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Interlimb transfer of sensorimotor adaptation:
predictive factors and underlying processes

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Abstract

Motor adaptation refers to the capacity of our nervous system to produce accurate movements while the properties of our body and our environment continuously change. Interlimb transfer is a process that directly stems from motor adaptation. It occurs when knowledge gained through training with one arm change the performance of the opposite arm movements. Experimentally, participants have to adapt their reaching movements to a force-field and are subsequently checked for transfer to the contralateral untrained arm. Interlimb transfer of adaptation is an intricate and hazy process. Numerous studies have investigated the patterns of transfer and conflicted results have been found. Some studies have reported incomplete transfer and some others no transfer of adaptation at all. As the experimental conditions changes across the studies, the conclusions on the behavioral response and the processes underlying transfer vary.

The attempt of my PhD project was to identify which factors and processes favor interlimb transfer of adaptation and thence may explain the discrepancies found in the literature. The first two experiments aimed at investigated whether paradigmatic or idiosyncratic features would influence the performance in interlimb transfer. We found that the type of sensory feedback during the experiments, that was no vision-proprioception, no proprioception-vision and both vision and proprioception did not affect either adaptation or interlimb transfer of adaptation. In contrast, we identified among a set of variables that individual characteristics, and more precisely the variability of initial direction and the peak velocity during the adaptation phase, as well as the laterality quotient (i.e. the extent of handedness) could account efficiently for the performances in transfer to the opposite arm movement in qualitative and, in a lesser degree, quantitative manners. The third experiment provided some insights on the processes allowing interlimb transfer by using the dual-rate model of adaptation put forth by Smith et al. (2006). We found that interlimb transfer was better characterized by a high contribution of the fast and a low contribution of the slow process. Interestingly, we also found that the subjects with better performance in interlimb transfer were those with better performance in retention of adaptation when tested on the same task 24 hours later.

Our results show that inter-individual differences are not necessarily a source of noise; instead it may be a key factor to consider when studying interlimb transfer of adaptation. Also, the study of the different sub-processes of adaptation seems helpful to understand how interlimb transfer works and how it can be related to other behaviors such as the expression of motor memory. Knowledge about interlimb transfer is not only interesting because it provides evidence about the global and local nature of underlying processes of adaptation, but it is also potentially important in applications regarding functional rehabilitation of patients with movement disorders and sports performance.
Résumé

L’adaptation motrice renvoie à la capacité de notre système nerveux à produire continuellement des mouvements précis et ce malgré le fait que notre environnement ainsi que notre corps puissent être soumis à des modifications. Cette habilité est primordiale pour interagir efficacement avec notre environnement. Elle se caractérise à la fois par des processus cognitifs et des actions motrices. Prenons l’exemple du bowling, lorsqu’on s’apprête à lancer la boule de bowling sur l’allée, si du fait du poids de la boule un déséquilibre se ressent et nuit à notre réussite, nous allons certainement essayer d’adapter notre mouvement à cette contrainte. Par ailleurs, les informations sur la direction de la boule sur l’allée et les quilles restantes nous indiquent quant à la réussite de nos mouvements. Au prochain essai, ces informations pourront être prises en compte afin d’adapter le plus efficacement possible notre lancé. Comme illustré dans cet exemple, l’adaptation va de pair avec la prise en compte des données sensorielles, on la nomme donc adaptation sensorimotrice. Selon Krakauer et Mazzoni (2011), l’adaptation sensorimotrice correspond à une amélioration, à travers la pratique, de la performance motrice guidée par les sens. En l’occurrence dans cette thèse nous allons essentiellement nous attarder sur le rôle de la vision et de la proprioception. La vision est un de nos sens majeurs, celui sur lequel on se repose principalement afin de jauger le monde extérieur, il est ainsi qualifié de sens extéroceptif. La proprioception est quant à elle intéroceptive. C’est le sens, conscient ou non, de la position des différentes parties du corps. Elle fonctionne grâce à de nombreux récepteurs musculaires et ligamentaires appelés des mécanorécepteurs. La combinaison de ces sens à notre système moteur permet d’interpréter les stimuli provenant de notre corps et de notre environnement afin de produire des réponses motrices appropriées (Desmurget et al., 1998; Scott, 2004). L’adaptation motrice est un champ d’étude vaste qui s’applique à différentes propriétés corporelles. Dans le cadre de cette thèse nous avons seulement étudié les mouvements des bras. Ce paradigme est abordé considérablement dans la littérature car il comporte l’avantage de caractériser à la fois des actions motrices de bas et de haut niveaux telles qu’une saisie ou du jonglage, et aussi des gestes indispensables à nos interactions sociales représentant nos attitudes et nos intentions.

Le transfert d’adaptation découle du processus d’adaptation. Spécifiquement, le transfert entre les membres est le processus par lequel les mouvements d’un bras affectent et généralisent aux mouvements du bras opposé. Il existe aussi le transfert intra-membre qui concerne la généralisation de mouvements à des mouvements légèrement différents au sein de ce même bras tels qu’à d’autres cibles, directions ou postures (Cohen, 1967; Shadmehr and Mussa-Ivaldi, 1994). Lorsque nous faisons un mouvement, on s’attend naturellement à ce que l’on ait appris généralise à des mouvements légèrement différents : à d’autres directions ou avec le membre opposé. Cependant nos
mouvements répondent à certaines spécificités musculaires et articulaires qui complexifient le processus de généralisation. En effet, un mouvement du bras vers le haut et vers le bas n’impliquent pas les mêmes activations musculaires et articulaires. Pareillement, un mouvement d’atteinte du bras droit vers la droite de la ligne médiane du corps peut seulement nécessiter une mobilisation de l’épaule tandis qu’un mouvement vers la gauche nécessite une coordination complexe de l’épaule et du coude. Du fait de l’anisotropie des membres (Gordon et al., 1994), il semble difficile de pouvoir généraliser complètement ce que l’on a appris à d’autres mouvements. D’autant plus que cette spécificité peut être requise si par exemple un mouvement du bras n’atteint pas sa cible parce qu’il est faible (ou plus fatigué), plus d’activations musculaires devraient être nécessaires pour ce bras mais pas pour le bras opposé qui est plus fort. Par conséquent un équilibre doit être obtenu entre la spécificité du mouvement et ses capacités de généralisation afin de résoudre efficacement les problématiques d’ordre motrices. L’étude du transfert est particulièrement pertinente car elle révèle ce qui est locale ou globale au sein des processus d’adaptation. En effet, si un mouvement ne peut pas se généraliser au bras opposé, alors le processus adaptatif est dépendant des spécificités musculaires et articulaires du membre. En revanche si la généralisation est dans une certaine mesure possible au bras opposé alors une partie du processus adaptatif est indépendant du membre qui fait le mouvement et résulte d’une représentation plus globale ou abstraite des contraintes environnementales et de la conséquence des mouvements (Mattar and Ostry, 2010).

Expérientalement l’adaptation est testée en imposant durant le mouvement du bras une perturbation visuelle (i.e. déplacement de la vision de la main par rapport à son emplacement réelle) ou mécanique (par un champ de force). Cela provoque une déviation cinématique (i.e. trajectoire) et dans certains cas une modification cinétique (i.e. force) par rapport au mouvement mesuré dans des conditions normales (sans perturbation). Ainsi on mesure les performances à s’adapter à cette perturbation en termes d’amplitudes des erreurs motrices et de vitesse de re-calibration à des performances normales. Lorsque la perturbation est arrêtée, on observe des post-effets qui sont la conséquence du phénomène de compensation développé durant la phase d’adaptation. Le mouvement est alors entraîné dans le sens opposé à la perturbation. Quant au transfert, il est testé après adaptation à une perturbation, et peut être mesuré soit à l’extérieur de la perturbation caractérisant ainsi des post-effets (Dizio and Lackner, 1995), soit durant l’exposition à la perturbation (Criscimagna-Hemminger et al., 2003), on mesure ainsi la capacité à appliquer ce que l’on a appris précédemment.

La mémoire motrice, tout comme l’adaptation, est élémentaire au comportement moteur (Robertson et al., 2004; Krakauer and Shadmehr, 2006). Cela nous permet d’apprendre et d’acquérir des connaissances et des compétences dans divers domaines aussi bien intellectuels que moteurs. Par exemple, apprendre à faire un revers en tennis exige de l’entraînement, mais après plusieurs...
sessions où de nombreux coups ont été manqués ou réussis, la nouvelle compétence devient automatique et permanente. Par ailleurs la capacité à s’adapter est intimement liée à la mémoire. En effet la faculté de se souvenir d’événements passés est cruciale à l’apprentissage et à l’adaptation. L’adaptation est une forme d’optimisation comportementale qui permet d’acquérir des connaissances supplémentaires sur un contexte spécifique. Ce processus modifie certains réseaux de neurones dont les processus mnésiques sont sous-jacents. Cette trace mnésique de l’adaptation permet de s’adapter plus rapidement lorsqu’un même contexte est présent, et de faire des inférences au sujet des conséquences de nos actions relatives au contexte. Expérimentalement, on mesure la mémoire de l’adaptation motrice en testant à nouveau la même tâche plusieurs minutes, heures ou jours plus tard. On estime qu’une formation d’une mémoire motrice a eu lieu lorsque les performances sont meilleures la deuxième fois que la tâche est présentée, c’est-à-dire lorsque les erreurs motrices sont moins importants et/ou lorsque l’adaptation est plus rapide que lors de l’adaptation initiale (Brashers-Krug et al., 1996).

Dans cette thèse nous avons étudié essentiellement le transfert d’adaptation sensorimotrice entre les bras et nous avons abordé dans une dernière étude son lien avec la formation d’une mémoire motrice.

**Objectifs de la thèse**

Le transfert entre les bras est un processus complexe. Certaines études n’arrivent pas à faire émerger du transfert de leurs données (Harris, 1963; Cohen, 1967; Kitazawa et al., 1997; Wang, 2008), et même celles qui en rapportent ne se réfèrent qu’à des performances limitées (Joiner et al., 2013; Carroll et al., 2014, 2016). Ce qui transfert d’un bras à un autre est sensible à différentes facteurs dont l’influence est largement débattue dans la littérature. Par exemple, certaines études rapportent que le transfert à des perturbations dynamiques (i.e. champ de force) n’est possible que du bras dominant à non-dominant (Criscimagna-Hemminger et al., 2003), tandis que d’autres études trouvent que cela est possible dans les deux sens (Carroll et al., 2014; Stockinger et al., 2015). Ces résultats s’opposent également aux études où la perturbation est visuomotrice car un consensus semble stipuler que dans ce paradigme le transfert entre les bras est bidirectionnel. Cette dichotomie entre les résultats trouvés avec des perturbations dynamiques et visuomotrices est sans doute due à la nature de la perturbation qui entraînerait des processus différents (Krakauer et al., 2000; Rabe et al., 2009; Donchin et al., 2012). Plusieurs études tentent d’apporter des explications quant à l’hétérogénéité des résultats sur le transfert. Une étude suggère que le transfert entre les bras serait la résultante de la conscience de la perturbation (et celle des erreurs) qui permettrait d’appliquer des stratégies explicites lorsque le bras opposé est testé (Malfait and Ostry, 2004). Malheureusement plusieurs études n’arrivent pas à dupliquer ces résultats (Taylor et al., 2011; Wang et al., 2011; Joiner
et al., 2013). Une hypothèse plus récente stipule que le transfert découlerait du fait que les erreurs motrices soient associées à des facteurs externes, relatives à l’environnement et qui seraient donc indépendantes de l’effecteur. Dans l’ensemble, ces différentes études dressent un tableau complexe du transfert entre les bras.

L’objectif de cette thèse était d’essayer d’identifier les facteurs et les processus amenant au transfert entre les bras, et qui pourraient expliquer, du moins en partie, l’hétérogénéité des résultats trouvés dans la littérature. Les deux premières études avaient pour but de déterminer si les conditions paradigmatiques et/ou idiosyncratisques avaient une influence sur le transfert. Tandis que la dernière étude avait pour but de déterminer si les performances de généralisation pouvaient 1) être en lien avec un des processus sous-jacents à l’adaptation, 2) être liées à des effets de mémoire motrice.

**Etude 1 : To transfer or not to transfer? Kinematics and laterality quotient predict interlimb transfer of motor learning**

Du fait qu’un nombre importants d’études rapportent que le transfert entre les bras n’est présent que lorsque la vision directe de la main durant le mouvement est obstruée (Cohen, 1967, 1973; Wang and Sainburg, 2004), nous avons voulu tester l’idée que la présence ou l’absence de la vision du bras pouvait influencer les performances de généralisation. Selon Berniker et Kording (2008), nous attribuons une erreur motrice soit à une cause interne liée à notre corps, soit à une cause externe liée à l’environnement. Le transfert entre les bras serait donc possible seulement si l’erreur motrice est attribuée à une cause externe. Nous avons donc fait l’hypothèse que la vision du bras intensifiait l’association de l’erreur motrice à des causes internes et c’est pourquoi le transfert dans cette condition ne pouvait pas être observé, en revanche lorsque la vision du bras est obstruée les erreurs motrices seraient associées à des facteurs externes permettant ainsi le transfert entre les bras. En parallèle nous avons supposé que les caractéristiques individuelles concernant la cinématique durant l’adaptation et le quotient de latéralité (i.e. le degré de l’utilisation de la main dominante) pouvaient être déterminants et prédictifs du transfert. En effet, Kanai et Rees (2011) ont montré que les différences individuelles sont inévitables, et peuvent être utilisées comme une source d’information pour faire le lien entre le comportement et la cognition.

Dans cette étude, nous avions 20 sujets : 10 dans le groupe avec vision de la main, 10 dans le groupe non-vision (tâche faite dans l’obscurité). Nous avons testé l’adaptation à une force de Coriolis (force de rotation) lors de mouvements de pointage avec le bras dominant droit. En post-adaptation, c’est-à-dire une fois la rotation arrêtée, nous avons testé les mouvements du bras gauche. Nous avons observé une déviation de la trajectoire initiale du mouvement du bras gauche en post-
adaptation par rapport au mouvement du bras gauche dans des conditions nulles. Cela signifie qu’il y avait un effet de transfert d’adaptation de la main droite à la main gauche chez l’ensemble des sujets en moyenne. En revanche, il n’y avait pas de différence significative entre la condition vision et non vision. Les deux groupes s’adaptaient et transféraient de façon équivalente. Toutefois les performances de transfert de l’ensemble des sujets révélaient une certaine hétérogénéité : certains transféraient (classe transfert) tandis que d’autres non (classe sans transfert). Grâce à une analyse reposant sur des techniques de machine learning, nous avons réussi à identifier plusieurs variables prédictives des performances de généralisation. Il s’agissait de la variabilité de la direction initiale à la fin de la phase d’adaptation, du pic de vitesse durant l’ensemble de la phase d’adaptation, ainsi que le quotient de latéralité. Une augmentation de chacune de ces trois variables augmentait la probabilité d’associer un participant à la classe transfert. De plus, l’association de ces trois variables était aussi pertinente et efficace pour décrire de façon quantitative via une régression multiple le transfert entre les bras.

Le type de retour sensoriel n’a pas montré de différences comportementales au niveau de l’adaptation ou du transfert entre les membres. En revanche il semble que les caractéristiques des sujets définissent les performances du transfert. Il a été montré que la variabilité pouvait être bénéfique à de nombreux domaines tels que l’apprentissage de nouvelles compétences (Shea and Morgan, 1979; Ranganathan and Newell, 2013), l’adaptation sensorimotrice et l’apprentissage par renforcement (Wu et al. 2014). La variabilité durant l’adaptation pourrait avoir un rôle quant à l’exploration de l’environnement afin de tester les différents effets du champ de force et de trouver des stratégies d’exploitation efficaces et/ou optimales (Wu et al. 2014; Cohen et al. 2007). Le pic de vitesse pourrait avoir un lien 1) avec le champ de force puisqu’il était vitesse-dépendant, 2) avec la taille des erreurs car un pic de vitesse élevé entraîne de plus larges erreurs, 3) ou avec des stratégies de planification puisque un pic de vitesse élevé diminue la possibilité de faire du contrôle en ligne. Ces différentes zones d’ombres nécessiteraient davantage de recherche afin de tester directement ces hypothèses. Le quotient de latéralité pourrait être en lien avec le rôle et l’implication des hémisphères durant les mouvements. L’hémisphère gauche dominant joue un rôle primordial dans la coordination des segments de la main droite et gauche. (Sainburg, 2002; Schambra et al. 2011 ; Mani et al. 2013). De plus, la contribution des hémisphères n’est pas symétrique : les mouvements de la main dominante droite impliquent davantage de contributions de l’hémisphère controlatéral gauche qu’ipsilatéral, en revanche les mouvements de la main non-dominante gauche entraînent des représentations un peu plus équilibrées entre l’hémisphère droit et gauche avec d’importantes projections ipsilatérales de l’hémisphère gauche (Kawashima et al., 1993; Kim et al., 1993; Dassonville et al., 1997; Callaert et al., 2011). Par conséquent, dans notre étude nous supposons que le fait que les individus très latéralisés (i.e. très droitiers) aient de meilleures performances de
généralisation soit dû à des activations plus importantes de l’hémisphère gauche durant l’utilisation de la main droite et/ou gauche. Nous avons également testé un groupe de 9 gauchers afin de vérifier s’il s’agit de l’étendue de la latéralisation (très ou peu gauchers/droithiers) ou de la latéralisation elle-même (droithiers ou gauchers) qui influence la généralisation. Il se trouve que le quotient de latéralité était toujours un facteur important quand à la prédiction du transfert chez les sujets gauches. De ce fait, on suppose que c’est l’étendu de la latéralisation qui importe, malgré que nous ne comprenions pas tout à fait les mécanismes sous-jacents.

Etude 2 : Generalization of force-field adaptation in proprioceptively-deafferenteted subjects

Cette étude était expérimentalement la même que précédemment sous la condition Vision. Nous avons testé deux individus GL et IW âgés de 66 et 61 ans au moment de l’expérience et désafférentés de façon proprioceptive. L’intérêt de cette étude était de tester si le manque de proprioception, qui est néfaste à la coordination des segments (Sainburg et al. 1995), empêche également de généraliser l’adaptation au bras non-dominant.

Nous avons observé que les deux sujets s’adaptaient et transféraient l’adaptation à la main non-dominante et ce malgré leur désafférentation. Nous avons également observé que les trois variables : pic de vitesse, variabilité et quotient de latéralité, décrites plus haut, permettaient de prédire, sur la base des 20 jeunes sujets étudiés précédemment, une probabilité de 99% à l’appartenance des deux sujets à la classe «Transfert». Ces trois variables ont également permis de prédire efficacement la valeur de transfert des 2 sujets, toujours sur la base des 20 jeunes sujets contrôles.

Nos deux premières études nous ont donc permis de montrer que la présence à la fois de la proprioception et de la vision n’est pas obligatoire pour pouvoir s’adapter et transférer tant qu’une des deux modalités sensorielles est présente pour compenser l’absence d’une autre modalité. Cette forme de substitution sensorielle avait déjà été montrée dans des études d’adaptation sensorimotrice en l’absence de vision (Scheidt et al., 2005; Franklin et al., 2007; Arce et al., 2009) et de proprioception (Sarlegna et al., 2010; Yousif et al., 2015). En conclusion nos deux études semblent montrer que les différences individuelles ne sont pas forcément une source de bruit à éliminer des données, mais peuvent influencer fortement les performances et doivent dans ce cas être prise en compte.

Etude 3 : Interlimb transfer of sensorimotor adaptation shares common processes with the motor memory

Dans les deux précédentes études le niveau d’adaptation du bras droit ne prédisait pas la performance de généralisation au bras gauche. Ce qui était légèrement surprenant étant donné que

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le transfert découle de l’adaptation, on aurait pu s’attendre à une corrélation entre ces deux processus. Par conséquent, nous avons fait l’hypothèse que le transfert découle, non pas directement de l’adaptation, mais d’un processus sous-jacent à l’adaptation. Smith et collègues (2006) ont défini un modèle «dual-rate model of adaptation» où l’adaptation est décrite comme étant la somme de deux processus : un «lent» qui apprend doucement des erreurs motrices mais les retient longtemps, et un «rapide» qui apprend rapidement des erreurs motrices mais les oublie vite. Ce modèle arrive à expliquer pertinemment plusieurs phénomènes découlant de l’adaptation et ne pouvant pas être défini simplement par le niveau d’adaptation atteint, comme la «retention» et le «savings» qui sont deux formes de mémoire motrice. La «retention» est une fraction de l’adaptation qui est retenue. Le savings correspond à une adaptation plus rapide lorsque l’adaptation à cette même tâche est testée à nouveau (Figure 14). La «retention» découle du processus lent et le «savings» du processus rapide. Nous avons fait l’hypothèse que tout comme pour la mémoire motrice le transfert serait le résultat soit du processus lent soit du processus rapide. En parallèle, nous avons testé les performances à se re-adapte à une perturbation de Coriolis 24 heures après l’adaptation initiale. Nous avons fait l’hypothèse que si le transfert et l’une de ces composantes mnésiques découlent du même sous-processus, lent ou rapide, alors les performances entre ces deux comportements seraient corrélées.

Nous avions 17 sujets qui étaient testés comme précédemment : après adaptation avec la main droite, la généralisation en dehors de la perturbation sur la main gauche était testée. Le lendemain nous avons à nouveau testé ces mêmes sujets au champ de force pour mesurer les performances de leurs mémoires motrices. Afin de définir la contribution des sous-processus de l’adaptation, lents et rapides, au transfert entre les membres, nous avons modélisé le dual-rate model à partir de nos données.

Nos résultats révèlent que les performances significatives de transfert au bras gauche sont définies par une forte contribution du processus rapide et une faible contribution du processus lent. Nous avons observé au jour 2, de la «retention» lors de la re-adaptation (i.e. plus petites erreurs au début de la re-adaptation en comparaison avec les performances de l’adaptation initiale). Nous avons également identifié que les sujets montrant du transfert sont aussi ceux qui présentent le plus de «retention» sur la tâche de re-adaptation.

Le processus rapide est défini comme engageant la mémoire explicite/déclarative (Keisler and Shadmehr, 2010), et qui est présent essentiellement lorsque les erreurs sont larges et inattendues. (Orban de Xivry et al. 2015; Huang et al. 2011; Stockinger et al. 2014). Cette forme d’apprentissage correspond à une mémoire qui est indépendante de l’effecteur car elle repose sur des représentations cognitives supérieures (Keisler et Shadmehr, 2008). En revanche, le processus lent englobe une forme implicite et procédurale de l’apprentissage qui est sensible aux erreurs...
sensorielles du mouvement et ne donne pas lieu au « savings » (Huberneau et al. 2015). Selon ces travaux, dans notre étude nous pourrions postuler que nos participants montrant à la fois de la généralisation et de la rétention comptaient davantage sur des stratégies d’ordre supérieures et moins sur des stratégies implicites d’ordre sensorimotrice (Figure 14).

