de détecter et de jauger plus facilement la perturbation que lorsque cette information n'est pas visible ou survient graduellement?

2- Apports principaux de cette thèse

2.1 Sur le traitement continu de l'information visuelle

En premier lieu, nous avons voulu déterminer si la planification et l'amorce d'une correction pour un saut de curseur empêche et/ou perturbe le traitement continu des afférences visuelles. Certains avaient proposé que le traitement des informations visuelles se faisait de façon continue tout au long du mouvement (Saunders et Knill, 2003, 2005) et que ces corrections ne nécessitaient que très peu (ou pas) d'attention (Castiello, et al., 1991 ; Day et Lyon, 2000 ; Franklin et Wolpert, 2008 ; Jonhson et al., 2002 ; Pisella et al. 2000 ; Proteau et al., 2009 ; Reichenbach et al., 2014). Pour mieux évaluer notre question d'intérêt, nous avons déterminé si la correction à un deuxième saut de curseur survenant temporellement près de l'amorce d'une correction à un premier saut de curseur était aussi efficace (précision et latence des corrections) que dans un contexte où un seul saut de curseur prenait place. Nos données ont montré que le traitement des deux sauts de curseur n'entrait d'aucune façon en conflit l'un avec l'autre et que, ni la précision spatiale, ni les délais requis pour amorcer les corrections n'étaient affectés (Brière et Proteau, 2011). Ces résultats supportent l'idée d'un contrôle continu du mouvement sur la base des afférences visuelles et démontrent aussi l'impressionnante efficacité du système nerveux central pour s'assurer de la précision du mouvement. Qui plus est, non seulement le processus de captation de l'information suit-il son cours lors de la planification/l'amorce d'une correction mais la réalisation de la correction n'est pas affectée par la nouvelle information associée à un deuxième saut de curseur. Cela a été particulièrement bien démontré par nos observations qui indiquent que la correction au deuxième saut de curseur est modulée en fonction de la grandeur de cette deuxième perturbation (annule, augmente ou diminue la correction requise par le premier saut de curseur; Brière et Proteau, soumis). Ces dernières observations confortent, elles aussi, l'idée que la position perçue de la main est continuellement rafraîchie sur la base de l'information visuelle disponible en cours de mouvement.

2.2 Sur la fréquence d'échantillonnage

Quelle est la fréquence du rafraîchissement de la position perçue de la main évoquée au paragraphe précédent? Pour répondre à cette question, nous avons repris le protocole expérimental utilisé par Proteau et al. (2009). Dans ce protocole, la période de visibilité du curseur est manipulée suite à un saut de curseur. Nous avons démontré que seulement 16 ms de visibilité du curseur étaient suffisantes pour entraîner une correction du mouvement dans la direction opposée au saut de curseur. Des corrections plus importantes étaient observées lorsque la durée de visibilité du curseur augmentait à 40 ms, puis à 64 ms. Dans ce dernier cas, les corrections observées étaient presque identiques à celles observées lorsque le curseur demeurait visible tout au long de sa trajectoire.

Nous avons démontré que les corrections plus grandes observées lorsque la période de visibilité « post-saut » du curseur augmentait n'indiquaient pas des corrections plus fréquentes. Plutôt, la grandeur de la correction de chaque essai augmentait avec une augmentation de la période de visibilité post-saut. Nos résultats suggéraient que la position perçue du curseur pourrait reposer sur le résultat d'intégration spatiale de sa position réelle au cours d'une période temporelle fixe.

En combinant les résultats des différents temps d'exposition utilisés, nous en sommes venus à la conclusion que la position perçue du curseur correspondait à la position moyenne réelle du curseur, intégrée sur une période de 70 ms. Cette intégration a pour avantage de réduire le bruit neuronal associé à la perception immédiate de la position du curseur et, ainsi, d'amorcer des corrections inappropriées résultant d'une mauvaise perception ponctuelle.