Ce lien entre les performances de généralisation et celles de rétention laissent suggérer que ces deux comportements reposent sur des processus communs, cependant le transfert semble découler du processus rapide selon nos résultats, et la « rétention » a été définie comme découlant du processus lent. Ce résultat contradictoire nécessiterait davantage de recherche. Le « savings » n’était peut-être pas complètement absent de la phase de re-adaptation. Sinon ce résultat pourrait découler de la complexité des processus sous-jacents à l’adaptation qui seraient plus nombreux que ce que modélise le dual-rate model.
Introduction
Introduction

Context

A hallmark of human behavior is the wide variety of movements that we can perform: it ranges from seemingly simple movements such as blinking an eye, to more complex motor skills such as playing an instrument (e.g. piano, violin) or performing acrobatic routines (e.g. gymnastics). However, even the motor behaviors which appear effortless require complex computations from our nervous system. For instance, reaching to an object entails defining the position of the object relative to our arm, and then specifying the motor commands to produce the desired joints’ displacements. Moreover, the set of motor commands must be selected among an infinite number of possibilities including the different paths and velocity profiles that the hand could use, and also the different joint angles and muscle activations for a chosen hand path (Wolpert, 1997). Given the complexity of the processes underlying the motor behavior, understanding how the nervous system controls movements is a fundamental challenge in psychology, neuroscience, bioengineering and sports sciences. Among the variety of movements, arm reaching has been widely adopted as an experimental protocol to study fundamentals of voluntary movement control.

Despite the largely implicit character of motor behavior, movements can be considered as an extension of our intentions, and hence the expression of our personality. Indeed, a facial expression, the way we stand or walk, or also our gestures give insights to our state of mind. However, motor behavior has often been presented as being in contradiction with the notion of mind or cognition. Rene Descartes in the 17th century claimed that “there is a great difference between mind and body, inasmuch as body is by nature always divisible, and the mind is entirely indivisible... the mind or soul of man is entirely different from the body.” Within the past few decades, an alternative view has emerged about the relation between cognition and body, wherein they would work in interaction. That is, not only does our cognition influence our body, but also our experiences in the physical world influence our cognition, because the outcomes of our interactions with the environment modify our knowledge and perception (Wilson, 2002). According to Antonio Damasio “A mind is so closely shaped by the body and destined to serve it that only one mind could possibly arise in it. No body, never mind.” (Damasio, 2000). In addition, the way we cope with these outcomes contribute to the extent to which we are adapted to our environment. For instance, a child would explore fearlessly its environment, but after some misfortunes, he/she would eventually learn what is better or not to do. Adaptation is a fundamental feature of behavior since it determines our survival. According to Darwin’s theory of evolution, species adapt to changes of the environment to gain an advantage in survival. Humans deeply depend on their senses to effectively adapt their behavior. These senses are
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a window onto our internal sensations and onto the external environment. In association with our motor system, our sensory system interprets the stimuli coming from our body and our environment, in order to produce an appropriate motor response (Desmurget et al., 1998; Scott, 2004).

As an example, let’s say that someone intends to seize a steady object. To this end, the nervous system must consider the properties of the arm and the implicit properties of the object (i.e. shape, weight) to send the appropriate motor commands. But if the object is lighter than what the person thinks, he/she would suddenly lift the object faster than necessary. However, the second time the person seizes the same object, he/she would adapt its clinch and strength to the perceived weight of the object (Flanagan and Beltzner, 2000). This type of motor adaptation is linked to the senses and is thus referred to as sensorimotor adaptation. Krakauer and Mazzoni (2011) stated that sensorimotor adaptation corresponds to an improvement, through practice, in the performance of sensory-guided motor behavior.

A process that directly stems from sensorimotor adaptation is the way we can generalize what we have learnt to other conditions or limbs (Shadmehr and Mussa-Ivaldi, 1994; Criscimagna-Hemminger et al., 2003). When knowledge gained through training in one situation is beneficial to unvisited states within the same arm, the process is called intralimb transfer; while when it is beneficial to opposite arm movements, the process is called interlimb transfer of adaptation. As in the previous example, if the object is seized with the opposite arm, a person may refer to his/her previous experience to adapt its clinch and strength accordingly. The study of interlimb transfer is particularly relevant to understand how the nervous system encodes movement characteristics. Indeed, the changes in performance may be totally tied to the limb and the movement made during adaptation: in such case the performance would be effector specific and there would be no or little transfer. Another possibility is that these changes may stem from a broader representation of the relationship between the body and the environment. In this case, the processes inducing the motor changes would be at least in some part effector-independent and would thus allow interlimb transfer. Studying transfer thus gives some insights into the structure of the representations formed during adaptation and also allows inferring the underlying processes of sensorimotor adaptation (Mattar and Ostry, 2010).

Another key feature of motor behavior is the ability to store in memory what has been learnt (Robertson et al., 2004; Krakauer and Shadmehr, 2006). Therefore, adaptation is closely related to memory. Adaptation generally results in an enhancement of motor behavior that reflects a gain in knowledge. This process will modify some specific neural networks to better reflect the new motor behavior. Memory is the both the fruit and the core of this adaptive process, the concrete trace of it that is left in your neural networks. Such as adaptation, memory can be seen as a fundamental process whose evolution helped survival of our specie. Indeed, this process contributes to the
minimization of the efforts and to the maximization of the reward associated with a given motor task. Experimentally, a classic method to study sensorimotor adaptation is to perturb a movement, for instance a reaching movement, and recording kinematic features such as movement velocity and trajectory. The memory trace is then assessed by comparing the performance in a same given task across different sessions, generally spaced across several hours or days.

Scope of the thesis

Interlimb transfer of sensorimotor adaptation is an intricate and hazy process. A body of literature addressed this issue but a lot of conflicting results have been reported. In this thesis, an attempt was made to identify which conditions favor interlimb transfer of adaptation and hence may explain the discrepancies found in the literature. To this end, our research objective was to determine whether paradigmatic characteristics have an influence on interlimb transfer. Given the well-known inter-individual differences in perceptual and motor skills, we also considered the possibility that idiosyncratic characteristics could influence interlimb transfer and aimed at identifying more precisely which characteristics could be relevant. Another goal of the research was to identify whether the performance in interlimb transfer 1) could be determined by a sub-process of adaptation and 2) could be linked to the performance in motor memory.

In the first chapter we start by introducing basic concepts about how voluntary movements may be controlled, with a particular interest in sensorimotor adaptation. In the second chapter, we focus on intralimb and interlimb transfer of sensorimotor adaptation and highlight how diverse the results and explanations can be. In the third chapter, we present the different forms of motor memory. The fourth, fifth and sixth chapters present our experimental contribution to the field of human motor control, before concluding with a general discussion.
Theoretical background
Chapter 1

Control of voluntary movements
When studying the control of voluntary movements, we question how the nervous system produces relevant and efficient movements (Woodworth, 1899). Every action requires the analysis of our environment and our body as well as the appropriate activation of the muscles. The underlying processes depend on a number of interacting elements including gathering of the relevant sensory information, decision-making, and implementation of both predictive and reactive control mechanisms (Desmurget et al., 1998; Prablanc et al., 2003; Wolpert et al., 2011). The primary element on which an action relies on is the sensory information; indeed without functional sensory system we would not be able to identify the relevant factors of a situation and much less to infer a motor behavior. There are multiple sensory modalities that can be used in the control of our movements: for instance we may refer to the exteroceptive senses such as vision, hearing and touch, and the interoceptive senses resulting from the vestibular and proprioceptive systems. Vision and proprioception have been found to be important for many movements as they convey an estimate about the state of both the environment and the body (Carlton, 1981; Bard et al., 1995; Scott, 2004).

To further describe the mechanisms involved in motor control, we mostly refer to studies wherein the task is to reach with an arm toward an object or a target. This model is particularly relevant because it represents an intermediate level of behavior that embodies both low-level motor mechanisms and higher-order cognitive processes (Krakauer and Mazzoni, 2011; Sarlegna and Mutha, 2015): indeed arm movements can range from waving to a friend, grasping an object to juggling. Reaching movements entail different stages such as planning, execution, and adaptation. For instance, when playing bowling, one may intend to plan the ideal trajectory to strike all the skittles at once. Then, during the execution of the movement, if some unexpected loss of balance occurs, the player will try to correct it as well as to adjust the arm trajectory to throw as well as possible. Once the ball strikes, or not, any skittle(s), the player may consider his/her errors to adapt his/her next movement to be successful, such as hitting harder if the ball was to slow to bring down all the skittles, or adjusting his/her movement so that the bowling ball goes straighter. Naturally, each of these stages benefits from the continuous integration of visual and proprioceptive feedbacks (among other senses).

In the following section, we briefly address the planning and execution of arm-reaching movements before focusing on the process of sensorimotor adaptation. The aforementioned sections are developed with a particular interest in the role of vision and proprioception. Later, we present different theoretical and computational models providing some insights in the processes underlying sensorimotor adaptation.
I. The roles of vision and proprioception during the different phases of the movement

Perception and motor control do not occur in isolation but rather resonate in the constant flow of one another (Ostry and Gribble, 2016). It is clear that motor behaviors are influenced by sensory signals when actions are triggered by a sensory stimulus. But even for an action which is triggered by an internal cue, effective motor control requires accurate information about the state of the body and of the environment. The position and velocity of body parts, the external forces acting on the body as well as the characteristics of the environment are all important variables in planning and executing an effective motor action (Wilson and Du Lac, 2011; Ostry and Gribble, 2016). For example, to perform a handstand, we must rely on our proprioceptive and vestibular feeling of our body position and orientation, and on our tactile and pressure information of the hands on the ground, thereby knowledge of our motor commands can be very helpful to interpret these sensory signals. In this thesis, we focus on vision and proprioception which are essential to motor control. Proprioception can be defined as the sense of the position and the movement of body segments based on mechanoreceptors localized in the muscles, tendons and joints. Vision is based on signals from the retina which have to be interpreted with reference to the current position of the head and eyes as well as the motor outflow to the ocular muscles (Gauthier et al., 1990).

1. Specificities of Vision and Proprioception

The eyes and the head are highly mobile, and we usually make between 150 000 to 200 000 saccades per day to scan the visual field (Panouillères, 2011; Robinson, 2011). The visual system plays an important role in exploring and constructing perceptual representations of our environment and our body. Specifically, our visual system enables us to determine different features of an object such as its color, shape, size, position and its speed and direction if it is moving. Peripheral vision appears specialized for collecting information about movement in the visual field while central vision seems more useful to assess the static properties of objects such as shape (Sivak and MacKenzie, 1990). Humans are highly dependent on vision compared to many other species which rely more on smell or hearing, and over our evolutionary history we have developed an incredibly complex visual system (Gibson, 1950; Wilson and Du Lac, 2011). The multiple features of the visual system provide continuous information which allows us to adjust our movements accordingly.

Proprioceptive receptors convey information about the body segments to the central nervous system to build an internal representation of our body and our environment (Cole and Paillard, 1995; van Beers et al., 2002) Proprioception may be mostly perceived at an unconscious level but it does not mean that it is a secondary sense: on the contrary, proprioception is essential to continuously
control our movements and positions. All physical activities ranging from the most basic such as being seated, standing or walking, to more complex motor skills such as dressing or eating benefit from proprioceptive feedback. The study of blind individuals has shown us the consequences of a severe sensory loss. It seems difficult to imagine being without proprioception, possibly because it is not easy to determine what proprioception is. Yet, the pioneer work of Mott and Sherrington, (1894) on non-human primates revealed that, after deafferentation by dorsal root section, motor behavior was severely impaired. The absence of proprioception has also been studied in deafferented patients and it has been shown that a massive, yet specific loss has profound effects on the coordination of body movements (Rothwell et al., 1982; Cole and Paillard, 1995; Sainburg et al., 1995). As a result of a severe neuropathy that destroyed its large-diameter peripheral nerves, a well-characterized patient known as IW lost sensations of touch and proprioception from his neck down to his feet at the age of 19. At the beginning of his hospitalization which followed his sudden illness, IW could not move. Then he had little control over where his body parts were moving and consequently, he could not sit, walk or even chew food. He managed to sit after 2 months, and to stand and walk after more than a year thanks to his constant physical and mental efforts. These daily life activities are effortless for most people but for IW, controlling movements and posture needs intense mental concentration and constant visual attention (Cole and Paillard, 1995; Ingram et al., 2000). Another patient, GL, has a somewhat similar history. She suffered from a severe neuropathy and since the age of 31, she lost most of her body sensations from her feet to her nose (Forget and Lamarre, 1987; Nougier et al., 1996; Coello and Delevoye-Turrell, 2007). Functionally, GL remains largely confined to a wheelchair but can perform daily manual tasks by using visual information and attentional resources (Blouin et al., 1993; Sarlegna et al., 2010). Studying the behavior of such patients is certainly valuable because it sheds some light on the importance of proprioception on every motor behavior (Cole and Paillard, 1995).

As stated earlier, vision provides information about the body and the environment. Proprioception also provides information about the state of the body and in particular about the effect that any external stimulus may have (e.g. a dynamic perturbation such as a collision). Each modality seems to have specificities with respect to its contribution to motor control. Indeed, vision seems determinant for precision. In the absence of vision, a systematic endpoint deviation persists (Lackner and Dizio, 1994; Coello et al., 1996; Sarlegna et al., 2006) and spatial estimates of hand position drift over time (Wann and Ibrahim, 1992; Brown et al., 2003). Vision appears to be particularly important for the fine tuning of arm movement trajectory (Franklin et al., 2007). On the other hand, proprioception plays an important role for the interjoint coordination (Sainburg et al., 1993, 1995; Sarlegna et al., 2006; Torres et al., 2014). Indeed, although individuals deprived of proprioception can compensate their impairment with visual information (Blouin et al., 1993;
Sarlegna et al., 2010; Yousif et al., 2015), their impairment usually remains visible in a number of tasks (Rothwell et al., 1982; Sarlegna et al., 2010; Torres et al., 2014). This is especially true when movements involve several joints: compensation by visual signals becomes not enough to perform smooth, coordinated movements. Proprioception is used to continuously control movements throughout their execution and it has also been suggested that precise coordination between muscle activities and interaction torques occur through feedforward mechanisms based on a proprioceptively-updated internal model of the limb (Sainburg et al., 1995; Riemann and Lephart, 2002). This internal model of the limb dynamics is useful to account for the complex mechanical interactions between the components of the musculoskeletal system (Riemann and Lephart, 2002), and proprioception would provide to the internal model the most efficient information.

In conclusion, although some of the afferent signals may seem to provide redundant information across the visual and somatosensory systems (e.g. location of the hand), vision and proprioception seem to have distinct contributions in motor control. Vision is generally considered as being mainly devoted to exteroception and proprioception to interoception (Cole and Paillard, 1995; Riemann and Lephart, 2002; Arce et al., 2009). Both vision and proprioception provide cues about the body and the environment to enable the most efficient motor control policy across the different phases of movement: planning, execution and adaptation (Desmurget et al., 1998; Scott, 2004).

2. Planning and execution of movements

In order to perform motor tasks, the central nervous system integrates several types of sensory inputs. Here we succinctly address the integration of vision and proprioception during planning and execution of movement (Desmurget et al., 1998; Sober and Sabes, 2003; Scott, 2004). Integration of multiple sensory modalities is generally beneficial for perception and action. It has been suggested that sensory integration consists in attributing a weight to the input of each modality, then the different inputs are combined to convey a single relevant state estimate (Desmurget et al., 1998; Sober and Sabes, 2003). Generally, in a reaching task toward visual targets, the estimate of the hand position relies more on vision than proprioception as vision may be considered as the most reliable source of information (Sober and Sabes, 2003; Bernier et al., 2005). Sober and Sabes (2003) inferred that vision and proprioception contribute differently to the planning of reaching movements: the desired movement direction was suggested to be essentially estimated by vision of initial limb configuration, and motor commands by proprioception. This is consistent with studies in individuals of proprioception showing impairment in interjoint coordination (Sainburg et al., 1995). Naturally, the relative weighting given to one source of sensory information may vary according to the condition of the task and the availability of the senses (Sober and Sabes, 2005; Sarlegna et al., 2007). Indeed, weighting is not a static process but is rather optimized for a given situation.
In movement planning, the key role of vision and proprioception is to build a consistent representation about the target location with respect to the body. Specifically, vision directly indicates the location of the hand relative to the target in extrinsic space. In contrast, proprioception conveys information related to configuration of the body segments in intrinsic space, but not about the target location. It is likely that a movement of the arm toward the visual target needs suitable calibration from muscle to hand space through vision (van Beers et al., 2002; Scott, 2004; Arce et al., 2009) Once a suitable representation is built according to the goal, the central nervous system may specify the motor commands (for a review: Desmurget et al., 1998).

The execution of the movement is subject to the changing properties of our environment. Therefore, it is required to constantly monitor and update the estimate of the hand and of the target to compare our actual movement to our goal (Desmurget and Grafton, 2000; Scott, 2004; Sarlegna and Mutha, 2015). Such online comparison allows modifying the ongoing movement in case of perceived sensorimotor errors. These errors may result from unexpected events (e.g. dynamic or visuomotor perturbation) or to inherent noise and delay related to motor or sensory signals (Harris and Wolpert, 1998). For instance, say that you intend to grasp an object on a table and this object falls for some external reason, you may certainly change your initial trajectory to try to catch the falling object. This correction is possible because we have the ability to modify online our movements by perpetually comparing the expectations of our actions to their actual consequences. Within the paradigm of goal-directed arm movement, online control is the reason why we observe rapid adjustment of trajectory in response to a target displacement or an abrupt perturbation of the arm (Figure 4B). Such adjustment relies on information about the arm position and the target location provided by the sensory systems such as vision and proprioception (Scott, 2004). These sensory signals are continuously integrated to adjust our movements to the goal of the task.

An important aspect in online control of movement is the influence of the temporal constraints. Indeed, there is a non-negligible delay between the state estimate derived from the afferent signals and the estimate based on the motor output. The time correction observed after a sudden target displacement during movement execution can be as fast as 150ms (Prablanc and Martin, 1992; Boulinguez et al., 2001). Such short-latency corrections occur whether participants are aware or not of the target displacement (Goodale et al., 1986; Blouin et al., 1995; Gritsenko et al., 2009) and are relatively resistant to cognitive control (Day and Lyon, 2000). These findings suggest that short-latency corrections correspond better to an automatic process rather than to a voluntary process.

Because sensory feedback loops are relatively slow, online control of movement is not solely based on sensory feedback. To compensate for the feedback delays, online control is also crucially dependent on the prediction of the sensory consequences of movement commands (Desmurget and Grafton, 2000; Gritsenko et al., 2009). This predictive process is made possible by internal models
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whereby neural mechanisms can mimic the association between motor commands and limb movement by means of efference copies (Kawato, 1999). For instance, the study of Ariff et al., (2002) showed that, after a brief perturbation on a reaching arm, an internal model was computed by means of real-time proprioceptive feedback to estimate the future hand position. They observed that a saccadic movement was made toward the future position of the hand that was unseen during the reaching movement.

There is a growing body of literature suggesting that state estimates are also deeply influenced by prior knowledge, in terms of statistics, of the task (Boulinguez and Nougier, 1999; Knill and Pouget, 2004; Körding and Wolpert, 2004; Gritsenko et al., 2009; Shadmehr et al., 2010). According to the theory of Bayes, the afferent signals are combined with the predicted sensory consequences of the task. These predictions are based on prior probabilities of different task configurations. Kording and Wolpert (2004) found that the participants’ correction to a new visuomotor perturbation while reaching to a target was a function of both participants’ prediction of the cursor location and its actual location relayed by visual feedback. The more uncertain participants were about the location of the cursor, the more they relied on their predictions about where the cursor would be to make the corrective response. In other words, weighting the sources of state estimate occurs in proportion to their reliability. This assumption may explain a striking result about the movements’ features revealing that the visual-proprioceptive integration varies with direction. Indeed, in depth, proprioception is weighted more heavily than vision, and in azimuth it is vision that is mainly weighted (van Beers et al., 2002). In this study, each source was actually weighted in accordance with its relative precision, therein the different sensory modalities tended to be integrated in a statistically optimal fashion which is consistent with the theory of Bayesian inference.

In conclusion, motor planning and motor execution are continuously influenced by the information conveyed by vision and proprioception about the environment and the body state. They are also deeply influenced by the prediction of the sensory consequences of the actions and the prior probabilities of the environment. When the movement is executed, if an error is perceived, the nervous system has the possibility to re-plan the subsequent movement according to its expectations: this phenomenon is called adaptation.

3. Sensorimotor adaptation

Adaptation refers to the capacity of our nervous system to produce accurate movements while the properties of our body and our environment change (Berniker and Kording, 2008). As for movement planning and execution, adaptation entails substantial contributions from the task-relevant sensory information. Also, adaptation can be induced by different type of perturbations.
A. The contribution of vision and proprioception to sensorimotor adaptation

Early work with prisms revealed that the interaction between vision and proprioception lead to plastic changes necessary to adaptation (Held, 1965). However, integration of the senses during adaptation depends on the availability of the senses. Despite the fact that interjoint coordination is severely impaired in the absence of proprioception (Ghez et al., 1990; Sainburg et al., 1993, 1995), individuals deprived of proprioception can adapt to new dynamic conditions with visual feedback (Sarlegna et al., 2010; Yousif et al., 2015). Similarly, a study with congenitally blind individuals (DiZio and Lackner, 2000) showed that proprioception alone was sufficient to adapt to new limb dynamics. In these examples, a sensory modality could compensate for the absence of another to provide information about the body state and update the control policy. Nonetheless, this lack of information has sometimes some detrimental consequences on the movement depending on the condition of the task. For instance, in (Pipereit et al., 2006), the degradation of proprioception by wrist vibration substantially impaired adaptation to a dynamic perturbation, but did not significantly impair adaptation to a visuomotor rotation. This result suggests that adaptation to dynamic perturbation relies more on proprioception, while obviously adaptation to a visual perturbation relies mostly on vision.

Overall, both proprioceptive and visual feedback can be used to compensate for environmental perturbations (see the decrease in error during Adaptation in Figure 1A and B), but it remains unclear exactly how multi-modal sensory information is combined to guide the adaptive updating of motor commands. Several studies manipulated the sensory feedback to test their distinct contributions to adaptation. Similarly to previously depicted studies, it was found that, without visual feedback,
adaptation to force-field perturbations occurred (Lackner and Dizio, 1994; Dizio and Lackner, 1995; Coello et al., 1996; Scheidt et al., 2005; Franklin et al., 2007; Arce et al., 2009). However, the condition where vision was not provided slightly impacted the kinematic of the trajectories. Without vision, some studies found that, across the experimental phases, the trajectories were less accurate and more variable in term of final position (Lackner and Dizio, 1994; Scheidt et al., 2005; Franklin et al., 2007). Thereby, it seems that vision plays a role in fine-tune corrections of hand trajectories at the end of the movement. Some other studies also found that in multi-force environment (Coriolis and centrifugal forces), visual cues of the hand position is needed prior to movement (Bourdin et al., 2001, 2006), indicating thus that when the environment is complex, proprioception is not enough to recalibrate the movement. Lastly, it was shown that during adaptation, trajectories tended to be more curved without vision than with vision of the hand (Franklin et al., 2007; Arce et al., 2009). Arce et al. (2009) suggested that the curved trajectories observed in their study represented a general strategy or a control policy to achieve accurate terminal position. They referred their results to a study that posited that to maximize rewards and minimize motor costs, trajectories may be reoptimized and have a curve shape (Izawa et al., 2008). These arguments are consistent with studies that reported more rectilinear movements but lower final accuracy (Lackner and Dizio, 1994; Franklin et al., 2007).