Intégrée à un modèle interne cinématique, cette information agglomérée serait considérée comme « véritable » par le système. Elle permettrait de prédire où le curseur se dirige et de déterminer si une correction doit être apportée à son déplacement afin de le replacer sur la bonne trajectoire. À notre connaissance, nous sommes les premiers à proposer ce genre de conclusion. Notre proposition semble s'opposer à une proposition antérieure de Shabbott et Sainburg (2009) qui supputaient que l'amplitude des corrections était basée sur le dernier point perçu. Dans cette étude, les participants devaient pointer une cible située à 20 cm. Pour environ 25% des essais, les participants étaient exposés à un ou plusieurs types de perturbation qui impliquaient soit une rotation de la trajectoire du curseur et/ou l'occlusion du curseur en cours de route. En variant les angles de rotation et les moments d'occlusion du curseur, les auteurs obtenaient différentes distances entre la main et le curseur au moment de son occlusion (distance CF). Les données démontrent que l'amplitude de la correction finale des participants n'était pas influencée par la grandeur de la rotation ni par le moment d'occlusion mais seulement par la distance CF. Ils concluent alors que les participants se basaient seulement sur la différence entre le dernier point perçu et la position de la cible pour planifier et amorcer une correction efficace. Or, dans cette étude, les périodes d'exposition dépassaient toujours 125ms. Nos données montrent que ce délai est suffisant afin d'obtenir une information véritable pour le SNC, ce qui explique l'apparent conflit entre notre position et celle de Shabbott et Sainburg.

En revanche, nous n'avons pas la prétention d'avoir trouvé une règle universelle expliquant précisément comment l'information visuelle est captée et traitée. La période d'intégration de 70 ms que nous avons observée est probablement modulable par le SNC en fonction de la tâche. Par exemple, pour une tâche où l'information visuelle serait floue et difficile à cerner, il serait plus efficace d'intégrer l'information spatiale sur une plus longue durée. Dans la même veine, pour des mouvements très courts, il pourrait être avantageux de favoriser une période d'intégration plus courte afin de permettre la planification et l'amorce d'une correction. Un compromis vitesse/précision prendrait alors place (Fitts, 1954 ; Plamondon et Alimi, 1997). Finalement, le poids relatif donné aux informations spatiales détectées au début de la période d'intégration pourraient fort bien être moindre que celui donné aux informations disponibles en fin de période d'intégration.

En résumé, nos résultats suggèrent que la position perçue du curseur ne correspond pas à la dernière position visible de ce dernier. La position perçue du curseur correspondrait plutôt à la position moyenne perçue du curseur au cours d'une fenêtre temporelle modulable en fonction des contraintes de la tâche.

2.3 Sur la fonctionnalité de ces corrections

Todorov et Jordan (2002) proposaient un mode de contrôle à intervention minimale. Cette position semblait difficile à réconcilier avec les résultats de nombreuses études (Franklin et al., 2014 ; Franklin et al., 2012 ; Dimitriou et al., 2013) qui proposent que la correction pour un saut de cible ou pour un saut de curseur s'apparente à un réflexe (Franklin et Wolpert, 2008). Les résultats d'études récentes dont ceux de la présente thèse permettent de réconcilier ces deux propositions. Nous et d'autres (Dimitriou et al., 2013 ; Franklin et Wolpert, 2008 ; Knill et al., 2011 ; Nashed et al., 2012 ; Veyrat-Masson et al., 2010) avons montré que la correction pour un saut de cible ou de curseur s'effectue en deux phases : l'amorce suivie du gain de la correction. L'amorce de la correction s'apparenterait à un réflexe tandis que le gain de la correction dépendrait des caractéristiques de la tâche, tel que le but à atteindre. Dans cette thèse, nous démontrons que l'amorce de la correction est liée à une déviation de la trajectoire planifiée/prévue du mouvement plutôt qu'à une comparaison entre la position de la cible et celle du curseur. Dès que le SNC détecte une différence entre la position perçue de la main et la position prévue de celle-ci, une correction est automatiquement amorcée de sorte à amorcer la correction de la trajectoire de la main, peu importe les dimensions de la cible visée (Veyrat-Masson et al., 2010) ou les consignes de l'expérimentateur (Day and Lyon 2000; Franklin et Wolpert 2008 ; Johnson et al., 2002 ; Pisella et al. 2000). La demande attentionnelle de cette phase de correction est faible mais l'amorce de la correction est stéréotypée comme le démontrent les résultats des travaux dans lesquels on demandait, sans succès, aux participants d'amorcer une correction dans une direction opposée à une correction efficace (Day et Lyon 2000 ; Franklin et Wolpert 2008 ; Johnson et al., 2002).

Sans être nécessairement sous un contrôle conscient du SNC, la phase d'exécution de la correction a un gain. Dans les travaux de la présente thèse, ce gain n'était pas influencé par la précision terminale exigée par la tâche. Toutefois, ce gain était fonction de l'écart induit par la perturbation entre la trajectoire du curseur et l'objectif visée. Nous avons démontré que la correction était basée sur une position perçue du curseur qui semblait avoir été intégrée sur une période de 70 ms, ce qui supporte l'idée d'un mode d'intervention minimal avancée par Todorov et Jordan (2002).

2.4 Sur l'apport de l'élément dynamique du saut

Les résultats de la présente thèse indiquent que l'information visuelle relative au saut de curseur ne modifiait en rien la précision des mécanismes de correction mis en jeu pour contrecarrer la perturbation. Ces résultats s'accommodent bien avec notre proposition que la position perçue du curseur fait suite à un processus d'intégration. En effet, si la position perçue du curseur est sa position moyenne au cours des 70 dernières millisecondes, la présence d'un saut dans cette période ne modifie pas de façon marquée la position perçue du curseur et, de ce fait, la qualité de la correction.

Toutefois, nous avons observé une latence de correction plus grande pour les essais déviés dans un contexte où les participants ne pouvaient pas voir l'information dynamique relative au saut du curseur. D'une part, cela pourrait indiquer que le saut de curseur favorise la détection d'une erreur. D'autre part, il est aussi possible que la période d'occlusion pendant laquelle le saut de curseur prenait place, pour la condition sans vision dynamique du saut, engendrait de l'incertitude quant à la position réelle de la main et, de ce fait, augmentait la latence de la correction. Des travaux supplémentaires seront nécessaires pour répondre à cette question.

Conclusion

En conclusion, le traitement des afférences visuelles se fait de façon continue lors d'un geste d'atteinte manuelle. Le processus de détection d'une déviation de la trajectoire prévue et l'amorce d'une correction sont rapides et de nature quasi-réflexe. Cette première phase évalue la différence entre la trajectoire prévue et la trajectoire voulue, puis planifie et amorce une correction pour corriger cet écart. Suite à cette première phase, un processus de correction adaptatif est mis en place. Ce processus de correction adaptatif évalue l'écart créé entre la position du curseur et la position de la cible. La position perçue du curseur ne semble pas correspondre à sa position immédiate mais plutôt à une position moyenne déterminée sur base temporelle très courte; 70 ms dans la présente thèse. Cette intégration a l'avantage de ne pas engendrer de correction inopportune qui pourrait résulter du bruit neuronal (un « glitch ») associé à la position perçue du curseur.