Scheidt et al. (2005) substituted the actual visual feedback of hand-path deviations to a constraining visual feedback of motion that always showed straight trajectories, even when the actual trajectory was curved. This manipulation prevented any online or trial-by-trial compensation of initial direction and final errors induced by force-field perturbations. Thus, while the cursor was reaching the target, the actual arm was not reaching toward the target. Intriguingly, the movements became straight trial after trial (even if they were not accurate). The authors concluded that vision and proprioception may have a dominant effect in different phases of movements. Specifically, proprioception would regulate predominantly the trajectory execution while vision would regulate final limb posture. In other words, the proprioceptive feedback would mostly help in straightening the trajectory while visual feedback would mostly minimize final errors.

All together these results show that visual and proprioceptive information are not required for sensorimotor adaptation. However, these modalities seem to contribute to different aspects of movement control: vision seems to contribute to final corrections and overall accuracy of the movement and proprioception seems to play a role in the coordination and the regulation of the trajectory.
B. The different phases of adaptation

In order to study sensorimotor adaptation of arm movements, one could consider that three main perturbations have been used in the literature so far: prismatic goggles, visuomotor rotations and alteration of limb dynamics (Figure 2).

In visually-guided reaching, it can be argued that the location of an object with respect to the initial position of the hand needs to be transformed into a desired movement, with the details of the hand path, speed and acceleration profiles (i.e. kinematic transformation; Desmurget et al., 1998; Sarlegna and Sainburg, 2009). Obviously, the arm is brought to its desired goal according to the planned limb trajectory by means of force or muscle activations, possibly based on an inverse internal model which underlies such dynamic transformation. If environmental conditions change, for instance when the mapping between the visual space and the motor commands is altered when we dive underwater, the visuomotor transformation needs to be updated. Two methods have been used to study adaptation to a novel visuomotor mapping, i.e. prisms and visuomotor rotation. Though, these methods are slightly different, which may correspond to slightly different adaptation processes. During prism adaptation, participants reach to targets that are viewed through prismatic lenses that bend the light before it reaches the eyes, shifting the visual image to one side (Harris, 1963; Cohen, 1967; Martin et al., 1996; Sarlegna et al., 2007). In this situation, the whole visual field is modified. Harris, (1963) and Bernier et al. (2007) proposed that participants could remap the felt position of the arm to the observed shifted position of the environment. During visuomotor adaptation (Figure 2A-B), participants generally do not see their arm but can see a cursor representing their finger displayed on a computer monitor. This cursor is then rotated to one direction while reaching to the target (Figure 2B). In this case, the alteration of hand visual feedback produces a conflict between visual and proprioceptive afferent signals (Figure 3A), which may prompt the recalibration of one or both sensory modalities to resolve the conflict (Sarlegna and Bernier, 2010).
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Figure 2: Experimental set-up A) Schematic illustration of an experimental set-up for either visuomotor or force-field perturbations (Carroll et al. 2016). B-C) Examples of the effect of visuomotor rotations and force-field perturbations (Joiner and Smith, 2013).

The perturbation of limb dynamics differs from prismatic deviation or visuomotor rotations since at no point does it introduce a conflict between visual and proprioceptive cues (Figure 3B). Dynamic adaptation is related to changes in the body characteristics, for instance using an external force field (Figure 2C). Thus, the dynamics of the limbs have to be adjusted to counter the external constraints and produce the desired kinematics, for instance by producing a straight trajectory with a bell-shaped velocity profile (Atkeson and Hollerbach, 1985). Limb dynamics have been initially altered with a mass (Smeets et al., 1990; Krakauer et al., 1999; Wang and Sainburg, 2004a) but since the pioneer work of Shadmehr and Mussa-Ivaldi (1994), it is generally tested with a robotic manipulandum allowing movements in the horizontal plane. The perturbation may be applied on the handle of the manipulandum that the participant holds (Figure 2A) although exoskeletons are also being used since the development of the KINARM (Scott, 1999). As in visuomotor perturbation, the vision of the limb is generally obstructed and a cursor representing finger position is projected on a screen above the arm. The robotic manipulandum is quite flexible and can apply different types of force fields on the reaching arm that are generally velocity-dependent (i.e. the faster the participant moves, the stronger the force field) (Shadmehr and Mussa-Ivaldi, 1994; Malfait and Ostry, 2004; Bays et al., 2005). An additional type of force-field perturbation consists in using a Coriolis force field (Lackner and Dizio, 1994; Dizio and Lackner, 1995; Coello et al., 1996; DiZio and Lackner, 2000; Bourdin et al., 2001, 2006; Sarlegna et al., 2010). In this paradigm, participants sit on a platform that can rotate and thus generate a force field on the reaching arm. The characteristic of the experimental set-up is that the movement is unconstrained and does not provide a mechanical
contact with the limb. Due to the perturbation, the arm is deviated to the opposite side of the rotation. Coriolis forces ($F_{cor}$) are proportional to the product of the arm mass ($m$), platform’s angular velocity ($av$) and tangential arm velocity ($pv$) according to the equation: $F_{cor} = -2m.pv.av$.

![Diagram](image)

**Figure 3**: Schematic representation of the impact of the different adaptation paradigms on the forward model (Sarlegna and Bernier, 2010). A) When visual feedback is artificially altered, such as during visuomotor rotation, a conflict arises between the predicted and actual visual consequences of the movement (depicted by “≠”), but not between the predicted and actual proprioceptive consequences of the movement (depicted by “=”). The conflict between visual and somatosensory estimates (i.e. proprioception) prompts the recalibration of these modalities. B) In the case of a novel force field, the visual and proprioceptive consequences of the movement are affected similarly, and there is no conflict between the two sensory estimates.

In all these paradigms, adaptation is tested in a similar way (Figure 4). First, participants reach to one or multiple targets successively without any mechanical constrain or visual shift to assess their baseline performance (also referred to as PRE-adaptation phase, Figure 4A). Then, a perturbation is applied on the reaching arm: although the participants generally receive no particular instructions, they generally counter the perturbation progressively such that, trial after trial, they restore their ability to perform similar rectilinear and precise movement as in the baseline (referred to as adaptation phase, Figure 4B). After a number of trials, when adaptation may be complete, the perturbation is removed. What could be surprising is that when the perturbation is removed, movement errors are observed. However they are in the opposite direction of those observed when the perturbation was first introduced. These errors are generally termed after-effects (in the POST-adaptation phase, Figure 4C). It suggests that the nervous system composed an internal model of the force-field used to predict and compensate the force-field (Shadmehr and Mussa-Ivaldi, 1994).
II. The models of sensorimotor adaptation

1. Internal models for sensorimotor adaptation

Many researchers have suggested that the brain constructs an internal model, an approximation of the state of the reality (i.e. the environment and the body) upon which motor actions are planned and executed. Any errors caused by the discrepancy between the internal model and reality then are used as the main driving signal for the brain to modify its model (Harris and Wolpert, 1998; Kawato, 1999; Desmurget and Grafton, 2000). There are two types of internal models: forward and inverse models (Figure 5). Forward models capture the causal relationship between the input to a system, for instance the motor commands sent to the arm muscles, and the output, namely the movement consequences in terms of kinematics for instance (Miall et al., 1993; Wolpert et al., 1995). A forward model of the arm predicts the next state (e.g. position and velocity) based on an efferent copy of the descending motor commands. It has been suggested that it is the forward model that determines adaptation (Flanagan et al., 2003). In contrast to the forward model, an inverse model determines the motor commands needed to achieve a desired change in state (Wolpert and Kawato, 1998;
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Wolpert and Flanagan, 2001). Motor behavior requires the combination of both forward and inverse internal models (Figure 5) because to start out, we need an inverse model to accurately determine the motor commands to reach a given desired goal. A forward model is useful to predict the sensory consequences of a given motor command and thus obtain an immediate state estimate. Together, they are well suited to act as controllers as they can provide the motor command necessary to achieve some desired state transition (Wolpert et al., 1998). Sensory signals are also useful to determine whether the prediction of the forward model was accurate and whether the inverse model selected an optimal set of motor commands. However sensory feedback loops are relatively slow and noisy (Kawato, 1999; van Beers et al., 2002). The advantage of internal models is that it a priori compensates for the complex dynamics of a multijoint limb (Desmurget and Grafton, 2000; Gritsenko et al., 2009). Also, internal models can respond before the central nervous system receives sensory feedback about the actual movement, based on a rapid estimate of the consequences of the motor commands. The controller (inverse model) could therefore issue motor commands and update these commands on the basis of predictive feedback from the forward model, thus avoiding the delays in the sensory feedback loop (Miall et al., 1993; Wolpert et al., 1998).

![Figure 5: Schematic representations of the forward model including the inverse model inspired from Kawato et al. (1999) and (Bubic et al., 2010). The forward model works as a loop which is based on the efference copy of the motor command. This model is formulated for predicting the sensory consequences of an action. This prediction is then compared with the actual sensory input to test whether there is a sensory discrepancy with the desired trajectory (i.e. goal). Finally, the motor command is adjusted to match the desired goal. The inverse model works in a feedforward manner (i.e. without any need for feedback loops). The motor command will be formulated according to the desired trajectory.](image)

According to recent models, the motor command is generated in real time through an error signal that continuously compares the relative locations of the hand and target (Desmurget and Grafton, 2000; Todorov and Jordan 2002; Scott 2004). Gritsenko and Kalaska (2009) postulated that, at least in the case of target jumps, kinematics of online control could only be approximated with an error correction mechanism using a forward model to compensate for sensory feedback delays and noise,

-20-
and additionally with an inverse model to adjust the outgoing predictive motor command to the original target location in a way that takes into account the dynamical properties of the limb.

2. **Computational models: the case of the dual-rate model of adaptation**

   A. **Generality**

Researchers in motor control aspire to describe and predict the human motor behavior. However, the motor behavior is intricate, hence diverging and conflicting theories co-exist to explain similar phenomena. Movement-related data and verbal reports are sometimes insufficient on their own given the very large number of parameters that could influence motor control. To develop a theory, one way to proceed is to use computational models. Similar to physicists who can predict the motion of an apple that is dislodged from its tree and explain its trajectory, researchers in motor control intend to answer questions on the behavior by relying on mathematical models. The selection of the parameters in the model has to be specified beforehand on the basis of theoretical and empirical knowledge and then tested on new behavioral experiments. Therefore, to elaborate relevant theories, computational modelling needs to advance hand-in-hand with experimental tests of human behavior. Computational models provide a viable way of specifying complex and detailed theories of the motor system. Consequently, they may provide detailed interpretations and insights that no other experimental or theoretical approach can provide (Lewandowsky and Farrell, 2010).

Models with single-time constant of adaptation can predict motor responses to novel environment (Baddeley et al., 2003) and can assess the pattern of generalization (Donchin et al., 2003). However these models are not able to explain many other phenomena resulting from adaptation. Thereby, Smith and colleagues (2006) proposed the dual-rate model of sensorimotor adaptation. Using computational modeling, the authors suggested that two distinct processes underlie the short-term motor adaptation when subjects experience a single training session. In this model, one learning process rapidly responds to movement error but has poor retention, possibly because it is linked to a short-term, working memory, whereas another process (more akin to the long-term memory) responds slowly to movement error but retains information well from one trial to the next (Figure 6). These processes are referred to as the fast process and the slow process, respectively.

The interactions between the fast and slow processes seem to provide a unifying explanation for several phenomena in motor adaptation that were previously considered to be unrelated such as 1) savings, wherein the second adaptation to a task is faster than the first, 2) interference, wherein learning a second task interferes with the recall of the first task, 3) spontaneous recovery toward an initial adaptation period (Figure 6B) 4) rapid unlearning, wherein washout of a previously learned
perturbation results initially in some retention (i.e. after-effects) and then decreases and converges toward baseline performance.

Figure 6. Dual-rate model of adaptation (adapted from Wolpert et al. 2011). A) Both fast and slow processes incorporate for each trial part of the previous performance \(x(n-1)\) and error \(e(n-1)\). The fast process learns more rapidly (indicated by a higher learning rate, \(B_f > B_s\)) but also forgets more rapidly (indicated by a lower retention factor, \(A_f < A_s\)) compared to the slow process. The motor output is the combination of the fast and the slow output, \(x_f(n)\) and \(x_s(n)\). B) Simulations of learning in the dual-rate model. When the task parameter is set to +1, the total motor output (shown in blue) increases to reduce the error. Initially, the fast process (shown in red) contributes most to the learning but with time the slow process (shown in green) takes over and the fast process’ contribution decays. When the task parameter is set briefly to –1 (i.e. opposite perturbation), the total motor output quickly falls to zero as the fast process contributes to rapid adaptation. However, although the total motor output now has the same value as before learning, the states of the fast and slow learners are not back at baseline. When the original task parameter setting of +1 is reinstated (i.e. relearning/recovery), the overall learning is faster than the initial learning (compare the rise in the blue curves on the first and second occurrence of task parameter +1) as the slow process has retained much of their learning, thereby demonstrating savings.

B. Model simulation and fitting

As described on Figure 6A, at each trial \(n\), the motor error input \(e\) is determined by the difference between an external perturbation \(f\) and the motor output \(x\) as follows:

\[
e(n) = f(n) - x(n)
\]

The model considers two processes: the fast process that allows rapid learning of a perturbation and the slow process that allows remembering well the previous perturbation. For each process, the model assumes separate retention factors (i.e. \(A\)) and learning rates (i.e. \(B\)) which are the core factors of the processes. These two processes are combined to produce the final output \(x\).
\[
\begin{aligned}
\begin{cases}
    x_f(n) &= A_f \cdot x_{n-1} + B_f \cdot e_{n-1} \\
    x_s(n) &= A_s \cdot x_{n-1} + B_s \cdot e_{n-1}
\end{cases}
\end{aligned}
\] \\
\[A_s > A_f, B_f > B_s\]
\[
x_n = x_f n + x_s n
\]

where \(x_f\) the fast component, \(x_s\) the slow component of adaptation, \(e(n)\) the error on trial \(n\), \(A\) the retention factor, \(B\) the learning rate and \(x_n\) is the motor output on trial \(n\).

Basically, the input parameters are the motor output for each trial \(n\) and the strength of the perturbation \(f\). Then, for solving the equation, Smith et al. (2006) proposed that the model has to be constrained so that \(A_s > A_f\), and \(B_f > B_s\). Also, all the model parameters are derived from a least-square fit to the raw learning data. The least-square is a regression method that approximates solutions for the overdetermined system so that variability is minimized. It is used to increase the accuracy of the solution and it is the reason why the curves of the different processes in the model are smooth (Figure 6B).
Chapter 2

Intralimb and interlimb transfer of sensorimotor adaptation
Intralimb and interlimb transfer of sensorimotor adaptation

Adapting to a perturbation can give rise to a new kinematic and dynamic mapping between the target position and the arm motor commands. In turn, this new acquired mapping can generalize to unvisited states within the same arm (i.e. intralimb transfer) or to another effector, for instance the opposite arm (i.e. interlimb transfer). Specifically, intralimb transfer, also known as generalization, is the process by which training affects movements of the same arm in situations not previously encountered such as different targets, directions or postures. Interlimb transfer is the process by which adaptation with one arm affects the opposite arm performance.

Being able to generalize what we have learnt to slightly different movements, for instance to other directions or to the opposite arm, is a fundamental feature of our motor behavior. For instance if I grab something with my right arm and I realize that it is heavier than I thought, I may adapt my subsequent movement with my left arm accordingly. However the extent of transfer is ruled by different constrains that causes transfer not to be always automatic and optimal. Indeed while a large generalization across movement directions or effectors would seem very efficient for the nervous system, the need for specificity has also to be considered. Each movement require the coordination of different muscles, consequently it may be difficult to expect that a movement that is learnt in one specific direction to be generalized in a direction that require totally different muscles activations. For instance, upward and downward movements of the arms are controlled by different patterns of muscles activations. Similarly a reaching movement with the right arm to the right of the body midline may only require a movement of the elbow, while a movement to the left of the midline may require coordinated motions of the elbow and shoulder. Because of the anisotropy of limb inertia (Gordon et al., 1994), it seems difficult to expect learning to move a single joint to immediately and completely benefit learning to move multiple joints in a coordinated fashion. The interaction torques between the joints has led researchers to suggest that in order to predictively account for these ‘self-inflicted’ perturbations, a central representation of limb dynamics was necessary (Ghez and Sainburg, 1995). At last, specificity is needed because one arm may be different, for instance, weaker than the other: if the reaching movement undershoots the target, more muscles activations may be necessary for the reaching movement with the same limb but not for the other, stronger or non-fatigued, limb (Berniker and Kording, 2008). Therefore a trade-off between generalization and specificity of sensorimotor adaptation seems necessary to account efficiently for the motor behavior.

In the field of motor control, the study of transfer is particularly relevant to understand how the nervous system encodes the motor commands. Indeed, the motor commands may be totally tied to the limb and the movement made during training, in such case the performance would be effector specific and there would be no effect or little transfer. Or, these motor commands may stem from a general representation of the new kinematic and dynamic that is not tied to the limb. In this case, the
processes inducing the motor commands would be effector independent and would thus allow better transfer. Therefore studies on transfer give some insights into the structure of the representations formed during learning, and thus it allows inferring the underlying processes of sensorimotor adaptation (Mattar and Ostry, 2010). In other words, it sheds some lights on the local (effector specific) or global (effector independent) nature of the adaptation process. Moreover the study of transfer is beneficial to understand in which coordinate frame adaptation is encoded: is it in world-based (Criscimagna-Hemminger et al., 2003; Malfait and Ostry, 2004) or in muscle/joint- based coordinates (Krakauer et al., 2000; Wang and Sainburg, 2003)? Usually world-based coordinate system is associated with extrinsic representation of the adapted arm since it should preserve the structure of the task. In contrast joint-based coordinate system is associated with intrinsic representation of the adapted arm since it should reflect the mirror symmetry of the joints. It is the pattern of the transfer performance that provides information about the coordinate system. For example, in the study of Criscimagna-Hemminger et al (2003) the authors observed that when the movements of the nondominant arm were tested within the force-field after adaptation of the dominant arm, transfer only occurred when the forces exerted by the robot were in the same direction for both arms (i.e. clockwise perturbation). In term of joints configuration the force-field applies opposite perturbation on both arms, therefore transfer could not occur in intrinsic coordinates. However the task remained the same for adaptation and transfer (i.e. same perturbation), thus according to the results of Criscimagna-Hemminger et al (2003) interlimb transfer occurs in extrinsic world-based coordinates.

Numerous studies have investigated the patterns of transfer and a tremendous amount of conflicting results have been found. As the experimental conditions change across the studies, the conclusions on the behavioral response and the processes underlying transfer vary. A striking evidence of the fragile aspect of transfer is that it is generally partial and often quite weak (Joiner et al., 2013; Carroll et al., 2014, 2016), even sometimes absent (Harris, 1963; Cohen, 1967; Kitazawa et al., 1997; Wang, 2008). Also, the component of learning that is accessible to the other limb (interlimb transfer) or to other movements (intralimb transfer) seems to vary with several experimental factors whose influence is highly debated in the literature. For instance, in the case of interlimb transfer, it is not clear in which direction transfer occurs, as some studies claimed that transfer happens only from the dominant to the nondominant arm (Criscimagna-Hemminger et al., 2003), particularly in dynamic learning, while some other studies found that it can be bidirectional (Sainburg and Wang, 2002; Stockinger et al., 2015). Researchers also seek to maximize the extent of interlimb transfer; to that purpose they tested different ways: does it require more training, better performance in adaptation (Joiner et al., 2013), or perhaps better alignment of coordinate frame system between training and testing (Carroll et al., 2016)? As for intralimb transfer, researchers looked intensively to what extent
Chapter 2: Intralimb and interlimb transfer of sensorimotor adaptation

training can generalize to another direction, amplitude or workplace (Krakauer et al., 2000). But again, the findings can be conflicting, especially when considering both learning of visuomotor rotations and dynamic perturbations: this may be in part because these two types of learning are thought to involve fundamentally different processes (Krakauer et al., 2000; Rabe et al., 2009; Donchin et al., 2012). To explain the different results found in the literature, some studies suggested that the presence and the extent of transfer could be a result of upstream processes concerning the awareness of the perturbation (Malfait and Ostry, 2004) and/or the assignment of the error (i.e. does the error come from external or internal sources?) (Berniker and Kording, 2008). Some other recent evidence seems to argue that the extent of both intralimb and interlimb transfer depends on the alignment of the motor outputs and visual inputs between the trained and the tested movement (Carroll et al., 2014, 2016). Jointly, these studies paint a complicated picture of inter- and intralimb transfer dependent on the tasks as well as the limb used.

In this section, we discuss the different factors that may influence intralimb and/ or interlimb transfer such as the location of the targets, the perception of our actions and the handedness. Particular attention is devoted to the studies on interlimb transfer because of its predominance in our own studies; therefore some sections do not address intralimb transfer at all. Lastly, we present the putative neural substrates that may underlie intra- and interlimb transfer.

I. The extent of transfer

Experimentally, intralimb transfer is determined after adapting to specific reference target(s) by comparing the transfer performance achieved to other targets to the baseline performance of those targets. Transfer can be measured within the perturbation, in such case it is the performance to counter the perturbation that is assessed, or outside the perturbation (e.g. without visual feedback and/or perturbation), in such case it is the kinematic response to the sudden removal of the perturbation that is assessed (i.e. after-effects of transfer). Interlimb transfer is assessed similarly except that it considers the performance of one arm after adaptation with the opposite arm. The researchers can take into account different variables when assessing adaptation and transfer: 1) The direction in angle or cm of the trajectory relative to the vector from the starting position to the endpoint location of the hand. This variable can be measured at different time points in the trajectory, e.g. at peak velocity, at the maximum deviation, at a desired time point or percentage of the trajectory or at the end of the movement (endpoint location) (Dizio and Lackner, 1995; Criscimagna-Hemminger et al., 2003). 2) The correlation of the velocity profile between the baseline performance and the performance within or outside the perturbation (Brashers-Krug et al., 1996). 3) In addition, in studies using force-field perturbation with a robotic device, it is common to assess the
performance of the arms with error-clamp trials (Scheidt et al., 2000; Joiner et al., 2013). During error-clamp trials, movements are constrained to the line between the start position and the endpoint by a stiff, one dimensional spring that counteract all movements perpendicular to the target direction (Figure 13). This method allows recording the compensatory force exerted by the subject onto the walls of the channel formed by the spring. As the force field that has to be learned is not present, these trials allow measurement of motor adaptation with respect to feedforward adaptation without overlapping error feedback or learning mechanisms. These variables are chosen according to the set-up and the problematic. For example, DiZio and Lackner (1995) tested adaptation of the dominant right arm during a Coriolis force perturbation (counterclockwise), and they assessed transfer of the nondominant left arm outside the perturbation. Precisely they looked at the after-effects of the opposite naïve arm movements induced by the adaptation to the force-field. They found that the endpoint location was significantly deviated relative to the baseline movements (PRE-adaptation phase) with the nondominant arm, indicating thus interlimb transfer.