Bibliographie

Abahnini K, Proteau L (1999) The role of peripheral and central visual information for the directional control of manual aiming movements. Can J Exp Psychol 53:160-175

Abahnini K, Proteau L, Temprado JJ (1997) Evidence supporting the importance of peripheral visual information for the directional control of aiming movement. J Motor Behav 29:230–242

Balslev D, Miall RC, Cole J (2007) Proprioceptive deafferentation slows down the processing of visual hand feedback. J Vis 7:1-7

Bard C, Hay L, Fleury M (1985) Role of peripheral vision in the directional control of rapid aiming movements. Can J Psychol 39:151-161

Bard C, Paillard J, Fleury M, Hay L, Larue J (1990) Positional versus directional control loops in visuomotor pointing. European Journal of Cognition and Psychology 10:145-156

Bédard P, Proteau L (2004) On-line vs. off-line utilization of peripheral visual afferent information to ensure spatial accuracy of goal-directed movements. Exp Brain Res 158:75-85

Bédard P, Proteau L (2003) On the role of peripheral visual afferent information for the control of rapid video-aiming movements. Acta Psychol 113:99-117

Bekkering H, Adam JJ, Aarssen A, Kingma H, Whiting HTA (1995) Interference between saccadic eye and goal-directed hand movements. Exp Brain Res 106:475-484

Bridgeman B, Lewis S, Heit G, Nagle M (1979) Relation between cognitive and motor-oriented systems of visual position perception. J Exp Psychol Hum Percept Perform 5:692–700

Brière J, Proteau L (2011) Automatic movement error detection and correction processes in reaching movements. Exp Brain Res 208:39-50

Brière J, Proteau L (2016) Goal directed movements are continuously visually monitored: modulation of movement execution for successive cursor jumps. Soumis à Psychol Res

Carlton LG (1981) Processing visual feedback information for movement control. J Exp Psychol Human 7:1019–1030

Carlton LG (1992) Visual processing time and the control of movement. Adv Psychol 85:3-31

Castiello U, Paulignan Y, Jeannerod M (1991) Temporal dissociation of motor responses and subjective awareness: A study in normal subjects. Brain 114: 2639–2655

Chua R, Elliott D (1993) Visual regulation of manual aiming. Hum Movement Sci 14:365-401

Carson RG, Chua R, Elliott D, Goodman D (1990) The contribution of vision to asymmetries in manual aiming. Neuropsychologia 28:1215-1220

Crossman ER, Goodeve PJ (1983) Feedback control of hand-movement and Fitts' Law. QJ Exp Psychol A 35:251-278

Day BL, Lyon IN (2000) Voluntary modification of automatic arm movements evoked by motion of a visual target. Exp Brain Res 130:159–168

Desmurget M, Epstein CM, Turner RS, Prablanc C, Alexander GE, Grafton ST (1999) Role of posterior parietal cortex in updating reaching movements to a visual target. Nat Neurosci 2:563–567

Desmurget M, Grafton S (2000) Foward modeling allows feedback control for fast reaching movements. Trends Cogn Sci 4:423-431

Desmurget M, Pélisson D, Rossetti Y, Prablanc C (1998) From eye to hand: planning goal-directed movements. Neurosci Biobehav Rev 22:761-788

Dimitriou M, Wolpert DM, Franklin DW (2013) The temporal evolution of feedback gains rapidly update to task demands. J Neurosci 32:10898 –10909

Elliott D, Garson RG, Goodman D, Chua R (1991) Discrete vs. continuous visual control of manual aiming. Hum Movement Sci 10:393-418

Elliott D, Helsen WF, Chua R. (2001) A century later: Woodworth's (1899) twocomponent model of goal-directed aiming. Psychol Bull 127:342-357

Fitts PM (1954) The information capacity of the human motor system in controlling the amplitude of movement. J Exp Psychol 47:381–91

Fisk JD, Goodale MA (1985) The organization of eye and limb movements during unrestricted reaching to targets in contralateral and ipsilateral visual space. Exp Brain Res 60:159-178

Fox MD, Snyder AZ, Vincent JL, Raichle ME (2007) Intrinsic fluctuations within cortical systems account for intertrial variability in human behaviour. Neuron 56:171-184

Franklin DW, Wolpert DM (2008) Specificity of reflex adaptation for task-relevant variability. J Neurosci 28:14165–14175

Franklin S, Franklin DW, Wolpert DM (2014) Fractionation of the visuomotor feedback response to directions of movement and perturbation. J Neurophysiol 112:2218–2233