Transfer is generally incomplete such as the first naïve movement never fully reaches the performance previously acquired to other targets (i.e. intralimb transfer) or with the other limb (i.e. interlimb transfer). The extent of intralimb transfer, also known as generalization, ranges widely from 20% to 100% (Krakauer et al., 2000; Pearson et al., 2010; Lei et al., 2013). As for interlimb transfer, its presence is generally limited and account from 9% to 26% in dynamic learning (Joiner et al., 2013; Stockinger et al., 2015; Carroll et al., 2016) and for 25% to 50% in visuomotor rotation learning (Wang and Sainburg, 2004b; Taylor et al., 2011), and can also be totally absent (Martin et al., 1996; Wang, 2008). More precisely, the extent of interlimb transfer is assessed by comparing after the adaptation phase the performance of the naïve arm (within or outside the perturbation) to the level of adaptation initially achieved with the arm that encountered the perturbation first (Lei and Wang, 2014). Often the performance of the naïve arm is normalized by its baseline performance (Joiner et al., 2013). Similarly, the extent of intralimb transfer is assessed by comparing the performance to new targets to the level of adaptation achieved after adaptation to the reference target(s) (Lei et al., 2013).

Some factors can extensively influence and modify the extent of transfer such as the targets and the workplace location, particularly in generalization, and also the length of training and the visual and motor alignment between the trained and the tested limb in interlimb transfer of adaptation.

1. Intralimb transfer of sensorimotor adaptation

A body of literature examined how adaptation in one particular limb posture or direction generalizes to different postures or directions. It has been shown that sensorimotor adaptation does generalize across movement direction (i.e. angular distance) and amplitude (i.e. movement’s length). However,
there is quite a large discrepancy in the extent of intralimb transfer, and some fairly recent work showed that generalization is greatly influenced by the location of the reference target whereby generalization is tested relative to the training target(s).

In term of generalization across movement direction, it has repeatedly been shown that the extent of generalization decreases as the angular distance between the trained direction and the tested direction increases (Gandolfo et al., 1996; Krakauer et al., 2000; Mattar and Ostry, 2007). The pattern of generalization of visuomotor rotations can be modified by training to multiple targets. It has been shown that as the training directions sampled larger amounts of the workspace, the extent of generalization increased (Krakauer et al., 2000; Wang and Sainburg, 2005). However, dynamic learning (i.e. force-field perturbation) is not influenced by the extent of the workspace explored during training, but only by the distance between the tested target and the nearest trained target (Figure 7A). In other words, regardless of the number of targets used during training (e.g. single or multiple targets directions), the extent of generalization in dynamic learning falls off as the separation between trained and tested target increases (Mattar and Ostry, 2007). The inability to benefice from extensive exposure may be consistent with the idea that dynamic learning is highly localized (i.e. limb specific), and consequently even a broader representation of the association between the multiple motor commands and their sensory consequences do not provide better generalization (Gandolfo et al., 1996; Mattar and Ostry, 2007). In summary, increasing the number of targets during adaptation enhances the extent of generalization of visuomotor rotations, but it does not change the extent of generalization when adapting to force-field perturbation.

![Figure 7: Generalization of dynamic learning recorded with error-clamp trials. In error-clamp trials, movements are constrained to the line between the start position and an endpoint by a stiff, one dimensional spring. This method allows recording the compensatory force exerted by the subject onto the walls of the channel formed by the spring. A) Generalization across movement direction (Mattar and Ostry, 2007). Curvature in the reference direction (represented trajectory) as a function of the direction(s) in which subjects made training movements (colored targets). In the pictographic labels, the colored targets indicate the direction of training movements for each condition. Hand paths depict representative movements in the reference direction. The blue and the green curves represent the performance after training to a single](image-url)
target and multiple targets, respectively. Higher values indicate higher extent of generalization. Transfer decreased as the separation between training and reference targets increased for both single and multiple targets conditions. B) Generalization across movement amplitude (Mattar and Ostry, 2010). It compares the expected force (blue; force required to compensate for the force-field) to the actual force production (red). In the top figures, the first panel represents the end of training on the 15cm target. Adaptation is complete since the expected and actual forces are matched. The middle panel represents the test for generalization. The actual force is much lower than the expected force, thus transfer is not complete. The last panel on the right the forces at the end of training on the 30cm target with the opposite limb. The panels below represent the results from 30cm to 15cm. As seen on the middle panel generalization is complete.

Generalization of motor learning has also been found across movement amplitude (Goodbody and Wolpert, 1998; Krakauer et al., 2000; Mattar and Ostry, 2010). Mattar and Ostry (2010) trained participants in a velocity dependent force-field while reaching to a 15 or a 30 cm straight ahead target (Figure 7B), and generalization was tested for a shorter or longer movement (i.e. trained target: 15cm, tested target: 30cm, or vice-versa). They found that from 30 to 15cm generalization was complete, but from 15 to 30cm kinematic and force measures generalized weakly (for around 56% as reported from a figure). In the 15 to 30cm condition, the velocity resulting from a movement of longer amplitude (i.e. 30cm) was higher, and thus the amount of force needed to compensate the velocity dependent force-field was outside the range experienced during training. In contrast, the force required for a closer target (i.e. 15cm) overlapped the force experienced during training as the velocity was lower, which in turn facilitated generalization. Mattar and Ostry (2010) concluded that generalization across movement amplitude, just like generalization across movement direction, is limited because dynamic adaptation generalizes within, but not beyond the range of subjects’ previous experience. In other words, interpolation of generalization to amplitude already experienced is quite easy while extrapolation of generalization to unexplored area of the workspace is more complex.

Consistent with the line of work of Matar and Ostry (2010), a study using visuomotor rotations Krakauer et al., (2000) reported that learning generalized completely to targets located closer to the starting point (smaller amplitude), but in contrast with the former depicted study, it also substantially generalized to a further target (larger amplitude). It is difficult to state why the performances are so different between this study and the study of Mattar and Ostry (2010). Perhaps it was due to the difference in movement amplitude that was in the former study of only 33% (against 100% in Mattar and Ostry 2010), and thereby movements could have overlapped enough to lead to substantial generalization. Alternatively, the results may differ solely because these two forms of perturbation (i.e. visuomotor rotations and dynamic force-field) involve independent, or at least different, mechanisms (Krakauer et al., 1999; Rabe et al., 2009; Donchin et al., 2012). As speculated by Mattar and Ostry (2010, 2007), dynamic learning may be more dependent on the specific forces encountered by the limb, and this would be why the performances are weaker in their studies.
Motor adaptation can also generalize across workspace. In this paradigm participants must adapt to a perturbation in an area of the workspace and then move their arm to another location where generalization is tested (Figure 8A). A body of literature illustrated that movements tend to generalize outside the portion of workspace explored during the period of force-field adaptation (Shadmehr and Mussa-Ivaldi, 1994; Shadmehr and Moussavi, 2000; Malfait et al., 2002). In dynamic learning, the nature of the force field influences the extent of generalization across the workspace.

When testing generalization, if the force field is a translation of the training field in joint coordinates, the performance is near optimum. However, if the force-field is a translation of end-point coordinates (that has different effects on the muscles), the performance is much lower (around 65% of generalization) (Shadmehr and Mussa-Ivaldi, 1994; Shadmehr and Moussavi, 2000). In agreement with these results, Malfait and colleagues (2002) showed that when the joint angles were preserved between two workspaces (starting position and targets were thus displayed at different positions), generalization was better than when the hand displacement was preserved between two workspaces (while joint angles differed). These different findings support the idea that in dynamic perturbations the mapping between motion and forces are highly encoded in intrinsic, joint centered coordinates.

Figure 8: Generalization across different workspace in a visuomotor rotations task (Lei et al. 2013). A) Different configurations of the workspace: one that dissociates vision and movement, two that associates both vision and movement in the middle or in the lateral workspace. B) Comparisons of the performance (angular error) between training (left column) and generalization (right column). The smaller the first errors are in the test for generalization, the higher is the extent of transfer. As represented, a higher extent of transfer is obtained when the condition of training matches the condition of generalization.
The generalization of visuomotor adaptation across workspaces has also been demonstrated extensively in studies using visuomotor rotations (Krakauer et al., 2000; Wang and Sainburg, 2005; Heuer and Hegele, 2011; Lei et al., 2013). Most of these studies reported substantial generalization when movements from these new starting positions were made in the same direction of training (100% according to Wang and Sainburg 2005). Different studies posited that learning of visuomotor rotations relies on the remapping of movement trajectory rather than final position (Krakauer et al., 2000; Wang and Sainburg, 2005). The representations of the movement’s trajectory (or movement vector) combine the hand position to the target position in an extrinsic coordinate system. This may explain why generalization of visuomotor rotations to new workplace locations is efficient when the configurations of the targets related to the hand are preserved (Krakauer et al., 2000; Wang and Sainburg, 2005). However generalization across workspaces can be weak under some conditions.

Indeed, another study showed that when visual and proprioceptive information in terms of workspace locations are separated during adaptation (dissociation condition), generalization to new workspace locations in which the sensory mapping is preserved (association condition) is weaker than when the sensory mapping is preserved in both adaptation and testing for generalization (Figure 8) (Lei et al., 2013). The decrease in performance observed from dissociation to association condition is due to the fact that conflicting internal models of the trajectory related to the hand position are used during training and testing. According to the authors, when visual and motor workspaces are separated, two internal models (vision-based one, proprioceptive-based one) are formed, and this conflict disrupts the development of an overall representation associated with a given visuomotor condition. In other words, generalization was minimal, because the representation developed during the adaptation phase of the dissociation condition was incomplete in the first place.

As exposed in the different paragraphs above, intralimb transfer is highly influenced by the locations of the targets. This influence is not always reciprocal in studies using dynamic perturbations and those using visuomotor rotations. It is noteworthy that overall, dynamic adaptation generalizes less than visuomotor rotations (as a comparison: Matar and Ostry 2007, and Krakauer et al. 2000). This discrepancy may be due to the nature of these two types of perturbations. Dynamic learning involves a remapping of the relation between the kinematic and the forces applied on the reaching arm. Forces appear to be encoded in intrinsic, joint-based coordinates and adaptation seems to be quite local. As for visuomotor rotations, it seems to require a remapping between the desired and the actual kinematics. Based on the idea that movements are planned as a vector with independent specification of extent and direction (Desmurget et al., 1998; Krakauer et al., 2000; Wang and Sainburg, 2005), the representation of movement kinematics seems to be encoded mainly in extrinsic, world-based coordinates. Recently, Carroll and colleagues (2014, 2016) showed that
visuomotor and dynamic remapping requires both intrinsic and extrinsic representations. Their results imply that remapping of combined joint-based and direction of motion takes place in either similar neuronal networks or in different areas of the brain acting conjointly. It would be the accessibility of this neural substrate that would determine the extent of intralimb or interlimb transfer (Carroll et al., 2014, 2016).

In summary, the extent of generalization falls off as a situation differs from what has been experienced. It is clear with generalization across movement directions: the extent of generalization decreases as the angular distance between the trained direction and the tested direction increases. Similarly generalization across movement amplitude is optimal when it concerns amplitudes that were already visited during adaptation (e.g. adaptation: 30cm, test for generalization: 15cm), but generalization is considerably reduced when it concerns longer amplitude (e.g. adaptation: 15cm, test for generalization: 30cm). The same assumption applies to generalization across workspace, namely generalization is better when it preserves both similar perturbation and the mapping between the hand and the target in term of movement trajectory.

2. Interlimb transfer of sensorimotor adaptation

Interlimb transfer was initially investigated with prismatic perturbation. In this paradigm, interlimb transfer is assessed by the after-effects of the unexposed arm. Several studies reported an absence of interlimb transfer after prism adaptation (Harris, 1963; Cohen, 1967, 1973; Taub and Goldberg, 1973; Kitazawa et al., 1997). As for the studies in which interlimb transfer was significant, the extent of transfer was very small. According to Redding and Wallace, the aftereffects measured for the unexposed hand was only of 20% of that for the exposed hand. Vision of the limb appears as an important factor for interlimb transfer of prism adaptation. Indeed, it was shown that transfer occurs only with terminal feedback but not with continuous feedback of the hand position (Cohen, 1967, 1973; Wallace, 1978). This result was maybe related to the way adaptation and transfer were assessed. In these studies, because of experimental constrains, the kinematic was only measured at the end of the movement; this implies that online correction can occur during the movement, especially when the vision of the limb is available. Thus the lack of interlimb transfer in the full vision condition may be due to online control strategies. In the following sections, we address essentially more recent paradigms such as force-field perturbation and visuomotor rotations since they assess adaptation and transfer at different points of the trajectory, similarly to our experiments.

As for generalization, interlimb transfer has also been tested across the workspace (Wang and Sainburg, 2006; Wang, 2008; Carroll et al., 2014, 2016). Adapting to a rotated visual display in a separate workplace (i.e. laterally to the right for the right hand and laterally to the left for the left hand) has been shown to transfer for 25% and 10% from the dominant to the non-dominant arm,
and for 20% and 25% from the non-dominant to the dominant arm in an arm reaching movement task and an isometric force aiming paradigm, respectively (Wang and Sainburg, 2006; Carroll et al., 2014). However, in another experiment, interlimb transfer did not occur despite substantial adaptation when visual and proprioceptive information were separated during adaptation and test for transfer (Wang, 2008). The authors speculated in a subsequent study that it may be due to a conflict between vision and proprioception that may have interfered with executive decisions made by the motor system (Lei et al., 2013). In agreement with this hypothesis, Carroll and colleagues (2014) found substantial extent of interlimb transfer (up to 86%) when visuomotor distortion had identical effect in extrinsic (world-based) and intrinsic (joint-based or muscle-based) coordinates, but when there were reference-frame misalignments interlimb transfer was very little (from 8% to 19%, see Figure 9). Carroll et al. (2014) conjectured that new visuomotor maps involve both extrinsic and intrinsic movement representations and are available to both limbs. Recently they examined if this statement was also true in interlimb transfer of dynamic learning (Carroll et al., 2016). As in visuomotor rotations, it turned out that the extent of interlimb transfer was greater when the force field had identical effect in extrinsic and intrinsic coordinates in both arms than when the imposed dynamic was conflicting in terms of reference frame information (Extent of interlimb transfer 25% vs 10%, respectively) (Carroll et al., 2016). The difference in extent of interlimb transfer between the studies on visuomotor rotations and dynamic perturbations is quite important, but as stated earlier, it may result from the fundamental nature of these two forms of learning that involve, at least partially, distinct neural mechanisms (Krakauer et al., 1999; Wang and Sainburg, 2004a; Rabe et al., 2009). The weak extent of transfer observed in dynamic perturbation probably indicates that a substantial component of the internal representation is functionally inaccessible for the opposite limb (Carroll et al., 2016).
Figure 9: Performance in interlimb transfer of visuomotor adaptation according to the alignment of vision and posture (Carroll et al. 2014). A) Three different configurations of subject posture and visual display location. Visuomotor maps for the 2 hands were, in the first left panel, identical in eye-based coordinates but opposite in joint based coordinates, in the middle panel, opposite in eye-based coordinates but identical in joint-based coordinates, and in the last right panel identical in eye and joint-based coordinates. The schematic diagram illustrates only right to left condition. B) Angular error in initial direction for the left (black) and right (grey) arm during adaptation (black circle) and transfer (white circle) for the three experimental conditions. The percentage is the extent of interlimb transfer when compared the performance in adaptation and transfer for the same arm; it averages the extent of transfer in both directions. The error bars represent the standard error. C) Exponential fits to the group mean of the angular deviation across the different trials for the three experimental groups. Both fits represent the performance for the left nondominant hand. As seen on the figure B the difference of performance in much higher in the sagittal aligned group.

Different ideas have been studied to increase the extent of interlimb transfer. As for generalization across movement directions, Wang and Sainburg (2004) intended to extend the magnitude of interlimb transfer by increasing the number of targets used during training (1 vs 8 target directions). They posited that adapting to multiple targets would result in a more complete internal model of the visuomotor perturbation, which would be in turn beneficial to interlimb transfer. Their results indicated that, in contrast to visuomotor generalization (Krakauer et al., 2000), multiple direction learning does not benefit interlimb transfer of visuomotor rotations. Wang and Sainburg stated that the lack of improvement in interlimb transfer suggests that the previously reported intralimb advantage of multiple direction learning was effector specific.

Another idea to increase the extent of interlimb transfer was to extend the adaptation phase by adding more trials. This method did not significantly change the extent of interlimb transfer across the different training duration (dynamic learning: Joiner and Smith, 2013; visuomotor rotations: Lei and Wang, 2014) even if it did increase the level of adaptation (Joiner et al., 2013). However, in the
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study of Joiner and Smith (2013), the duration of the training period had a pronounced effect on the stability of interlimb transfer, with longer training resulting in substantially increased retention over the trials. They posited that during training an internal model of the required dynamic is accessible within the untrained limb. But as this representation is weak and unstable, a longer training period would result in a slower decay of the adaptation.

A very different approach to enhance interlimb transfer consisted in using model-free learning. In this paradigm the successful actions are reinforced by providing binary error feedback about the task success or failure during the adaptation phase (Wang et al., 2015). This method does not provide feedbacks of sensory errors, and it is thus classically opposed to model-based learning in which sensory errors that provide information about the movement direction and amplitude are included. Model-free learning has been shown to strengthen the retention of newly acquired movements (Shmuelof et al., 2012). Therefore, Wang and colleagues (2015) thought that reinforcing successful actions would also possibly lead to better extent of interlimb transfer. However, model-free learning did not influence interlimb transfer: the performances were similar to participants doing the task under regular feedback conditions (i.e. sensory errors). Thus, model-free learning did not seem to alleviate the effector specific component of learning.

Alternatively, in the same study of Wang and colleagues (2015) motor instances were given to the opposite limb by allowing the participants to move its arm during training. Specifically, the participants were doing the regular adaptation task with one limb while the other limb (the limb tested for transfer) was free to move to the target but without receiving any form of feedback, which prevented adapting to a visuomotor rotation with this arm. By using this method, the authors observed nearly complete interlimb transfer (i.e. >90%). The authors referred to the instance theory of automaticity proposed by Logan (1988) to account for the limitation in interlimb transfer generally observed in the literature. This model postulates that learning encompasses two independent internal models known as the algorithmic and instance-reliant learning. The first internal model results from the early portion of the exponential learning curve, and it is dominated by algorithmic learning, in which one successively improves a rule-based method of control. The improvement of the performance is thus dependent on the accumulation of specific instances of behavior (e.g. trials). The second internal model is elicited at the asymptotic portion of the curve, namely when increasing the number of instances of behavior can no longer lead to substantial improvements in performance. This internal model is caused by instance-reliant learning because at this level of performance the repetition of the movements increases the effector-specific instances. Considering that the algorithmic phase of learning represents acquisition of an internal model of the altered inertial dynamics, Wang and Sainburg (2004a, 2004b) suggested that only this aspect of learning can transfer across the limbs. Wang and colleagues (2015) showed that giving instances to the untrained arm of
the movements required to counter the perturbation during adaptation seems beneficial to interlimb transfer since the untrained arm can access internal representations of the adequate performance usually inaccessible. In contrast when the passive movement of the untrained arm was directed toward the target (thus without aiming to the direction that counters the perturbation), smaller interlimb transfer was observed (<50%). These results echo some other motor leaning studies in which passive movements of the arm along a desired trajectory increased the extent of motor learning (Wong et al., 2012; Bernardi et al., 2015). In these studies, the passive movements were beneficial to learning because it stimulated the somatosensory system. Unfortunately, the underlying mechanisms remain unclear and require further work.

These findings contribute to the emerging picture that shows relatively small extent of interlimb transfer no matter what the experimental conditions are, suggesting that motor adaptation is primarily specific to the trained arm. As a point of comparison, intralimb transfer is generally 2 to 3 times more important than what observed in interlimb transfer (Morton et al., 2001). To distinguish between these two forms of transfer, Morton and colleagues (2001) suggested that the central nervous system may elicit different internal representations of the task and the limb: one that is effector independent and that may be used by brain regions underlying the controlling of both arms’ movements, and another one that is effector specific and that may be stored in brain regions specific to a single arm. It seems that interlimb transfer remains limited across a large set of studies because the representation that is specific to the trained limb seems to share a limited amount of information with the representation of the opposite arm. As Carroll and colleagues suggested, the extent of interlimb transfer reflects the degree to which a sensorimotor map is compatible to both limbs in terms of extrinsic and intrinsic representations, and also the degree to which the motor representation is accessible to the opposite limb given that motor learning remains whatever local (Brayanov et al., 2012; Carroll et al., 2014, 2016).

II. The perception of our actions

There are alternative hypotheses to explain the discrepancy of the findings on interlimb transfer and generalization. These hypotheses are based on the way we perceive the environment and our body, considering that both can substantially influence our actions. Some authors claimed that the awareness of our environment and more specifically of the perturbation is decisive for interlimb transfer (Malfait and Ostry, 2004). Some other authors claimed that, above all, it is the perceived source of the errors that drives motor learning and by extension interlimb transfer and generalization (Berniker and Körding, 2008; Wei and Körding, 2009).
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1. The awareness of the perturbation

The role of awareness of the perturbation on interlimb transfer was originally tested by Malfait and Ostry (2004). The authors reported that interlimb transfer of a viscous force field occurred only when the perturbation was introduced abruptly but not when there was a gradual introduction over multiple trials (Figure 10A). Precisely, they reported an extent of interlimb transfer of 50% in the abrupt condition. They argued that as adapting to a sudden perturbation generates large initial errors, training results in better awareness of the force field, and thus leads to certain cognitive strategies which can influence the untrained arm. In contrast, Malfait and Ostry (2004) posited that adapting to a gradual perturbation relied more on a sensorimotor process as participants were not fully aware of the perturbation (but could still automatically counter it with the exposed arm). In line with this idea, Hwang et al. (2006) developed a model in which motor performance is a sum of a strong implicit model that is based on proprioception and is effector specific and a weak explicit model that depends on vision and is effector independent. According to their model, interlimb transfer would be a consequence of the subject becoming explicitly aware of the novel environment.