Franklin S, Wolpert DM, Franklin DW (2012) Visuomotor feedback gains upregulate during the learning of novel dynamics. J Neurophysiol 108:467–478

Gaveau V, Pisella L, Priot A-E, Fukui T, Rossetti Y, Pélisson D, Prablanc C (2014) Automatic online control of motor adjustments in reaching and grasping. Neuropsychologia 55:25-44

Goodale MA, Pelisson D, Prablanc C (1986) Large adjustments in visually guided reaching do not depend on vision of the hand or perception of target displacement. Nature 320:748-750

Gritsenko V, Kalaska JF (2010) Rapid online correction is selectively suppressed during movement with a visuomotor transformation. J Neuphysiol 104:3084-3104

Gritsenko V, Yakovenko S, Kalaska JF (2009) Integration of predictive feedforward and sensory feedback signals for online control of visually guided movement. J Neurophysiol 102:914-930

Helsen WF, Elliott D, Starkes JL, Ricker KL (2000) Coupling of eye, finger, elbow, and shoulder movements during manual aiming. J Motor Behav 32:241-248

Helsen WF, Starkes JL, Buekers MJ (1997) Effects of target eccentricity on temporal costs of point of gaze and the hand in aiming. Motor Control 1:161-177

Henriques DYP, Crawford JD (2000) Direction-dependent distortions of retinocentric space in the visuomotor transformation for pointing. Exp Brain Res 132:179-194

Henriques DYP, Medendorp MP, Gielen CCAM, Crawford JD (2003) Geometric computations underlying eye-hand coordination: orientations of the two eyes and the head. Exp Brain Res 152:70-78

Jeannerod M (1988) The neural and behavioural organization of goal directed movements. Clarendon Press, Oxford

Johnson H, van Beers RJ, Haggard P (2002) Action and awareness in pointing tasks. Exp Brain Res 146:451–459

Khan MA, Lawrence GP, Franks IM, Buckolz E (2004) The utilization of visual feedback from peripheral and central vision in the control of direction. Exp Brain Res 158:241-251

Khan MA, Elliott D, Coull J, Chua R, Lyons J. (2002). Optimal control strategies under different feedback schedules: kinematic evidence. J Motor Behav 34:45-57

Khan MA, Franks IM (2003) Online versus offline processing of visual feedback in the production of component submovements. J Motor Behav 35:285-295

Khan MA, Franks IM (2000) The effect of practice on component submovements is dependent on the availability of visual feedback. J Motor Behav 32:227-240

Khan MA, Lawrence GP, Fourkas A, Franks IM, Elliott D, Pembroke S (2003) Online versus offline processing of visual feedback in the control of movement amplitude. Acta Psychol 113:83-97

Keele SW (1968) Movement control in skilled motor performance. Psychol Bull 70:387-403

Knill DC, Bondada A, Chhabra M (2011) Flexible, task-dependent use of sensory feedback to control hand movements. J Neurosci 31:1219-1237

Land MF, Hayhoe M (2001) In what ways do eye movements contribute to everyday activities? Vision Res 41:3559–3565

Lawrence GL, Khan MA, Buckolz E, Oldham ARH (2006) The contribution of peripheral and central vision in the control of movement amplitude. Hum Movement Sci 25:326-338

Lhuisset L, Proteau L (2002) Developmental aspects of the control of manual aiming movements in aligned and non-aligned visual displays. Exp Brain Res 146:293-306

Lhuisset L, Proteau L (2004) Planning and control of straight-ahead and angled planar movements in adults and young children. Can J Exp Psychol 58:245-258

Mackrous I, Proteau L (2007) Specifiity of practice results from diverences in movement planning strategies. Exp Brain Res 183:181–193

Magescas F, Urquizar C, Prablanc C (2009) Two modes of error processing in reaching. Exp Brain Res 193:337–350

Messier J, Kalaska JF (1999) Comparison of variability of initial kinematics and endpoints of reaching movements. Exp Brain Res 125:139–152