Two additional studies tested whether the awareness of the perturbation also played a role in visuomotor learning (Taylor et al., 2011; Wang et al., 2011). The results for both showed that the extent of interlimb transfer did not significantly vary between the conditions in which the perturbation was introduced abruptly or gradually. Seemingly, awareness did not favor interlimb transfer of visuomotor learning. Besides, both studies tested the effect of participants using a strategy to offset the abrupt perturbation (e.g. consciously aim at 30° to the left to counter the 30° rightward perturbation). Nevertheless, this condition did not change the extent of interlimb transfer, actually it even decreased the global level of adaptation. This result provided further support to the idea that explicit strategies, or awareness of the perturbation, have little effect on interlimb transfer. It is also consistent with several findings that revealed that applying an explicit strategy during adaptation to a visuomotor rotation tends to increase the errors over the course of the adaptation phase as sensorimotor learning is mostly driven by implicit processes (Mazzoni and Krakauer, 2006; Benson et al., 2011; Taylor et al., 2011). In other words, sensorimotor learning can occur regardless of whether the participants have explicit awareness of the condition to be learned.

Wang and colleagues stated that interlimb transfer could not be a result of a cognitive process (or at least not entirely) because some influential factors of the performance in transfer are totally unrelated to cognition, such as the order of the hands during the task (i.e. from right to left, or vice versa), the features of movement assessed (i.e. initial direction or final position) and the nature of the sensorimotor task employed (i.e. visuomotor or dynamic perturbation). Indeed, if interlimb transfer occurred because of certain cognitive strategies, the extent of transfer should not vary
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regardless of task conditions. That being said, it remains unclear why Malfait and Ostry (2004) observed interlimb transfer of adaptation only when the perturbation was introduced in an abrupt manner.

One possibility is that the reports described above disagree because the type of perturbation differed: indeed, Malfait and Ostry (2004) used a dynamic perturbation while Wang et al. (2011) and Taylor et al. (2011) used a visuomotor perturbation. To address these issues, Joiner et al. (2013) re-examined interlimb transfer of dynamic learning, and intriguingly they did not find significant difference in the extent of interlimb transfer between abrupt and gradual schedules (Figure 10B). Further, they observed an extent of transfer of only 9 to 12% which is considerably less than the 50% reported by Malfait and Ostry (2004). In an additional experiment Joiner et al. (2013) sought to examine whether this discrepancy of results was not due to the method used to test interlimb transfer: they used error-clamps (wherein movements are constrained in a channel and sensory errors minimized) while Malfait and Ostry (2004) tested transfer in the force field. Interestingly, they found that when transfer was tested during the abrupt perturbation, small kinematic errors occurred, irrespective of the orientation of the force field encountered in initial learning (i.e. counterclockwise or clockwise, Figure 10C). They argued that it was a consequence of a strong impedance control policy (i.e. muscle stiffness) in response to large errors encountered early in training. Specifically, they found that limb stiffness accounted for 75% of the apparent transfer of learning. When this percentage is brought back to the 50% of transfer observed in the study of Malfait and Ostry (2004), it appears that the true extent of transfer seemingly did not exceed 12%. Moreover, this decrease in kinematic errors could also have been the result of a learning process, since when transfer is measured with force-field trials, and not with error-clamp trials, feedback of sensory errors are presented. Especially that transfer was assessed at the angular deviation at peak velocity that occurred around 230ms which is temporally long enough to observe an effect of online correction. In summary, according to Joiner and Smith, the better extent of interlimb transfer reported in Malfait and Ostry (2004) was influenced by limb stiffness and feedback control. In agreement with Joiner et al. (2013), Carroll and colleagues (2016) recently found interlimb transfer of force-field learning irrespective of gradual or abrupt introduction of the perturbation with an extent of transfer of 10%.

To date, it seems that the awareness of the perturbation has no role or a negligible role on interlimb transfer of sensorimotor adaptation since that this type of learning is tied to implicit processes that are broadly local (Mazzoni and Krakauer, 2006; Carroll et al., 2016). However, it is reasonable to think that awareness could contribute to other types of interlimb or bimanual learning that are more cognitive in nature (Mosha and Robertson, 2016).
2. The source of the motor errors: credit assignment

The way we perceive our environment, either consciously or not, deeply influences our actions. Indeed, the process of motor adaptation can be understood as a credit assignment problem: it seems that a critical issue is to determine what the cause of an error signal is. Only once an error is considered as relevant and a cause is estimated, the nervous system can adapt accordingly (Wei and Körding, 2009). Wolpert and colleagues (2011) gave a good illustration of the credit-assignment problem: following adaptation of a force field through a robotic manipulandum, large after-effects are seen when the force-field is suddenly turned off (Shadmehr and Mussa-Ivaldi, 1994). However, these after-effects are substantially reduced when participants release the robotic handle before...
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making a movement (Kluzik et al., 2008). This result suggests that most of the perturbation was credited to the context (the grasped handle, connecting the hand to the robot, which is external to the body) while a smaller portion of the perturbation was credited to other sources, including internal sources such as changes in the dynamics of the arm. The proportion of the perturbation that is attributed to the robotic handle seems to be reduced when forces are introduced gradually over the trials so that participants are not aware of the perturbation. This would explain why the after-effects observed after gradual introduction of a perturbation are larger and are retained longer than after an abrupt perturbation (Kagerer et al., 1997; Huang and Shadmehr, 2009; Taylor et al., 2011). Similarly, Huang and Shadmehr (2009) related these robust after-effects to the statistics of the learning experience. They argued that the brain estimates a gradual introduction of a perturbation as being permanent and therefore the decay rate of memory is slow. In contrast, a sudden perturbation is rather associated with transient changes that will be thus quickly forgotten.

A source estimation model has been proposed by Berniker and Kording (2008) to formalize the problems described above. They built a probabilistic model that compensates for motor errors and estimates the sources of these errors (i.e., the body or the world). These estimations arise from the certainty of the body-based (internal causes) vs. world-based (external causes) sources that are coupled into a unique internal representation. According to this model, the pattern of transfer would change depending on whether the nervous system attributes motor errors more to the world or to the body. For instance, if errors are attributed more to the body (i.e., effector specific), motor adaptation should generalize across workspaces, but not across different motor effectors, whereas if errors are attributed more to the world (i.e., effector independent), adaptation should generalize across different effectors (Lei and Wang, 2014). Berniker and Kording (2008) gave an interesting example that highlights the role of the assignment of errors’ cause in interlimb transfer. If I throw a stone with my right hand and it travels less than I had expected, I could think of two interpretations: the stone may be heavier than I thought (external cause), or my arm may be weaker (internal cause). If I believe the stone to be heavier, I will adjust accordingly the next time I throw the same stone, with my right or my left arm because. If, on the other hand, I believe my right arm to be weaker, I will adjust future movements with this arm, with or without the stone, but not subsequent movements of my (unaffected) left arm. Further, this model offers an explanation for the inconsistent findings on extrinsic and intrinsic representations for internal models. For instance, if an action (in terms of kinematic and dynamic) reflects more an intrinsic coordinate system, the body state may be more weighted; alternatively if an action reflects more an extrinsic coordinate system, the world state may be more weighted. This model may also give an explanation on the asymmetry of transfer observed in many studies that showed that transfer only occurs from the dominant to the non-dominant arm but not vice versa in dynamic learning. Since the dominant arm is more proficient in controlling the
dynamic of the limb than the nondominant arm, the motor errors are more likely to be attributed to the environment, information that can facilitate the subsequent movement with the nondominant arm as it is effector independent. On the other hand, motor errors with the nondominant hand are more likely to be attributed to a misestimate of that limb’s properties, information that does not facilitate subsequent movements with the dominant limb.

III. The influence of lateralization on interlimb transfer

1. The direction of interlimb transfer

After reading at least some of the literature on generalization of sensorimotor adaptation, one quickly realizes there are plenty of discrepancies. One more source of conflict between the studies on interlimb transfer is the direction of learning: does it transfer only from the dominant to the nondominant arm, only vice-versa or both?

In studies assessing transfer of adaptation to a dynamic perturbation, it was thought that interlimb transfer only occurred from the dominant to the nondominant arm (Teixeira, 2000; Criscimagna-Hemminger et al., 2003; Wang and Sainburg, 2004a; Galea et al., 2007). It was hypothesized that the dominant arm yields a more proficient internal model compared to the nondominant arm and that this model is fundamental for the transfer to the contralateral arm. The idea that the nondominant arm is less proficient at developing a model of limb dynamics is consistent with findings indicating that the dominant arm and more precisely the dominant hemisphere (the left one for right-handers) is better in coordinating intersegmental dynamics than the nondominant hemisphere (Sainburg, 2002; Mani et al., 2013). Based on these hemispheric differences, Criscimagna-Hemminger et al. (2003) proposed another interpretation of the asymmetry of interlimb transfer. Since the dominant hemisphere was shown to effectively control the nondominant arm via ipsilateral projections but not vice versa (Kawashima et al., 1993; Kim et al., 1993; Gazzaniga, 2000), they assumed that when a novel dynamic is learnt by the dominant arm first, the nondominant arm can then have access to the knowledge stored in the dominant hemisphere via ipsilateral projections. However, since they did not observe significant transfer from the nondominant to the dominant arm, they proposed that when the non-dominant arm adapts first to a dynamic perturbation, the dominant arm can hardly refer to what has been previously learnt because of the absence of efficient ipsilateral projections (Haaland and Harrington, 1996; Gazzaniga, 2000).

However, recent evidence showed that interlimb transfer of dynamic learning can be bidirectional (Stockinger et al., 2015; Carroll et al., 2016). The authors argued that previous studies found an asymmetric pattern of interlimb transfer because of methodological reasons. Indeed, to assess interlimb transfer both studies analyzed lateral forces recorded with error-clamp trials (Figure
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13). Whereas the aforementioned studies analyzed kinematic variables recorded during the exposition to the force field (Criscimagna-Hemminger et al., 2003; Wang and Sainburg, 2004a; Galea et al., 2007). In these studies, the straighter movements characterizing transfer observed when first exposed to the force field with the opposite nondominant limb were likely due to adaptive impedance (i.e. arm stiffness) and online control strategies as nicely demonstrated by Joiner et al. (2013). Indeed, in their study, they reported that the compensation of the tested nondominant arm during the perturbation for transfer was similar irrespective of the direction of the force field (i.e. counterclockwise and clockwise, see Figure 10C). One possible implication of these recent findings is that the asymmetry of transfer may be explained by stronger reliance on these strategies (i.e. impedance and online correction) when exposed to the force field from the dominant to the non-dominant arm but not vice-versa. Stockinger et al. (2015), in light of their results, proposed that the formation of an internal model can be accomplished for either arm in comparable quality and serve as basis for bidirectional transfer.

In studies assessing transfer of adaptation to a visuomotor perturbation, despite a few exceptions (Wang and Sainburg, 2004b; Mostafa et al., 2014), interlimb transfer was commonly found to be bidirectional (Sainburg and Wang, 2002; Wang and Sainburg, 2006; Taylor et al., 2011; Carroll et al., 2014). Nonetheless, there exists an asymmetry of transfer on certain features of movement (i.e. initial direction or final position). There is an elegant model that explored intensively this problematic (Sainburg, 2002, 2014). It is referred to as the dynamic dominance model and it concerns the specificities of the hemispheres to control the movement (see below).

2. The dynamic dominance model: hemispherical specialization for motor control

This model was initially developed by Robert Sainburg (Sainburg and Wang, 2002; Sainburg, 2014), but it was echoed in other studies from other groups (e.g. Anguera et al., 2007). The model derives from the observations that different features of movement transfer in different directions: adaptation of the non-dominant arm to a visuomotor rotation improves the initial direction of the dominant arm movements, and training of the dominant arm improves the final position of the non-dominant arm (Sainburg and Wang, 2002; Wang and Sainburg, 2006) Based on these findings, Sainburg and colleagues postulated that the two-hemisphere/limb systems are specialized for stabilizing different features of task performance. For instance, the dominant arm more effectively accounts for coordinating intersegmental dynamics as assessed with kinematic data (Sainburg and Kalakanis, 2000; Sainburg, 2002; Sainburg and Wang, 2002) and electromyography recordings (Bagesteiro and Sainburg, 2002). In contrast, the non-dominant arm seems more proficient in controlling impedance, which leads to better movement accuracy (Sainburg and Wang, 2002; Bagesteiro and Sainburg, 2003; Wang and Sainburg, 2007).
Consistent with these reports, it was shown that individuals suffering from motor deficits following unilateral stroke reflect the hemispheric specializations described above. Specifically, right-handed patients with left (dominant), but not right (non-dominant), hemisphere damage showed reduced modulation of acceleration amplitude that were associated with poor coordination of intersegmental dynamics. However, right-handed patients with right (non-dominant), but not left (dominant), hemisphere damage made well-coordinated and fairly straight movement but showed significantly larger errors in final position, which corresponded to reduced modulation of acceleration duration (Schaefer et al., 2007, 2009; Mani et al., 2013). These impairments are visible on the ipsilateral and contralateral arm of the lesions; those results resonate with the fact that both hemispheres are involved when controlling a unilateral movement, even if the contralateral hemisphere is predominantly activated (Kawashima et al., 1993; Kim et al., 1993).

Similar findings have also been found for left-handers. That is, left-handers showed a mirror-imaged pattern of interlimb transfer in visuomotor adaptation to that previously reported for right-handers (Wang and Sainburg, 2006; Przybyla et al., 2011). However, in term of nondominant arm performance, left handers are more accurate and better coordinated than right-handers. Left-handers certainly develop better coordination of their nondominant (right) arm because of environmental pressure for right-handed manipulations.

IV. Neural mechanisms involved in transfer

1. The role of the hemispheres in interlimb transfer

Transfer of a skill learned with one hand to the other has been used as evidence for the role of the hemispheres in controlling that skill. There are two possible mechanisms by which a passive limb might access the motor program acquired by the active limb (Figure 11). For the following explanations we describe the case of right-handers.

Bilateral access models entail that the motor engram is encoded in a single network that is accessible by either hand (Ruddy and Carson, 2013). According to the callosal access hypothesis (Taylor and Heilman, 1980) the motor engram, that is located exclusively within the dominant (left) hemisphere (in right-handers), would be accessible to both limbs through callosal connections. This hypothesis predicts better transfer only from the dominant to the nondominant arm. Precisely, the nondominant right hemisphere would be trained via the callosal connections during the time that the left dominant hemisphere is being exposed to the perturbation. This would in turn lead to interlimb transfer when the nondominant left arm is tested. Criscimagna-Hemminger et al. (2003) rejected the callosal access hypothesis because they tested a split brain patient (i.e. complete resection of corpus callosum) who could efficiently elicit interlimb transfer of dynamic learning. Even
if callosal projections may be part of the processes involved in interlimb transfer (Ruddy and Carson, 2013), it may not be the main and/or the only mechanism on which interlimb transfer relies on. Although this hypothesis emphasized the role of the corpus callosum as a means for information transfer from a single hemisphere in which the motor engram has been elaborated, such a connection may not be necessary. Rather, the motor engram could be encoded in a more abstract fashion, at a locus that is also accessible for the control of the opposite untrained limb without callosal projections (Perez et al., 2007; Ruddy and Carson, 2013; Figure 11 modified model).

![Diagram of each model of interlimb transfer based on Anguera et al. 2007. The diagram is presented for a given right-handed individual. The top row represents activation during right-hand (RH) adaptation for each model, while the bottom row represents activation at transfer with the left hand (LH). 'M' illustrates the location of the motor programs used/developed during RH adaptation or at transfer with the LH following RH adaptation. The bilateral models posit that the representation of the acquired movement is stored in a network accessible for both hands. The callosal model states that at transfer, the right hemisphere gains access to the acquired representation (note the faded 'M'), which was stored in the left hemisphere, via the corpus callosum. The modified bilateral model states that the representation is stored in a nucleus. The cross-activation model states that during right-hand adaptation, a weaker version of the motor program is created in the right hemisphere (note the smaller 'M'), and it is this program that would be used at transfer. The modified version of the cross activation model hypothesizes that a weaker version of the motor program will be accessible via the left hemisphere at transfer with the left-hand. Alternatively, the cross-activation model (Parlow and Kinsbourne, 1989) posits that the representation of the required movement could occur simultaneously in both hemispheres following training with the dominant arm (Figure 11). Thereby, the motor program would be specified predominantly in the contralateral dominant hemisphere but also to a lesser degree in the ipsilateral non-dominant hemisphere. In that case, the non-dominant untrained arm will have access to the weaker representation stored in the ipsilateral hemisphere of the trained arm. The callosal model and the cross-activation model have mostly addressed the issue of transfer from the dominant to the nondominant arm because in their studies transfer was only observed in that direction. But since then interlimb transfer was observed in both directions. Therefore if interlimb transfer from the
nondominant to the dominant arm presents a mirror pattern of hemispherical activation as described above, perhaps these models could partly explain transfer in either direction such as implicitly proposed in other studies (Sainburg and Wang, 2002; Wang and Sainburg, 2006; Stockinger et al., 2015). For instance, Sainburg and Wang (2002) proposed a modified access model, which states that information stored during learning with either arm can subsequently be accessed by its contralateral homologue.

Several studies referred to the cross-activation model to explain their results. For instance, Joiner et al. (2013) speculated that the weak representation of the required compensation (within the ipsilateral hemisphere) is unstable, and thus quickly decays during the retention period. However, they observed that transfer was slower to decay with prolonged training, probably because the weak internal representation became more stable. This model is also in line with the findings of Stockinger et al. (2015), who failed to observe retention of interlimb transfer after a period of 24 hours. Regardless of the number of trials, the unexposed period was probably too long to retain the weaker representation that is usually available for the opposite limb.

It is possible that the hemisphere that was used during adaptation with the contralateral arm can also control the ipsilateral arm (Criscimagna-Hemminger et al., 2003). In other words, in the cross-activation model, it is assumed that it is the ipsilateral hemisphere of the trained dominant arm that contributes to interlimb transfer (i.e. right hemisphere if the participant is right-handed). But as proposed by Criscimagna-Hemminger et al. (2003), it may be the contralateral hemisphere of the trained dominant arm that allows eliciting transfer through ipsilateral projections (i.e. left hemisphere if the participant is right-handed). This alternative of the cross-activation model may be a key explanation of the asymmetric behavior described in some studies in dynamic learning (Crismagna-Hemminger et al. 2003). Indeed, the movements of each arm are represented by greater activation in its contralateral hemisphere but the amount of ipsilateral activation is greater when using the nondominant arm (Kawashima et al., 1993; Pool et al., 2014). It has been suggested that the dominant hemisphere can effectively control the nondominant arm but not vice versa. For instance, when split brain patients are asked to point toward a visually presented target, if the visual information is presented to the left hemisphere, reaching with the ipsilateral arm is highly accurate (Gazzaniga, 2000). If the visual information is presented in the left hemisphere. However, if the target is presented in the right hemisphere, reaching with the ipsilateral arm is only moderately accurate. While this alternative view of the model does not clearly state how interlimb transfer can occur from the nondominant arm to the dominant arm, we could hypothesize that there are two possibilities: either through ipsilateral or contralateral activations of the untrained nondominant arm.
In summary, it is still unclear how interlimb transfer works but it could result from a combination of ipsilateral activations (either during training or testing for transfer), callosal projections and contributions of subcortical areas, with different weighting on each process.

2. Putative neural substrates involved in intralimb and interlimb transfer

Multiple distinct processes seem to come into play to explain transfer of learning. Unfortunately, the neural substrates of transfer that have identified seem to vary according to the type of task, the direction of training and the neurophysiological technics used to record the performance. Thus they do not really help to clarify the globally complex issue of transfer.

fMRI\textsuperscript{1} investigations found that the regions involved in interlimb and intralimb transfer of visuomotor adaptation are similar to those involved at the end of the adaptation phase (Figure 12). (Seidler and Noll, 2008; Seidler, 2010). Seidler and colleagues (2008, 2010) found that intralimb transfer was associated with a reduction in activity of brain regions that play a role early in the adaptation process, including the right inferior frontal gyrus, primary motor cortex, inferior temporal gyrus, and the cerebellum (medial HIII and lateral HIV/V). Moreover, the degree of transfer was correlated with activity in the right cingulate gyrus, left superior parietal lobule, right inferior parietal lobule, left middle occipital gyrus, and bilaterally in the cerebellum (HV/VI). These results are in line with the dual-rate model put forth by Smith et al. (2006) that postulates that two processes underlies adaptation: one more active at the beginning of the adaptation phase (fast process) and another one more active at the end of the adaptation phase (slow process). Overall, it thus seems that the brain structures involved in intralimb transfer as described by Seidler et al. (2008, 2010) characterize the slow process. They stated that transfer seems to involve retrieval of a previously formed motor memory, allowing the learner to move more quickly through the early stage of learning.

In Seidler work, interlimb transfer was associated with activation in the temporal cortex as well as the right medial frontal gyrus and the middle occipital gyrus (Anguera et al. 2007). For intralimb transfer and for intralimb transfer the right inferior frontal gyrus, primary motor cortex, inferior temporal gyrus, and the cerebellum (medial HIII) (Seidler and Noll, 2008). These regions have been observed in another study during the late phases of sensorimotor adaptation (Seidler, 2004).

\textsuperscript{1} Functional magnetic resonance imaging
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Figure 12: Brain areas contributing to early (square) and late (circle) intralimb transfer of learning (Seidler, 2010). Early learning involves the medial cerebellum (MC), the anterior cingulate cortex (ACC), the inferior frontal gyrus (IFG), and visual (VC) and parietal (PC) cortical areas. According to Seidler et al. (2008, 2010) intralimb transfer of learning is associated with reduced contributions of the early learning network, and overlapping activation with late learning regions. Late learning involves the lateral cerebellum (LC), parietal (PC) and cingulate motor areas (CMA). Transfer of learning is associated with reduced contributions of the early learning network, and overlapping activation with late learning regions.

Perez and colleagues ran a number of experiments to investigate the neurophysiological mechanisms involved in intermanual transfer of skills. They used serial reaction time tasks in which motor sequence skills (i.e. typing keys) were tested first with the dominant hand, then with the nondominant hand. They found that the supplementary motor area (SMA) could encode a memory trace that can be accessed by both hands (Perez et al., 2007a, 2008). When repetitive transcranial magnetic stimulation was applied over the SMA, it blocked intermanual transfer without affecting skill acquisition. Further, they found that the BOLD\(^2\) activity of the ventrolateral posterior thalamic nucleus was positively related to good intermanual performance (Perez et al., 2007a). They also identified that some aspects of the performance with the transfer hand (nondominant hand) was associated with decrease of interhemispheric inhibition between the motor areas (M1) from the dominant to the nondominant hemisphere (Perez et al., 2007b). This finding is consistent with the cross-activation model which speculates that transfer results from activation of the ipsilateral hemisphere of the trained arm (i.e. right hemisphere).

To date, it is difficult to state which neural substrates specifically underlie interlimb transfer of dynamic learning (Joiner et al., 2013). Some imaging studies that examined force-field adaptation found bilateral activation in the primary and secondary somatosensory cortex during early learning (Diedrichsen et al., 2005) and bilateral activation of prefrontal cortex and the deep nuclei of the cerebellum late in learning (Nezafat et al., 2001). Since both hemispheres are involved in the

\(^2\) Blood oxygen level-dependent
Intralimb and interlimb transfer of sensorimotor adaptation performance, it echoes the cross-activation model whereby interlimb performance results from the ipsilateral activation of the trained arm. In addition, some cells in primary motor cortex and dorsal premotor cortex demonstrate effector-independent activity; the cells discharge for both contralateral and ipsilateral arm movements, supporting the view that both contralateral and ipsilateral training may affect the same neural substrates (Donchin et al., 1998; Cisek et al., 2003). Presently it is difficult to distinguish whether interlimb transfer of force-field perturbation is the result of two separate internal models formed based on a common error or whether it is the result of the transfer of the adaptation from the trained to the untrained hemisphere.
Chapter 3

The expressions of motor memory
As seen in the previous chapters, one of the defining features of primates is the remarkable ability to learn and acquire skills. These skills encompass a wide array of behavior which can closely interact such as social, intellectual and motor abilities. The acquisition of a skill as well as the adaptation to novel conditions are shaped by practice and knowledge. For instance, learning how to do a backhand with a tennis racket requires practice, but eventually after several training sessions and successful actions, the new skill becomes automatic and permanent. This switch from practice to automatic successful actions stems from the formation of a long-term motor memory. In cognitive sciences, motor memory often refers to the implicit/procedural memory which resides below the level of conscious awareness as the stored actions can be automatically retrieved without the need of conscious control or attention. Procedural memory is classically opposed to the explicit/declarative memory, a form of memory of facts and events that can be consciously recalled such as remembering an event from years ago or an appointment (Cohen and Squire, 1980). Both forms of memories seem to be fundamentals to adapt and evolve in our environment. Indeed, the capacity of the declarative memory to reconstruct past experiences constitutes the core of our personal identity (Locke, 1841), while the procedural memory is the expression of our intention and motivation. Considering the human motor behavior, the capacity to remember past experiences certainly seems critical to any learning and adaptation. It has been hypothesized that declarative and procedural memories are independent processes. This conception arises from studies on people suffering from amnesia who, following the onset of neurological impact, can generally not store semantic information (e.g. about events or knowledge) but can learn and retrieve implicit motor skills such as a hand-eye coordination skill (i.e. mirror drawing) (Milner, 1965; Milner et al., 1998). In contrast, an alternative approach considers these two processes as tightly coupled. It postulates that the development of sensorimotor capacities (i.e. implicit abilities) not only enables us to successfully interact with the environment, but it also allows us to develop cognitive processes (i.e. explicit abilities)(Piaget and Cook, 1952; Wilson, 2002). According to Ester Thelen “both sensorimotor capacities and cognition would be inseparably linked, together they would form the matrix within which memory, emotion, language, and all other aspects of life are meshed” (Thelen et al., 2001).

In this chapter, we discuss the studies concerning motor memory. Notably, we expose the specific behavioral forms of memory observed in motor learning paradigms: retention, savings and in a latter part consolidation of motor memory. And secondly, we relate these forms of motor memory to some specific sub-processes of adaptation.

I. The forms of motor memories involved in adaptation

Adapting to a perturbation can lead to the formation of a motor memory. One form of motor memory is retention of a fraction of learning which is generally tested between learning or
adaptation sessions. The other form of memory is exhibited through savings, whereby learning or adaptation is faster the second time the perturbation is encountered. Both retention and savings can be observed in a short-term period (Cricimagnana-Hemminger and Shadmehr, 2008; Kitago et al., 2013), a few minutes after initial learning, or in a longer-term, hours, days or weeks after initial adaptation or learning (Brashers-Krug et al., 1996; Shadmehr and Brashers-Krug, 1997; Joiner and Smith, 2008). There is an additional form of motor memory which is a more flexible and durable expression of savings and retention and this is referred as consolidation of motor memory. Thereby, a motor memory is consolidated, namely stabilized, when it becomes less sensitive to interference and more stable with the passage of time (Robertson et al., 2004). These types of motor memory are not mutually exclusive, and might be complementary. But their behavioral properties and the criteria that must be satisfied to demonstrate their existence differ. Here we discuss the evidence for these three types of motor memory which most likely underlie trial-to-trial sensorimotor adaptation.

1. Retention of motor adaptation

When a motor output results in an error detected by the sensory system, a change in the motor command is required to successfully do the task on the subsequent trial. The repetition of trials result in a memory trace that can remain for days, weeks or month after training (Shadmehr and Brashers-Krug, 1997; Yin and Kitazawa, 2001; Joiner and Smith, 2008). This process is called retention of motor adaptation and it is probed differently according to the type of paradigm.

Retention of sensorimotor adaptation has been studied for a long time (Harris, 1963; Martin et al., 1996; Fernández-Ruiz and Díaz, 1999; Sarlegna et al., 2007). It started initially with prisms studies in which once the prisms are withdrawn, the degree and strength of the adaptation can be measured by the aftereffects (Harris, 1963). It was showed that prism aftereffects depend on the number of interactions between the visual and the motor systems (thus on the number of trials) and not on the time wearing the prisms, specifically if there is no interaction, there is no aftereffects (Prablanc et al., 1975; Fernández-Ruiz and Díaz, 1999). In addition the persistence of aftereffects depends on the number of trials after adaptation is complete: the greater the number of trials the longer the retention of aftereffects (Fernández-Ruiz and Díaz, 1999; Inoue et al., 2015). More specifically, aftereffects do not decay gradually: the initial decay is substantial within the first 6 hours, then the aftereffects recover from day 1 to day 3 (i.e. it increases slightly), and are present up to seven days later (Hatada et al., 2005). The drawback of this technic to measure retention is that it provides both motor and visual feedback errors and thus relearning overlap with retention.

In visuomotor rotation paradigms, retention can be assessed while visual feedback of the hand is occluded (Galea et al., 2011, 2015). The target remains visible throughout the trial but the cursor representing the hand disappears once the hand move out of the starting position. As the visual error
signal is absent, the error-dependent learning is minimized and the recorded motor output may remain stable and retention may be observed more easily.

In force-field adaptation paradigms, retention is assayed through error-clamps trials (Scheidt et al., 2000; Criscimagna-Hemminger and Shadmehr, 2008; Joiner and Smith, 2008) in which the movement is constrained to the line between the start position and an endpoint by a stiff, one dimensional spring (Figure 13A). This method allows recording the compensatory force exerted by the subject onto the virtual walls of the channel formed by the spring. When error-clamps are applied after the training session the memory trace is reactivated but the error-dependent learning is minimized because there is no kinematic error. In other words, we can still observe the changes resulting from learning to compensate for the novel force field but, because of the absence of visual feedback and proprioceptive mismatch and thus sensory errors, de-adaptation is minimized.

Also, in both visuomotor and force-field paradigms, retention can be tested during a washout period (i.e. via after-effects) such as in prism paradigms (Scheidt et al., 2000; Hadipour-Niktarash et al., 2007; Galea et al., 2011; Kitago et al., 2013; Panouillères et al., 2015) in which the error of the movement is visible. The drawback of this method is that, trial after trial, retention decays because participants adapt based on motor errors and correct their movements accordingly (Galea et al. 2011).

Figure 13: Retention in force-field learning. A) Representation of an error-clamp trial (Joiner et al., 2013). The movements are constrained to a straight line by a stiff one-dimensional spring. The blue arrows represent the forces exerted on the hand. The green circle is the target, and the black arrow, the hand path. B) Evolution of the adaptation index assessed with error-clamp trials over an experiment (Brennan and Smith, 2015a). The curve of the 500 last trials represents the retention immediately after learning (blue and orange dots) and 24 hours after (brown dot).

After training, it has been shown that the memory trace decays rapidly back to baseline (Lackner and Dizio, 1994; Martin et al., 1996; Scheidt et al., 2000) When the participant is not in the context of the task, the memory induced by a robotic perturbation decays with a time constant of approximatively 18.5 hours. In the context of the task, this memory decays in 1-3% per trial, which translates into a time constant of 200-600 ms (Criscimagna-Hemminger and Shadmehr, 2008). Most
of these studies explained the memory decay by asserting that memory is transient and decreases in
the absence of ongoing error signals. Therefore, the reduction of the memory trace would be
attributed to the natural process of forgetting which can be seen as a useful feature supporting
robust motor learning. Indeed, transient motor memories are more appropriate in the context of
unstable environments just as stable memories in persistent environment. These processes which
differ according to the context allow flexibility in the motor control system (Kording et al., 2007;
Huang and Shadmehr, 2009).

Even if the memory trace irremediably decays after training, a small fraction of learning remains
resistant to forgetting (Criscimagna-Hemminger and Shadmehr, 2008; Brennan and Smith, 2015a). To
investigate the decay of learning, Brennan and Smith (2015) tested 500 error-clamp trials after
learning of 200 reaching movements with a viscous curl force-field (Figure 13B). They found that the
amount of retention observed at the end of the error-clamp period was strictly the same when
tested again 24 hours later and represented approximately 21% of the level of adaptation achieved
at the end of learning. This decay-resistant component of learning was stable against a longer
extinction period and its amount could not be improved by repetitive training periods. These results
reveal that a small fraction of learning is resistant to decay and training, and remains stable over a
long period of time.

Retention of motor adaptation can also be observed within the motor task (Brashers-Krug et al.,
1996; Krakauer et al., 2005), namely when the perturbation is applied again after initial adaptation
(immediately, hours or days later). For instance, Krakauer and colleagues (2005) found that re-
adaptation to a visuomotor perturbation one week after initial adaptation to the same visuomotor
perturbation leads to smaller initial errors in the first movements relative to those in initial learning
(Figure 14A). Similarly, Panouillères et al. (2015) ran an experiment to investigate the improvement
of motor adaptation. Here, they used a visuomotor adaptation task in which the movements were
controlled by a joystick. They tested the performance on a second adaptation period after a 50
minutes break. As Krakauer et al. (2005), they observed in the first trials of the second adaptation
phase errors of smaller magnitude than in initial learning.
Figure 14: Adaptation curves over a first session (white) and a second session (black, one week later) in the study of Krakauer et al. (2005). A) The smaller offset in the first trials on relearning one week after initial learning characterizes retention of sensorimotor adaptation. B) Both curves start at the same performance but on relearning 48 hours later, the participants adapted faster, hence characterizing savings of sensorimotor adaptation.

2. Savings of motor learning

A learning curve represents the performance during the acquisition of a skill, how it changes trial after trial. Such curves are often used to compare the effect of practice and context manipulations on motor performance. For instance, the slope of the curve, which indicates the rate of motor learning for a task, may be used to investigate the formation of a motor memory. When the slope of the curve is steeper when sensorimotor adaptation is assessed a second time relative to initial sensorimotor adaptation, it reflects an improvement in adaptation which characterizes savings of motor acquisition. In other words, savings is characterized by faster learning the second time the task is experienced (Figure 14). As retention, savings can be observed within a few minutes (Kitago et al., 2013), hours or days (Brashers-Krug et al., 1996; Shadmehr and Brashers-Krug, 1997; Stockinger et al., 2014) or even a week (Krakauer et al., 2005) after initial adaptation. In the context of the research tackling these issues by testing visuomotor or force-field adaptation of reaching movement, savings is observed while assessing the acquisition of the motor skill, contrary to retention that is mainly assessed when the perturbation is removed (Kantak and Winstein, 2012; Stockinger et al., 2014). However, both retention and savings can be combined and observed in the same performance. For instance, in Krakauer 2005 (Figure 14A), not only is adaptation faster (i.e. savings) but also the first trials show a smaller offset at re-learning (i.e. retention). The improvement in learning rate from one learning session to another appears to be sensitive to multiple experimental conditions.

The perturbation schedule in a motor task influences the performance in re-learning. Specifically, challenging schedules resulting in large and unexpected errors in initial learning are beneficial to savings (Stockinger et al., 2014; Orban de Xivry and Lefèvre, 2015). A recent study showed that faster re-learning is observed after abrupt but not after gradual introduction of a visual perturbation.
This study also reveals that it is the errors encountered at the beginning of the initial learning phase that yield to the formation of a motor memory responsible for savings thereafter. The effect of large errors is also observed in dynamic perturbations. Indeed, the random and intermittent introduction of catch-trials, in which the force-field are removed, during the initial learning phase, result in better savings performance in the subsequent exposition of the perturbation (Overduin et al., 2006; Stockinger et al., 2014). This may be because large errors enhance the ability to form an appropriate internal representation of the perturbation, which in turn may lead to better performance in savings thereafter. However, large errors do not improve initial learning (Overduin et al., 2006) and can even worsen it (Stockinger et al., 2014), because it increases the uncertainty which prevents the sensorimotor system of accurately predicting the disturbing forces (Franklin and Wolpert, 2008). An alternative interpretation, as to why large errors are beneficial to savings, may be found in skill learning studies. A study of Kantak and Weinstein (2012) for instance suggests that challenging and variable practice schedules influence memory formation causing deeper cognitive processing and therefore stronger and more elaborate motor memory representations (Kantak and Weinstein, 2012).

In sensorimotor adaptation, Orban de Xivry and Lefèvre (2015) suggested that large errors give rise to model-free learning whereby movement correction is prompted by reward prediction errors. Specifically in model-free learning the successful actions are reinforced by providing scalar or binary error feedback about the task success or failure during the adaptation phase. This method does not provide feedbacks of sensory errors, and it is thus classically compared to model-based learning in which sensory errors about the movement are available. The importance of the reward prediction error has been highlighted in a study showing how it can be used to retrieve a previously learned motor memory and lead to savings regardless of the state of the internal model (Huang et al., 2011). The paradigms that put forth the causal relationship between model-free learning and savings use operant-reinforcement. Specifically in this framework, two opposite perturbations are learned in two separate sessions (e.g. A: 30° visuomotor rotation then B: -30° visuomotor rotation), and the targets are arranged so that the solution required to counter any of the perturbation coincides in hand movement direction. In this situation, savings occur from session A to B because the particular movement associated with reward creates an attractor centered on the movement in hand space. In other paradigms whereby similar targets are used for opposite perturbations, model-based learning carries greater weight and savings does not occur because there is a conflict between the hand-space solutions associated with success in sessions A and B. Therefore, recent evidence claimed that enhanced relearning relies more on a model-free memory for successful actions, rather than on the reexpression of a previously learned internal model (Huang et al., 2011; Huberdeau et al., 2015; Orban de Xivry and Lefèvre, 2015). It is noteworthy that cognition contributes more to model-free,
reward-based (Ridderinkhof et al., 2004) than to model-based learning which is considered rather like an implicit process. This dichotomy with respect to the involvement of cognition echoes studies in skill learning that postulate that the memory formation is enhanced by cognitive control in learning (Kantak and Winstein, 2012).

In a similar vein, recent evidence showed that explicit but not implicit components of learning may be responsible for savings (Haith et al., 2015; McDougle et al., 2015). Several studies in sensorimotor learning (Keisler and Shadmehr, 2010; Benson et al., 2011; Taylor and Ivry, 2014) and in postulate that explicit contributions are large and exploratory early in learning and then implicit learning takes over to stabilize and reinforce learning. The role of the explicit component in the formation of a motor memory is endorsed by the finding that declarative memory (that is typically associated with awareness) allocates resources to the process underlying savings. Indeed, Keisler and Shadmehr (2010) showed that this process is disrupted if a cognitive task that engages declarative memory follows initial learning and consequently savings does not occur on relearning (Keisler and Shadmehr, 2010).

In summary, savings seems to be attributable to large and unexpected errors (Overduin et al., 2006; Stockinger et al., 2014; Orban de Xivry and Lefèvre, 2015) that probably enhance the contribution of reward prediction errors useful for the recall of a previously successful action (Huang et al., 2011). Also, motor learning has to engage explicit and declarative processes to exhibit savings (Keisler and Shadmehr, 2010; McDougle et al., 2015). Taken together these findings highlight the idea that the formation of a motor memory through savings may result from higher-order cognitive strategies sensitive to task success and less from automatic sensorimotor policies (Figure 15).
3. Consolidation of the motor memory

The declarative memory is characterized by its ability to retain a tremendous amount of semantic knowledge. For instance, as a child, we all had to learn the multiplication tables. And we had to challenge ourselves through learning and forgetting phases before the knowledge was stored, more or less, within our mind. This phenomenon of remembering is made possible by the neuroplasticity whereby lasting changes occur within the neurons (Cajal, 1894; Hebb, 1955). Similar to the declarative memory, the motor memory is able to store and recall skills.

New motor memories are initially labile and susceptible to interference, but over time the motor representations progressively become more stable and resistant to such interference (Rachman and Grassi, 1965; Robertson et al., 2004). For instance, if we start playing tennis and squash in the same period of time, some habits learned during the first session which happened to be the tennis session may have to be unlearned as we start the first squash session. Over time, two distinct and independent motor representations may be developed, just like distinct representations underlie our behavior with or without glasses (Martin et al. 1996). This time-dependent process is generally referred to as memory consolidation and it contributes to enhanced performance when the adaptation is assessed a second time (Robertson et al., 2004; Krakauer and Shadmehr, 2006). Specifically consolidation of motor memory refers to the capacity of the nervous system to transform an initial fragile motor memory into a robust and stable motor memory (Robertson et al. 2004). Numerous studies investigated the consolidation process of the motor memory by using an A-B-A
paradigm (where A and B designate opposite perturbation) in the context of dynamic adaptation of reaching movements (Brashers-Krug et al., 1996; Shadmehr and Brashers-Krug, 1997; Caithness et al., 2004; Overduin et al., 2006; Focke et al., 2013; Stockinger et al., 2014) and visuomotor adaptation of reaching movements (Alahyane and Pelisson, 2005; Krakauer et al., 2005). Thereby, consolidation is tested by interlaying an interference task B of opposite perturbation between initial learning and relearning of task A (Figure 16).

![Figure 16: Representation of an experiment testing consolidation of motor memory (inspired from Robertson et al., 2004). The slope of the curve in relearning is smaller than in initial learning, thus savings occurs. Two types of interference to savings can be observed: retrograde interference from task B to task A, and anterograde interference from task B to task A2.](image)

Recently, consolidation of motor memory is often characterized by faster relearning, i.e. savings, and it is observed under certain conditions. One of the main concerns seems to be the temporal difference between the tasks within the experiment. Take the Figure 16, the task B may interfere with relearning of task A if sufficient time between initial learning A and the task B is not allocated (retrograde interference, illustrated Figure 16). Studies using a dynamic perturbation showed that an interval of 4 to 5.5 hours between initial learning of task A and task B is needed to prevent retrograde interference (Brashers-Krug et al., 1996; Robertson et al., 2004; Shadmehr and Brashers-Krug, 1997). However, in visuomotor and prism adaptation, several studies failed to replicate these results (Bock et al., 2001; Goedert and Willingham, 2002; Caithness et al., 2004) as they reported a flat gradient of interference: task B prevented savings in task A regardless of the interval between A and B. These findings suggested that consolidation may not occur in visuomotor adaptation.
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However, an alternative hypothesis argued that the absence of savings, rather than being a result of an incapacity of consolidation, was certainly due to an incapacity to maintain and/or to retrieve the expression of the memory (Dudai, 2004; Krakauer et al., 2005; Krakauer and Mazzoni, 2011).

This hypothesis was borne out by an additional study revealing that anterograde interference (from task B to relearning of task A, Figure 16) was masking ongoing consolidation (Krakauer et al., 2005). The authors could erase the interference by adding blocks of baseline trials as washout before relearning (Robertson et al., 2004). Krakauer et al. (2005) observed that when the subjects returned to their baseline performance, consolidation in the form of savings was found in relearning two days after initial learning. Besides, the amount of improvement on relearning increased as the time interval between the interference task B and initial learning grew. At 24 hours, there was no interference, namely no reduction of performance on relearning as compared with control subjects (i.e. who did not experience an interference task). At 5 min and 2.5 hours, relearning was faster but smaller than in control subjects, the 2.5 hours group performing better than the 5 min group, thus showing an effect of retrograde interference.

In summary according to the studies on motor consolidation, interference of dynamic adaptation is mediated by retrograde, not anterograde, mechanism, while interference of visuomotor adaptation is mediated by both retrograde and anterograde mechanisms. Perhaps dynamic adaptation is more sensitive to retrograde interference and visuomotor adaptation to anterograde interference (Miall et al., 2004). Alternatively anterograde interference may have been absent from the studies of Shadmehr’s group (1996; 1997) because of methodological reasons. Indeed, in their studies, the time delay between interference and re-adaptation may have been long enough to erase the anterograde mechanism. In the experiment of 1997, relearning was made 1 week after initial adaptation. The authors stated that they wanted to ensure against any anterograde effects because in their previous study (Brashers-Krug et al., 1996) in which re-adaptation was tested 24 hours later, they observed “poor” performance of consolidation that they associated to anterograde interference.

To our knowledge, there is only one study that addressed consolidation of retention with an ABA paradigm (Criscimagna-Hemminger and Shadmehr, 2008). In this study, the authors disrupted the memory of a perturbation A (session of 384 trials with what type of perturbation) with the short introduction of a perturbation B (session of 20 trials) right after initial learning of A. Then retention was assayed by means of error-clamp trials at different time interval. They found that at 0 and 2 minutes after initial learning A the memory of B was competing with the memory of A. At the beginning of the error-clamp trials, the motor output was close to the baseline performance but trial after trial, the motor output converged to the motor output characterizing retention of the memory of A only. This early influence of B on A is attributable to retrograde interference. At 6 and 24 hours
after initial learning, the motor output was totally unaffected by the memory of B, revealing thus a form of retention of consolidation.

II. Role of the sub-components of adaptation in the motor memory

Adaptation is the result of many processes (see chapter 1-II), each differing qualitatively. Its study is critical to understand the nature of the motor control system and its properties. In classical adaptation paradigms, it is challenging to identify these different processes since the measured behavior corresponds to the summed contribution of all components. However, Smith and colleagues (2006) put forth a computational model, i.e. the dual-rate model, which dissociates some of these processes so that it can be independently measured. This model suggests the existence of at least two processes: the fast process that learns quickly from movement errors but forgets fast, and the slow process that learns slowly from movement errors but remains stable over time (see chapter 1-II). As described above, both savings and retention stem from the formation of a motor memory but have different properties. The integration of the dual-rate model into behavioral studies of reach adaptation has shed some new light on the respective upstream processes of retention and savings.