Meyer DE, Abrams RA, Kornblum S, Wright CE, Smith JE (1988) Optimality in human motor performance: ideal control of rapid aimed movements. Psychol Rev 95:340-370

Morasso P (1981) Spatial control of arm movements. Exp Brain Res 42:223-227

Nakano E, Imamizu H, Osu R, Uno Y, Gomi H, Yoshioka T, Kawato M (1999) Quantitative examinations of internal representations for arm trajectory planning: minimum commanded torque change model. J Neurophysiol 81:2140-55

Nashed JY, Crevecoeur F, Scott SH (2012) Influence of the behavioral goal and environmental obstacles on rapid feedback responses. J Neurophysiol 108:999–1009

Neggers SFW, Bekkering H (2002) Coordinated control of eye and hand movements in dynamic reaching. Hum Movement Sci 21:37-64

Neggers SFW, Bekkering H (2001) Gaze anchoring to a pointing target is present during the entire pointing movement and is driven by a non-visual signal. J Neurophysiol 86:961-970

Neggers SFW, Bekkering H (1999) Integration of visual and somatosensory target information in goal-directed eye and arm movements. Exp Brain Res 125:97-107

Neggers SFW, Bekkering H (2000) Ocular gaze is anchored to the target of an ongoing pointing movement. J Neurophysiol 83:639-651

Nijhof EJ (2003) On-line trajectory modifications of planar, goal-directed arm movements. Hum Movement Sci 22:13-36

Osu R, Morishige K, Nakanishi J, Miyamoto H, Kawato M (2015) Practice reduces task relevant variance modulation and forms nominal trajectory. Scientific Reports 5:17659. DOI: 10.1038/srep17659

Paillard J, Amblard B (1985) Static versus kinetic visual cues for the processing of spatial relationships. Brain Mechanisms and Spatial Vision 21:299-330

Pelisson D, Prablanc C, Goodale MA, Jeannerod M (1986) Visual control of reaching movements without vision of the limb. II. Evidence of fast unconscious processes correcting the trajectory of the hand to the final position of a double-step stimulus. Exp Brain Res 62:303–311

Pisella L, Gréa H, Tilikete C, Vighetto A, Desmurget M, Rode G, Boisson D, Rossetti Y (2000) An ‘automatic pilot’ for the hand in human posterior parietal cortex: toward reinterpreting optic ataxia. Nat Neurosci 3:729–736

Plamondon R, Alimi AM (1997) Speed/accuracy trade-offs in target-directed movements. Behav Brain Sci 20:279-349

Prablanc C, Echallier JE, Jeannerod M, Komilis E (1979) Optimal response of eye and hand motor systems in pointing at a visual target. II. Static and dynamic visual cues in the control of hand movement. Biol Cybern 35:183-187

Prablanc C, Echallier JF, Komilis E, Jeannerod M (1979) Optimal response of eye and hand motor systems in pointing at a visual target. I. Spatio-temporal characteristics of eye and hand movements and their relationships when varying the amount of visual information. Biol Cybern 35:113-124

Prablanc C, Martin O (1992) Automatic control during hand reaching at undetected twodimensional target displacements. J Neurophysiol 67:455-469

Proteau L (1992) On the specificity of learning and the role of visual information for movement control. In L Proteau & D Elliott (Eds.) Vision and motor control 67-103 Amsterdam: North Holland

Proteau L (2005) Visual afferent information dominates other sources of afferent information during mixed practice of a video-aiming task. Exp Brain Res 161:441-456

Proteau L, Isabelle G (2002) On the role of visual afferent information for the control of aiming movements toward targets of different sizes. J Motor Behav 34:367–384

Proteau L, Roujoula A, Messier J (2009) Evidence for continuous processing of visual information in a manual video-aiming task. J Motor Behav 41:219-231

Reichenbach A, Franklin DW, Zatka-Haas P, Diedrichsen J (2014) A dedicated binding mechanism for the visual control of movement. Curr Biol 24:780-785