Joiner and Smith (2008) showed that retention is not predicted by the overall performance level but rather by the level of the slow process achieved at the end of the initial learning phase (Figure 17A). In particular, they found that 24hr long-term retention corresponded to 60-70% of the slow process learning level (see also Brennan and Smith, 2015). The slow process encompasses an implicit and procedural form of learning that is driven by sensory prediction errors (Keisler and Shadmehr,
Chapter 3: The expressions of motor memory

2010; Huberdeau et al., 2015; McDougle et al., 2015) As illustrated on Figure 17A, the slow process tends to dominate late rather than early in learning. This property supports the idea of an involvement of the slow process into implicit learning; indeed it is widely considered that a motor skill becomes automatic and requires less attention after some time of training. Another property of the slow process is its ability to exhibit small decay as a function of time, hence it is referred as the temporally stable component of adaptation (Sing et al., 2009; Hadjiosif and Smith, 2013; Brennan and Smith, 2015a)

On the other hand, savings relies rather on the modulation of the fast process. This process engages explicit components of learning. McDougle et al. (2015) dissociated in their study explicit learning (using verbally reported strategies) from the implicit component in a typical sensorimotor task. They found striking similarities between the purported fast process and explicit learning and also between the slow process and implicit learning (Figure 17B). The contribution of the explicit form of learning in savings is also supported by the evidence that the fast component of motor learning shares critical resources with the declarative memory (Keisler and Shadmehr, 2010). Also, the fast process is described as decaying rapidly with time constants of 15-20 seconds (Sing et al., 2009). Contrary to the slow process that is stable across breaks, the fast process is referred as the temporally labile component of learning (Hadjiosif and Smith, 2013; Brennan and Smith, 2015a). Another property of the fast process is its sensitivity to reward (Huberdeau et al., 2015). Learning from reward, such as a scalar, leads to higher trial-to-trial variability than learning from sensory error, since it lacks some critical information about the directional error. Thus, it exhibits quite high exploratory behavior (Wu et al., 2014) especially at the beginning of the learning session (McDougle et al., 2015; Orban de Xivry and Lefèvre, 2015) which may reflect an explicit strategy. The properties of the fast, namely its sensitivity to reward as well as its temporal characteristics, are in line with the more active contribution of the fast at the beginning of the learning phase (Figure 18).

![Figure 18: List of the different properties of the slow (green) and the fast processes (blue).](image)

The dual-rate model of adaptation is quite successful in explaining several phenomena such as savings, spontaneous recovery, interference etc. but it is still an
approximation of sensorimotor adaptation and it remains elusive on certain mechanisms. Indeed, some findings remain difficult to explain within this particular dual process account. For instance, Galea et al. (2015) showed that the presence of reward during learning, that is typically associated with savings, also promotes retention better than equivalent punishment. It is possible that these processes may be partitioned into distinct sub-processes. Notably, some studies suggest that the slow process (Lee and Schweighofer, 2009; Brennan and Smith, 2015a; Inoue et al., 2015; McDougle et al., 2015) as well as the fast (Kim et al., 2015) may be decomposed into at least 2 components

Conclusion and objectives of the experimental studies

We described a complicated picture of interlimb transfer of adaptation. It is indeed an intricate and hazy process that seems sensitive to many conditions. The goal of my PhD project was to help resolve these diverse contradictory findings and identify, eventually, the factors and processes that favor interlimb transfer of adaptation. Our first two experiments investigated whether interlimb transfer of Coriolis force could be explained by paradigmatic and/or idiosyncratic features: thereby we addressed the importance of visual feedback conditions and individual differences on interlimb transfer. More specifically, in the first study we tested the influence of the presence or absence of visual feedback on transfer with healthy young individuals. In the second study, we addressed the importance of proprioceptive feedback conditions with individuals deprived of proprioception. Alternatively to test the influence of individual characteristics, we extracted different predictive factors of interlimb transfer based on the kinematic features of the adaptation phase and the laterality quotient (i.e. the extent of handedness). Our third and last experience concerned not the factors, but the processes that characterize interlimb transfer. Thereby, we investigated whether the performance in interlimb transfer could result from the modulation of sub-processes of adaptation as defined by the dual-rate model of adaptation (Smith et al. 2006). Also, we intended to link the performance observed in transfer to the performance observed in motor memory as it has been shown to result for a specific interaction of these sub-processes.
Experimental Studies
Chapter 4

Influence of the visual feedback and individual characteristics
Chapter 4: Influence of the visual feedback and individual characteristics

I. Forework

Several studies have reported various results on interlimb transfer of sensorimotor adaptation, with incomplete interlimb transfer (Sainburg and Wang, 2002; Joiner et al., 2013) and sometimes no interlimb transfer at all (Harris, 1963; Cohen, 1973; Wang, 2008). This suggests that sensorimotor adaptation is largely specific to the effector, but it remains unclear why interlimb transfer varies across studies. In fact little is known about the factors which determine whether, and to what extent, adaptation to a particular condition generalizes to other conditions or effectors. Two possibilities were considered in the first study: interlimb transfer may be determined by 1) environmental conditions or by 2) individual differences. Below we develop in further details the reasoning that brought us to address these two types of issues, especially for the environmental hypothesis since for space constrains, it was succinctly addressed in the article.

1) Environmental conditions: the importance of the type of sensory feedback

It is well established that adaptation of voluntary arm movements depends critically on sensory feedback such as vision and proprioception. Several prism adaptation studies in which direct vision of the limb was continuously available reported no significant interlimb transfer (Cohen, 1967, 1973; Martin et al., 1996). In contrast, interlimb transfer was observed when vision of movement trajectory was precluded (Cohen, 1967, 1973; Wallace and Redding, 1979; Dizio and Lackner, 1995). This suggests that sensory feedback may be key for the generalization of sensorimotor adaptation. In line with this idea, studies of reaching movements performed with an indirect visual feedback of hand position (e.g., a cursor) showed interlimb transfer of adaptation to a visuomotor rotation (Sainburg and Wang, 2002; Anguera et al., 2007; Taylor et al., 2011) or a novel force field. DiZio and Lackner (1995) also showed that when direct vision of the moving arm was precluded, Coriolis force adaptation of the dominant arm transferred to the opposite, naive arm. Therefore, we wanted to test the hypothesis that interlimb transfer is observed in the absence, but not in the presence, of direct vision of the limb.

A classic study suggested that interlimb transfer of force-field adaptation may depend on cognitive factors such as the conscious perception of a perturbation or trajectory error. Berniker and Kording, (2008) later suggested that generalization of sensorimotor adaptation may depend on the estimated source of motor errors, which could be assigned to either the world or the body. Based on this credit assignment theory, adaptation would generalize to the opposite limb if the error is associated to a change in the environmental force field but would be restricted to the effector if the error is associated to a change in the reaching arm. Here we analysed kinematic data in the light of debriefing questionnaires to test the hypothesis that the conscious assignment of motor errors to
internal or external factors determines interlimb transfer of sensorimotor adaptation. It is unknown whether the credit assignment theory may be linked to the influence of vision on interlimb transfer. However, if interlimb transfer is observed when direct visual information is precluded (Dizio and Lackner, 1995) and when motor errors are assigned to environmental factors (Berniker and Kording, 2008), one hypothesis is that direct vision of trajectory errors enhances the association of these errors to internal factors, thus preventing interlimb transfer of sensorimotor adaptation.

2) individual differences

How motor errors may be assigned to internal or external factors remains unclear, and this may vary across subjects. Moreover motor performance varies across subjects. Indeed, Currently, between-subject differences are often treated as a source of noise, and discarded by averaging data from a group of participants (Kanai and Rees, 2011). Heterogeneity of performance is inevitable as individuals’ actions reflect natural variations of neuropsychological attributes as well as genetic, environmental and biological factors. We were thus intrigued by the possibility that interlimb transfer may vary according to individual characteristics instead of task conditions. Therefore we analysed movement kinematics and looked for predictor(s) of interlimb transfer.
II. Article

To transfer or not to transfer? Kinematics and laterality quotient predict interlimb transfer of motor learning

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Running head: Individual characteristics determine interlimb transfer of adaptation

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Abstract

Humans can remarkably adapt their motor behavior to novel environmental conditions, yet it remains unclear which factors enable us to transfer what we have learned with one limb to the other. Here we tested the hypothesis that interlimb transfer of sensorimotor adaptation is determined by environmental conditions but also by individual characteristics. We specifically examined the adaptation of unconstrained reaching movements to a novel Coriolis, velocity-dependent force field. Right-handed subjects sat at the center of a rotating platform and performed forward reaching movements with the upper limb toward flashed visual targets in pre-rotation, per-rotation (i.e., adaptation) and post-rotation tests. Here only the dominant arm was used during adaptation and interlimb transfer was assessed by comparing performance of the non-dominant arm before and after dominant-arm adaptation. Vision and no-vision conditions were tested but the availability of visual feedback had no significant effect on interlimb transfer. On average, significant but limited transfer was observed, but we uncovered a substantial heterogeneity of interlimb transfer across subjects. The main finding of this study is that interlimb transfer can be qualitatively and quantitatively predicted for each healthy young individual. A classifier showed that in our study, interlimb transfer could be predicted based on the subject’s task performance, most notably motor variability during learning, and his/her laterality quotient. We further show that these individual characteristics can predict the presence and the magnitude of interlimb transfer of left handers. Overall, this study suggests that individual characteristics shape the way the nervous system can generalize motor learning.
1. Introduction

If you exclusively learned to write with your dominant hand and have to write for the first time with your non-dominant hand, you may write legibly. Such performance necessarily reflects an interlimb transfer of the learned skill. Understanding generalization of motor learning is important since it reveals the local or global nature of the underlying processes (Harris 1963; Poggio and Bizzi 2004; Seidler and Noll 2008; Carroll et al. 2014; Sarwary et al. 2015). By studying goal-directed upper-limb movements in sensorimotor adaptation paradigms, previous work showed that interlimb transfer is generally limited (Dizio and Lackner 1995; Criscimagna-Hemminger et al. 2003; Wang and Sainburg 2004a, 2004b; Taylor et al. 2011; Joiner et al. 2013; Mostafa et al. 2014) although it can be absent (Martin et al. 1996; Kitazawa et al. 1997). This suggests that sensorimotor adaptation is largely specific to the effector, but it remains unclear why interlimb transfer varies across studies. In fact little is known about the factors which determine whether, and to what extent, adaptation to a particular condition generalizes to other conditions. In the present study, we considered that interlimb transfer may be determined by environmental conditions but also by individual characteristics.

Malfait and Ostry (2004) suggested that sensorimotor adaptation could generalize across limbs when task conditions allow the conscious perception of a perturbation/movement error. Berniker and Kording (2008) then suggested that generalization depended on the perceived source of motor errors, adaptation generalizing mostly if the error is assigned to a change in the environment. Sensory feedback, which is critical to perceive errors and adapt (Della-Maggiore et al., 2004; Scheidt et al., 2005; Hwang et al., 2006; Franklin et al., 2007; Sarlegna et al., 2010), may thus influence interlimb transfer. In fact, previous work showed that the availability of visual feedback was important for the generalization (Shabbott and Sainburg 2010; Taylor et al. 2013) and the interlimb transfer of visuomotor adaptation (Cohen, 1973), which may be linked to a strategic processing of motor errors (Malfait and Ostry 2004; Berniker and Kording 2008; Taylor et al. 2011). One aim of the present study was thus to test whether different environmental conditions, with or without vision, influence the conscious perception of motor errors and interlimb transfer of adaptation.

While environmental conditions do seem to influence interlimb transfer, individual characteristics may also influence interlimb transfer. Currently, between-subject differences are often thought as reflecting noise, and discarded by averaging data from a group of participants, but heterogeneity of performance is inevitable as it reflects natural variations of genetic, environmental and biological factors (Kanai and Rees 2011). Inter-individual differences may be a key to understand the processes underlying sensorimotor adaptation. For example, Wu et al. (2014) recently showed that the more subjects were variable in a pre-learning phase, the better they learned a novel arm-reaching task.
Although variability can be seen as antagonistic to performance, this study provided evidence that increased variability can relate to better performance. The functional aspect of variability may be linked to the exploration of multiple solutions, at both brain activity and behavioural levels (Deco et al. 2011; Garrett et al. 2011). A second aim of the present study was thus to examine the possibility that interlimb transfer depends on individual characteristics such as movement kinematics, in particular variability of movement trajectory, or the conscious perception of motor errors. Laterality quotient (Oldfield 1971) has also been shown to influence interlimb transfer of motor learning (Chase and Seidler 2008) and we investigated this issue first by testing the influence of the degree of handedness on interlimb transfer in right handers, and then by assessing interlimb transfer in left handers.

Several studies showed that interlimb transfer can only be observed from the dominant to the non-dominant arm (Criscimagna-Hemminger et al. 2003; Galea et al. 2007) although transfer has also been found to be bi-directional (Wang and Sainburg, 2004a; Sarwary et al., 2015) In the present study, we thus used a paradigm allowing us to assess, for each individual, transfer of sensorimotor adaptation from the dominant to the non-dominant arm. We specifically addressed the interlimb transfer of adaptation to new limb dynamics by using a rotating platform which could generate Coriolis forces on the entire arm while subjects perform unconstrained arm reaching movements (Dizio and Lackner 1995).

2. Materials and Methods

Experiment on healthy right-handed young adults

Subjects. Twenty subjects with no known sensorimotor impairment participated. Ten young adults (5 males, 5 females, mean age: 24.6 years) were tested with direct vision of the limb and workspace throughout the experiment (VP group). Ten other young adults (5 males, 5 females, mean age: 23.3 years) had no visual feedback, only proprioceptive feedback of hand movement as the room was in darkness (P group).

All 20 subjects were right-handed (Laterality Quotient≥70%). The laterality quotient (LQ), i.e. the degree of handedness, was assessed by asking subjects to complete the 10-item version of the Edinburgh Inventory (Oldfield 1971). This questionnaire assesses hand dominance in daily activities (e.g., writing, throwing), LQ ranging from −100 (left handed) to 100 (right handed). Laterality quotient was 80±10% on average for the P group and 87±11% for the VP group.

All subjects had normal or corrected-to-normal vision and were naive to the purpose of the experiment. Participants gave their informed consent prior to the study, which was approved by the
institutional review board of the Institute of Movement Sciences and performed in accordance with the ethical standards of the Declaration of Helsinki.

Experimental set-up. Participants sat in a bucket seat (adapted from a car seat) at the center of a motorized rotating platform and were asked to reach toward flashed visual targets (Figure 19A). An adjustable headrest was used to restrain the head. On a horizontal board, at waist level, a visual and tactile landmark indicated the starting hand position. Visual targets were low-intensity red light-emitting diodes (3 mm in diameter). Three targets were positioned on a 37 cm radius circular array at 0° (straight-ahead), 20° (to the right) and -20° with respect to start position.

Infrared active markers were taped to the right and left index fingertips whose positions were sampled at 350 Hz using an optical motion tracking system (Codomotion cx1 and MiniHub, Charnwood Dynamics Ltd, Leicestershire, UK). As in Sarlegna et al. (2010), the experimenter controlled the tracking system, the motorized platform and the presentation of the visual targets from an adjacent room by using a customized software (Docometre) governing a real-time acquisition system ADwin-Pro (Jäger, Germany).

Procedure. At the beginning of each trial, participants had to actively position their hand at the starting location (Figure 19A). They were asked to reach as fast and accurately as possible with their hand toward the visual target which was illuminated for 0.3 s. No explicit instructions were given with respect to hand path. However, participants were required to ‘reach in one movement’ and not to correct after their finger contacted the horizontal board. 1.6 s after trial onset, an auditory 100-ms tone informed the subject to go back slowly to the starting location. 7.4 s after trial onset, a 600-ms tone signalled to the participant that the trial had ended and that the next trial would start immediately. Peak velocity of the targeted, outward reaching movement was ~10 times greater than that of the backward arm movement toward the start position. All participants were familiarized with the task during a preliminary phase.

The experimental session consisted of 3 phases (Figure 19B):

• **PRE-rotation test (baseline):** Participants executed 30 reaching movements with the dominant arm (DA) then with the non-dominant arm (10 trials per target for each hand, in a pseudorandom order which was similar for all 20 participants) while the platform remained stationary, providing baseline reaching performance in the normal force field. After the PRE-test, the rotating platform was accelerated in 80 s up to a constant velocity of 120 °/s, i.e., 20 rpm.

• **PER-rotation (adaptation) phase:** Participants performed 100 movements with the DA to the central target while the platform was rotating counterclockwise at 120°/s, generating clockwise Coriolis forces on the moving limb. Coriolis forces (Fcor; see DiZio and Lackner, 1995) are the product of the arm mass (m), platform’s angular velocity (av) and tangential arm velocity (tv)
according to the equation: $F_{cor} = -2m(\omega \times \mathbf{v})$. After the adaptation phase, the rotating platform was slowed to a stop within 80 s.

- **POST-rotation test**: Once the platform was stationary, participants executed 30 reaching movements with the non-exposed NDA first, and then with the DA (10 trials per target for each hand). The first presented target was the central one (then left, right...).

![Diagram showing experimental protocol](image)

*Figure 19: A, Experimental Setup B, Illustration of the experimental protocol.*  

Participants were instructed not to move any body part, including their head and opposite arm, during or between trials, and an infra-red camera allowed continuous monitoring of subject’s behavior. A 60 s delay was used between the end of the platform’s acceleration and deceleration phases and the first reach trial to allow the vestibular semi-circular canals to return to their resting discharge frequency. The PER-rotation test lasted approximately 20 min, the complete reaching task lasting approximately 45 min.

At the end of the experimental session, the subject, still in the bucket seat, filled a questionnaire which combined open-, multi-choice, and forced-choice questions related to awareness and credit assignment of errors. We wished to determine whether subjects consciously perceived errors in movement trajectory during the first trials of the PER-rotation phase, asking first ‘Did you feel something in particular in the first trials of the PER-rotation phase?’ and ‘Were you surprised by your performance in the first trial of the PER-rotation phase?’. If the subject talked about motor errors, he/she was considered to be aware of his/her errors; otherwise he/she was not. Then we showed a top view of each subject’s arm trajectory in the first trial of the PER-rotation phase and asked subjects to fill a questionnaire to determine whether errors were assigned to internal and/or external factors. We thus asked, in a counterbalanced order, ‘Did you associate the errors you made early in
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the PER-rotation phase to external factors?’ and ‘Did you associate the errors you made in the PER-rotation phase to yourself (e.g., internal factors such as fatigue, inattention...)?’ Subjects here had to answer ‘Strongly disagree’, ‘Somewhat disagree’, ‘Somewhat agree’ or ‘Strongly agree’. At last subjects were asked to circle whether errors were more associated to ‘Internal’ or ‘External’ factors.

Kinematic data analysis. Data were analysed using Matlab (Mathworks, Natick, MA, USA). A few trials (1.6%) had to be discarded because they were not properly performed by the subjects or were corrupted by noise. Position data from the markers on the right and left index fingertips were low-pass filtered with a dual-pass, no-lag Butterworth (cut-off frequency: 8Hz; order: 2). Movement onset was defined as the first time tangential hand velocity reached 3 cm/s and movement offset as the first time hand velocity dropped below 3 cm/s.

Initial direction was computed as the angle between the vector from the start position to the target position and the vector from the start position to the hand position at 150 ms after movement onset. Initial movement direction at 150 ms was considered the most critical dependent variable because it mostly reflects the initial motor plan, before online corrective feedback loops influence movement execution (Prablanc and Martin, 1992; Saunders and Knill, 2003; Sarlegna et al., 2004; Franklin and Wolpert, 2008). Besides, 150 ms corresponded to the mean time (averaged across healthy, right-handed subjects) of peak velocity, and therefore the time at which the magnitude of the Coriolis forces acting on arm movements is maximum during platform rotation. As in DiZio and Lackner (1995), we computed the lateral endpoint error, i.e. the perpendicular deviation (in cm) between the index fingertip at movement offset and the straight line connecting the starting point (i.e., movement onset) to the target, and the maximum perpendicular deviation (in cm) between the index fingertip and the straight line connecting the hand position at movement onset and the target (Malfait and Ostry 2004). For all the measures, we assigned positive values to rightward deviations and negative values to leftward deviations.

To assess adaptation and interlimb transfer, we employed a procedure similar to that used by DiZio and Lackner (1995). First, to assess adaptation of the DA, we compared the mean of the 10 trials of the PRE-test (baseline) with the first two trials and the last trial of the PER-rotation phase (to observe the effects of the velocity-dependent force field and the final adaptation, respectively) and the first two trials of the POST-test (to observe an after-effect and re-adaptation) for movements toward the central target (0°). To assess whether adaptation differed between groups, we fitted exponential curves to each individual data of initial direction \( y = a \times e^{-bx} + c \), in which \( a \) represents the amplitude of the initial error, \( b \) the time constant and \( c \) the offset. To assess interlimb transfer of DA adaptation to the NDA, we compared the 10 NDA movements toward the central target (0°) of the PRE-test to the first NDA movement of the POST-test for movements toward the central target.
The level of adaptation was assessed for both initial direction and lateral endpoint error using the formula \((\text{First adaptation trial} - \text{Final adaptation})/(\text{First adaptation trial} - \text{Baseline})\) with Final adaptation referring to the mean of the last 10 trials of the adaptation phase and Baseline referring to the mean of the 10 trials towards the central target in the pre-adaptation phase.

Statistical analysis. Repeated-measures analyses of variances (ANOVAs) were used to assess the significance of DA adaptation and interlimb transfer. To assess DA adaptation, we conducted 6x2 [PHASE (PRE-, PER-Initial, PER-2nd trial, PER-Final, POST-Initial, POST-2nd trial) x VISION (P and VP groups)] ANOVAs and to assess interlimb transfer, we used 2x2 [PHASE (PRE-, POST-Initial) x VISION (P and VP groups)] ANOVAs.

All data had a normal distribution as verified with the Kolmogorov-Smirnov method. The variance homogeneity across experimental groups was also confirmed using Levene test. Newman-Keuls tests were used for post-hoc analysis. For all tests, the significance threshold was set at 0.05.

The transfer value of each subject was defined using the formula: \(t_i = \frac{X_i - \mu_i}{S}\), where, for each subject \(i\), \(X\) was the initial direction of the first POST-test NDA trial, \(\mu\) the initial direction averaged across NDA baseline movements, \(S\) was the standard error of the baseline. We used the standard error instead of the standard deviation as it is more appropriate for relatively small samples (Chin and Lee 2008). We used the transfer value to assess the impact of different factors on transfer (i.e. the 3 variables used in the classification model). As data analysis showed significant interlimb transfer with a mean leftward shift (i.e. the values of the after-effects were negative), we multiplied for ease of understanding the \(t\)-scores by -1 so that any increase in the \(t\)-score would correspond to an increase in interlimb transfer. The after-effects on the dominant arm were computed with the same method.