Rizzo M, Darling W (1997) Reaching with cerebral tunnel vision. Neuropsychologia 35:53-63

Robin C, Toussaint L, Blandin Y, Proteau L (2005) Specificity of learning in a video-aiming task: Modifying the salience of dynamic visual cues. J Motor Behav 37:367–377

Rossetti Y, Koga K, Mano T (1993) Prismatic displacement of vision induces transient changes in the timing of eye-hand coordination. Percept Psychophys 54:355-364

Sailer U, Eggert T, Ditterich J, Straube A (2000) Spatial and temporal aspects of eye-hand coordination across different tasks. Exp Brain Res 134:163-173

Sarlegna F, Blouin J, Bresciani JP, Bourdin C, Vercher JL, Gauthier GM (2003) Target and hand position information in the online control of goal-directed arm movements. Exp Brain Res 151:524–535

Sarlegna F, Blouin J, Vercher JL, Bresciani JP, Bourdin C, Gauthier GM (2004) Online control of the direction of rapid reaching movements. Exp Brain Res 157:468–471

Sarlegna F, Blouin J (2010) Visual guidance of arm reaching: online adjustments of movement direction are impaired by amplitude control. J Vis 10:1-12

Sarlegna F, Blouin J, Bresciani JP, Bourdin C, Vercher JL, Gauthier GM (2003) Target and hand position information in the online control of goal-directed arm movements. Exp Brain Res 151: 524–535

Sarlegna F, Blouin J, Vercher JL, Bresciani JP, Bourdin C, Gauthier GM (2004) Online control of the direction of rapid reaching movements. Exp Brain Res 157:468–471

Saunders JA, Knill DC (2005) Humans use continuous visual feedback from the hand to control both the direction and distance of pointing movements. Exp Brain Res 162:458–473

Saunders JA, Knill DC (2003) Humans use continuous visual feedback from the hand to control fast reaching movements. Exp Brain Res 152:341–352

Saunders JA, Knill DC (2004) Visual feedback control of hand movements. J Neurosci 24:3223–3234

Schmidt RA, Zelaznik H, Hawkins B, Frank JS, Quinn JT Jr (1979) Motor-output variability: A theory for the accuracy of rapid motor acts. Psychol Rev 86:415-451

Shabbott BA, Sainburg RL (2009) On-line corrections for visuomotor errors. Exp Brain Res 195:59–72

Soechting JF, Lacquaniti F (1983) Modification of trajectory of a pointing movement in response to a change in target location. J Neurophysiol 49:548-564

Soucy M-C, Proteau L (2001) Development of multiple movement representations with practice: Specificity vs. flexibility. J Motor Behav 33:243-254

Spijkers WAC, Lochner P (1994) Partial visual feedback and spatial end-point accuracy of discrete aiming movements. J Motor Behav 26:283-295

Temprado JJ, Vieilledent S, Proteau L (1996) Afferent information for motor control: the role of visual information in different portions of the movement. J Motor Behav 28:280-287

Todorov E, Jordan, MI (2002) Optimal feedback control as a theory of motor coordination. Nat Neurosci 5:1226-1235

Uno Y, Kawato M, Suzuki R (1989) Formation and control of optimal trajectory in human multijoint arm movement. Minimum torque-change model. Biol Cybern 61:89-101

Van beers RJ, Haggard P, Wolpert DM (2004) The role of execution noise in movement variability. J Neurophysiol 91:1050-1063

Vercher JL, Magenes G, Prablanc C, Gauthier GM (1994) Eye-head-hand coordination in pointing at visual targets: spatial and temporal analysis. Exp Brain Res 99:507-523

Woodworth RS (1899) The accuracy of voluntary movement. Psychol Rev Monographs 3:1-119

Zelaznik HZ, Hawkins B, Kisselburgh L (1983) Rapid visual feedback processing in single-aiming movements. J Motor Behav 15:217-236