Classification model. A linear discriminant analysis, a form of classification model, was used to separate subjects in a qualitative manner according to their after-effects on the NDA. Two classes were considered: ‘Transfer’ and ‘No transfer’. Each subject was assigned to a class based on the difference in NDA initial direction between PRE- and POST-tests. Specifically, the 10 NDA movements toward the central target in the PER-test were used to compute a 99% confidence interval (CI):

\[
\text{CI}_i = \left[\bar{x}_i - t_\alpha \frac{s_i}{\sqrt{n}} ; \bar{x}_i + t_\alpha \frac{s_i}{\sqrt{n}} \right],
\]

where for each observation \(i\), \(\bar{x}\) designs the mean of the baseline, \(t_\alpha\) is the value of the Student distribution for a 99% CI in function of the degree of freedom \(\alpha\), \(s_i\) is the standard deviation of the mean of the baseline, and \(n\) the number of trials. Based on DiZio and Lackner (1995)’ study, we expected a negative shift in NDA initial direction; thus, if the initial direction of the first NDA movement of the POST-test fell below the lower bound of the CI, the
subject was assigned to the ‘Transfer’ class. If the initial direction fell within the CI or above the upper bound, the subject was assigned to the ‘No transfer’ class.

Three variables were eventually selected (see below) to perform the linear discrimination: variability (standard deviation) of the mean initial direction across the last 10 trials in the PER-rotation phase, mean peak velocity (PV) across all 100 trials in the PER-rotation phase and Laterality Quotient (Oldfield 1971).

A 5 fold cross-validation method was used to assess the accuracy of the classification model, i.e. 80% of the observations was used to build the model (training dataset, n=16) and predict the remaining 20% of the observations (test dataset, n=4) in an iterative manner until all the observations were tested once. Thirty iterations of the 5 fold cross-validation were run to have a better estimate of the model performance.

In order to evaluate the efficiency of the model, a receiver operating characteristic (ROC) curve was employed. A ROC curve displays the probabilities in term of sensitivity and specificity of the model at each decision threshold (i.e. a value ranging from 0 to 1 above which the observation is assigned to the class 1). In our study, sensitivity (True Positive rate) measured the proportion of actual ‘Transfer’ subjects who are correctly classified by the model. Specificity (True Negative rate) measured the proportion of actual ‘No transfer’ subjects who are correctly classified.

\[
\text{Sensitivity} = \frac{TP}{TP + FN} \times 100\%
\]
\[
\text{Specificity} = \frac{TN}{TN + FP} \times 100\%
\]

Selection of the variables. The variables used for the linear discrimination analysis were selected among a set of 57 variables with a backward stepwise method, i.e. by eliminating the least necessary variable one by one (and by evaluating the resulting errors through cross validation). As the backward stepwise method cannot be performed if there are more observations than variables, the selection was applied first on multiple sets of 9 to 12 variables. For each set, we kept the variables that contributed the most to the prediction of transfer. We reiterated the selection until we got the 12 last best variables.

The variables were the laterality quotient and kinematic variables. In the adaptation phase, the kinematic variables representing the errors resulting from the force field (i.e. initial direction at PV and at 150 ms, maximum perpendicular deviation, lateral endpoint) were determined across the first and last 10 trials, as well as across the 100 trials, while other variables were determined across the 100 trials, except for the area under the curve (first 10 and 10 last only).

1) From the adaptation phase:
The variability and the mean of: lateral endpoint error, PV, maximum curvature, initial direction at peak velocity and at 150 ms.

The mean of: reaction time, movement time, difference in peak velocity between the PER and the NDA POST-rotation phase, area under the curve with respect to a straight trajectory (first 10 and 10 last trials only), perpendicular deviation throughout the trajectory, peak acceleration, time to PV.

- Amplitude and slope of the exponential fit of the adaptation curve (i.e. unknown $a$ and $b$).

2) From the baseline, the mean and standard deviation of: maximum perpendicular deviation, initial direction of the DA and NDA at lateral endpoint, PV and 150 ms (10 trials).

3) From the NDA post-rotation phase, the reaction time, movement time, time to PV and PV of the 1st trial.

To determine whether the variables used for the linear discrimination analysis could determine the amount of interlimb transfer, we performed a multiple regression analysis using the transfer value (see statistical analysis section) as the dependent variable.

**Experiment with left-handed individuals**

We tested left handers to both test the robustness of the model on new data and test whether our findings on right handers were valid for right handers and left handers.

**Subjects.** Nine young left-handed individuals (7 males, 2 females, mean age: 23.4±3 years old) performed the experiment in darkness, like the P group of the main experiment. Mean laterality quotient was -70±37%. One subject was a self-declared left hander, who preferred to write or draw with the left hand, but had a LQ=+10%.

**Procedure.** The experimental procedure was the same as for the right-handed subjects of the P group except that subjects were tested with a clockwise platform rotation. This was done so that the biomechanical consequences of the perturbation were matched for left- and right-handers. The left, dominant arm was tested during the adaptation phase while interlimb transfer was tested as the difference in right, non-dominant arm performance between trials immediately before and after the PER-rotation phase. Apart from the arm used, data analysis was similar for right- and left handers. For the sake of understanding, results of left handers were flipped so that they corresponded to the other right-handed subjects.

**3. Results**

*Adaptation of the dominant right arm to the novel force field*

A classical pattern of adaptation was observed in the right-handed group. Figure 20A-B shows that dominant arm movements were generally straight and accurate in both groups in the PRE-test.
Chapter 4: Influence of the visual feedback and individual characteristics

However, the counter-clockwise rotation generated Coriolis forces which clearly perturbed, rightward, the hand path on the initial trial of the PER-rotation phase in the VP and P groups. Indeed, when considering only movements toward the central target, a 2x6 [VISION (VP, P) x PHASE (PRE-test (mean of 10 trials), PER-Initial, PER-2, PER-Final, POST-1 and POST-2)] ANOVA only showed an effect of the experimental PHASE on initial direction (F(5,90)=6.7; p<.0001), revealing that initial direction was substantially shifted to the right compared to baseline (by 6.4° on average across groups, Figure 20D). Also, when subjects first encountered the biomechanical consequences of the platform rotation on the arm movement, visual feedback was used to adjust online the last portion of the arm trajectory compared to subjects without vision. Indeed, a 2x6 ANOVA on the lateral endpoint error revealed an effect of VISION (F(1,18)=21.2; p<0.001), PHASE (F(5,90)=36.0; p<0.001) and an interaction (F (5,90)=3.1; p<0.02; Figure 20D) which revealed that endpoint error in the first two trials of the PER-rotation phase differed from baseline in the P group (mean shift of the first trial=4.6 cm; p<0.001) but not in the VP group (p=0.24). As trials were repeated, subjects gradually compensated for the rightward deviation to restore straight, accurate movement performance. T-tests for independent samples did not reveal any significant difference in adaptation between the P and VP groups for any of the 3 parameters of the exponential fit of the initial direction data (see Materials and Methods).

Once the rotation stopped, and after the non-dominant left arm was tested in the normal force field, substantial after-effects were observed on the right, dominant arm (DA). In the first trial of the POST-test, toward the central target, DA trajectory differed from baseline with an 11.8° shift in initial direction and a 4.6 cm shift in lateral endpoint on average across groups. Similar findings were observed when initial direction was computed at 150 ms or at peak velocity (PV). Overall, PV and movement time was similar in PRE-, PER- and POST-tests and across experimental groups (mean in P Group=2.4±0.9 m/s and 423±16 ms; mean in VP Group=2.6±0.9 m/s and 429±16 ms).

We tested different target directions in PRE- and POST-tests to assess whether the force-field adaptation of DA movements toward the central target generalized to movements performed in other directions. For the lateral, right and left targets, separate 2x3 ANOVAs [VISION (VP, P) x PHASE (Baseline (mean of 10 trials), POST-1 and POST-2)] on initial direction revealed only a significant effect of experimental PHASE (left target: F(2,36)=11.0; p<0.001; right target: F(2,36)=4.3; p<0.05). Post-hoc analyses revealed that for the left target, initial direction in the first trial of the POST-test tended to differ (p=0.06) from baseline (mean shift=-3.0°) and for the right target, the shift was significant (mean=-2.6°; p<0.05), indicating limited intralimb generalization (across movement directions).
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**Right-handed Group (N=20) Dominant Arm**

**A**
- VP Group

**B**
- P Group

**C**
- Mean initial direction (degree) of the central target averaged for the PRE-test (baseline), for each trial across the adaptation phase and the POST-test for the Proprioception (blue) and Vision-Pro proprioception (red) groups.

**D**
- Mean initial direction (degree) for the Proprioception (blue) and Vision-Pro proprioception (red) groups in the PRE-test (baseline), the first, the second and the last trial of the PER-rotation phase, and the first and second trials of the POST-test.

Figure 20: Adaptation of the dominant arm movements toward the central target. A-B, Top view of DA hand paths for a representative subject of the VP group (A) and the P group (B). C, Mean initial direction (degree) of the central target averaged for the PRE-test (baseline), for each trial across the adaptation phase and the POST-test for the Proprioception (blue) and Vision-Proprioception (red) groups. Shaded blue and red areas represent the standard error of the mean. D, Mean initial direction (degree) for the Proprioception (blue) and Vision-Pro proprioception (red) groups in the PRE-test (baseline), the first, the second and the last trial of the PER-rotation phase, and the first and second trials of the POST-test. For each PRE-test, all ten trials were averaged to obtain a baseline reference. Error bars represent the standard error of the mean. Asterisks indicate significance (*p<0.05, *** p<0.001).

**Interlimb transfer of dynamic adaptation to the non-dominant left arm**

Figure 21A-B show how motor performance of the left NDA was influenced by adaptation of the right, DA movements: a 2x2 [(VISION (VP, P) x PHASE (PRE-, POST-test)] ANOVA showed that NDA initial direction differed between baseline and the first trial of the POST-test by -2.8° (F(1,18)=5.6; p<0.05), as illustrated on Figure 21C. There was no significant VISION effect (F(1,18)=0.1; p=0.76) and no significant interaction (F(1,18)=0.0; p=0.99), indicating that interlimb transfer of force-field adaptation was not influenced by vision. It should be noted that the mean difference POST-PRE in initial direction was negative (leftward shift), which is consistent with a representation of the limb dynamics in extrinsic coordinates. Also, the mean interlimb transfer represented 20% of the mean after-effect observed on the DA movements toward the central target (Figure 21D). We found no significant after-effects on initial direction for the left (F(1,18)=0.61, p=0.44) and right targets.
(F(1,17)=0.01, p=0.90), indicating that adaptation of DA movements toward a single target only generalized, to a significant but limited extent, to NDA movements toward the same target (and to DA movements toward different targets).

The analysis of lateral endpoint errors revealed slightly different results since an interaction (F(1,18)=7.9, p<0.05) indicated a significant transfer only for the P group. Indeed, on the first trial of the POST-test, visual feedback mechanisms enabled subjects with vision (VP group) to correct the errors induced by the after-effect on the NDA and reach more accurately the target at the end of the movement compared to subjects without vision. Maximum perpendicular deviation occurred on average 264±84ms after movement onset in the P group and after 239±90ms in the VP group. The 2x2 [(VISION (VP, P) x PHASE (PRE-, POST-test)] ANOVA revealed an interaction (F(1,18)=6.18, p<0.05) which showed that the difference between PRE- and POST-test trials was significant only for the P group, not for the VP group. Vision thus appears to influence interlimb transfer only when considering late or terminal kinematic features of the movement, as in some previous studies (Cohen, 1973), but this really highlights the efficiency of visual feedback mechanisms to minimize motor errors.

**Figure 21:** Interlimb transfer of force-field adaptation in the right-handed group. **A-B.** Top view of NDA hand paths for a representative subject of the VP group (A) and the P group (B) in the PRE-test (representative trial in black) and in the POST-test (first trial in green). **C.** Initial direction in baseline and the 1st trial of the POST-test with the NDA for both groups (no groups effect). **D.** After-effects (Post – baseline at initial direction) for the non-dominant, left arm and the dominant, right arm. Error bars represent standard error of the mean. Asterisks indicate significance (* p<0.05).
**Awareness and assignment of motor errors**

The possible link between conscious assignment of errors (i.e. to internal or external factors) and interlimb transfer was investigated using debriefing questionnaires at the end of the reaching experiment. Three subjects out of ten in the P group and one subject out of ten in the VP group reported not being aware of trajectory errors in the first trials of the PER-rotation phase. A Mann-Whitney non-parametric test showed that the transfer value did not differ according to the awareness of errors ($p=0.25$). When asked “Did you associate the errors you made in the first trials of the PER-rotation phase to external factors?”, all 20 subjects agreed. When subjects were asked whether they would associate these errors to internal factors, 6 subjects (4 of the P group, 2 of the VP group) agreed but interlimb transfer was similar for subjects who agreed or not ($t(18)=-1.2$, $p=0.25$). When forced to choose whether errors were mostly due to internal or external factors, only one subject (from the VP group) out of 20 assigned his errors to internal factors.

**Heterogeneity of DA-to-NDA interlimb transfer across subjects**

Most studies on interlimb transfer have determined whether transfer was significant based on group averages. However, the goal of the present study was to explore inter-individual differences and Figure 22A shows a substantial heterogeneity in interlimb transfer across subjects. We determined whether transfer occurred for each subject based on their baseline confidence interval (see Statistical analysis). This method revealed that 12 out of 20 subjects were classified as ‘Transfer’ subjects. Four subjects presented little difference in initial direction between PRE- and POST-tests, and 4 subjects seemed to produce an opposite pattern of transfer compared to the ensemble average, but for statistical reasons, we grouped the eight subjects who did not perform as the ensemble average and classified them as ‘No transfer’ subjects.

**Classification model of interlimb transfer based on individuals’ characteristics**

To determine whether the presence of interlimb transfer could be linked to any characteristic of the subjects, we first employed a qualitative approach and used a linear discriminant analysis to find the combination of variables which best characterizes the interclass differences (here ‘Transfer’ vs. ‘No transfer’). A backward-stepwise method was first used to find the variables which could best discriminate the 2 different classes of behaviour (Figure 22B; see Materials and Methods). For the sake of simplicity, we selected the best three variables, i.e. variability of DA initial direction in the last 10 trials of the PER-rotation phase, laterality quotient (Oldfield, 1971) and mean DA peak velocity across all 100 trials of the PER-rotation phase. Figure 22C shows the Receiving Operator Curve (ROC) of the linear discriminant analysis based on these 3 variables: the area under the curve (AUC) was 97%, which indicates strong discriminating ability at different decision thresholds. Such thresholds
influence the sensitivity and specificity of the classification model, but both were well balanced as high sensitivity was not obtained at the cost of low specificity. In other words, the classification model using a linear combination of the 3 variables could accurately predict observations from the classes Transfer (class 1) and No transfer (class 0). For instance, at the threshold 0.25 (red circle), the sensitivity was equal to 0.83 and specificity was 0.88 (10/12 ‘Transfer’ subjects and 7/8 ‘No transfer’ subjects were well detected). At the threshold 0.21 (green square), sensitivity was 0.92 and specificity was 0.75 (11/12 ‘Transfer’ subjects and 6/8 ‘No transfer’ subjects were well detected, respectively). Combinations of 2 variables could also well discriminate the classes ‘Transfer’ and ‘No transfer’: for instance, AUC when LQ was removed from the analysis was 79%.

**Video 1 (Supplemental material) shows how ‘Transfer’ and ‘No transfer’ subjects were discriminated with three individual characteristics.** The variable with the highest coefficient in the discriminant function of the classification model was the variability of DA initial direction over the 10 last adaptation trials, followed by the laterality quotient and the mean PV during adaptation. Figure 22D shows a positive linear correlation between the transfer value and the variability (R=0.49; p=0.03). The transfer value was correlated with other measures of motor variability such as variability of DA direction at PV across the adaptation phase (R=0.59; p<0.01), variability of DA initial direction across the adaptation phase (R= 0.56; p<0.05).
The correlation between LQ and the transfer value was marginally significant ($p=0.06$). There was no significant correlation between peak velocity and the transfer value ($r=0.18; p=0.44$) but PV marginally differed ($t(18)=2; p=0.06$) between the ‘Transfer’ class (mean=2.6±0.3m/s) and the ‘No Transfer’ class (mean=2.3±0.3m/s; see Figure 22E). No effect of VISION was observed on the 3 variables (variability: $p=0.45$; PV: $p=0.33$; laterality quotient: $p=0.24$). The 3 variables were not significantly correlated to each other.

We also investigated the link between interlimb transfer and the level of adaptation. However, the level of adaptation (see Methods) when considering initial direction and lateral endpoint error could not be linked to interlimb transfer as the level of adaptation did not significantly differ across classes of transfer ($t(18)=-0.36, p=0.71$; $t(18)=0.88, p=0.39$; respectively) and there was no significant correlation with the amount of transfer ($r=0.05, p=0.8$; $r=-0.10, p=0.7$; respectively).

**The amount of interlimb transfer can be determined based on individuals’ characteristics**

To examine whether the magnitude of interlimb transfer could be predicted based on the 3 variables of the model, we used a multiple regression analysis. Figure 22F shows that the variables could predict the observed transfer value ($F(3,16)=7.5; R^2=0.58$; adjusted $R^2=0.50$; $p<0.01$). All the variables contributed significantly to the model ($p<0.01$ for variability and PV; $p<0.05$ for laterality quotient). The equation of the multiple regression was: 46 +2.8 x Variability + 0.2 x Laterality quotient + 0.08 x Peak velocity.

We tested whether the after-effects on the dominant right arm could be predicted by the variables listed in the Methods, with the exception of variability of DA initial direction in the baseline as it was used to assess the DA after-effects. We applied a multiple regression with stepwise selection (forward and backward) similar to the methods used to predict interlimb transfer but none of the (combination of) variables could predict the DA after-effects.

**Interlimb transfer of dynamic adaptation in left handers**

*Adaptation of the dominant, left arm*

To test the influence of handedness on interlimb transfer and to test our qualitative and quantitative models of transfer, we repeated the experiment with 9 left-handed subjects. Figure 23A-B shows a classical pattern of adaptation in initial direction. A one-way ANOVA [PHASE (PRE-test (mean of 10 trials), PER-Initial, PER-2, PER-Final, POST-1 and POST-2)] revealed an effect of the experimental phase ($F(5,35)=5; p<0.01$). The first trial of the PER-rotation, adaptation phase differed from all other trials (all $p<0.05$; the difference with baseline being marginally significant, $p=0.05$). The mean shift in initial direction of the first trial compared to baseline was 5.8±6° and the mean after-effect, on initial direction, was -5.4±5.2°.
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**Left-Handed Group (N=9)**

![Figure 23](image)

*Figure 23: Adaptation and interlimb transfer in left handers. A, Top view of DA hand paths for a representative subject. B, Initial Direction (in degree) for the DA averaged across subjects in the PRE-test (baseline), the first, the second and the last trial of the PER-rotation phase, and the first and second trials of the POST-test. Asterisks indicate significance (*** p<0.001). Error bars represent the standard error of the mean. C, Top view of NDA hand paths for two representative subjects. D, Magnitude of NDA after-effects (1st trial of the POST – baseline) on initial direction for the classes “Transfer” and “No transfer”.*

**Interlimb transfer of dynamic adaptation to the non-dominant, right arm**

On average, initial direction was similar in PRE-test (mean=−1.7±3.5°) and POST-test (mean=0.1±6.2°) such that there was no significant interlimb transfer for the group (t(8)=−0.76; p=0.4). However, for 4 subjects out of 9, initial direction in the first trial of the POST-test differed from the 99% confidence interval of the NDA PRE-test (baseline), indicating interlimb transfer. For these 4 ‘Transfer’ subjects interlimb transfer (mean=−6.3±3.9°) was consistent with a representation of limb dynamics in extrinsic coordinates. In the ‘No transfer’ class, the mean shift between PRE- and POST-test was 1.9±1.8°.

**Test of the classifier on left-handed individuals**

Testing left handers gave us the opportunity to test the robustness of the model on new data, and to investigate whether the laterality quotient had an influence on transfer among left handers (in other words, does the extent of handedness and handedness itself matter to interlimb transfer?).

With respect to the individual characteristics which were identified as determining interlimb transfer, variability of initial direction during the last 10 trials of the adaptation phase did not significantly differ between left and right handers (mean variability= 3.4±1.2°; t(27)=−0.9; p=0.4). Although all subjects were instructed that they should reach as fast and as accurately as possible, left handers were faster than right handers during the adaptation phase (mean peak velocity= 3.2±0.3
versus 2.5±0.3 m/s; t(27)=−7; p<0.001). This advantage in left handers in term of movement speed is consistent with previous work (Kilshaw and Annett 1983).

**Classification and Regression Models (left and right-handed, N=29)**

The large difference in PV between right- and left handers greatly reduced the classifier’s accuracy because the discriminant function is very sensitive to out-of-range data. Hence only laterality quotient and variability were used for the classifier, which was built with the data of the 20 right-handed subjects (training dataset) and tested on the 9 left-handed subjects. At the threshold 0.58, the model misclassified only 1 “Transfer” subject.

Next, we pooled the data of the healthy left- and right handers and ran the cross-validation on all the subjects to consider the distribution of the 2 variables. We ran a 5-fold 30 iterations cross validation on 29 subjects: 16 were in the class “Transfer”, 13 in the class “No Transfer”. The area under the curve indicated 77% of good discrimination, which was higher that when the 2 variables were tested on the 20 right-handers (A). At the threshold 0.58, the sensitivity and the specificity were equal to 0.62 and 0.85 respectively (i.e. 10/16 “Transfer” subjects and 11/13 “No transfer” subjects were well detected; the misclassified subjects were 6 right- and 2 left handers).

When considering more quantitative aspects, B shows that variability was correlated to the transfer value (n=28, r=0.43; p<0.05). Figure 24C shows that the laterality quotient was marginally significant to discriminate the classes “Transfer” and “No Transfer” (p=0.08). Altogether, variability and laterality quotient were useful to discriminate ‘Transfer’ and ‘No transfer’ subjects (Figure 24D).
Finally, we conducted a multiple regression analysis to examine whether the magnitude of interlimb transfer could also be predicted by variability and laterality quotient with both right and left-handers in the data set. Figure 24E shows that the observed transfer value could be predicted (F(2,26)=10.3; R=0.65; R²=0.42; adjusted R²=0.37; p<0.01), with a combination of the 2 variables. The equation of the multiple regression was: 15.2 + 2.9 x Variability + 0.1 x Laterality quotient.

4. Discussion

Conflicting results have been reported on the interlimb transfer of sensorimotor adaptation (Imamizu and Shimojo, 1995; Morton et al., 2001; Anguera et al., 2007; Galea et al., 2007) and we sought to identify the factors which determine interlimb transfer. We first used an experimental approach which showed, on average in healthy right-handed subjects, significant interlimb transfer of force-field adaptation. Interlimb transfer was similar irrespective of the sensory feedback conditions (vision/propiroception and proprioception only), the conscious perception of motor errors and the level of adaptation. Previous studies already reported similar level of adaptation irrespective of visual feedback conditions (Franklin et al., 2007; Hinder et al., 2008; Arce et al., 2009) and our study appears to extend these findings to the interlimb transfer of sensorimotor adaptation. More importantly, the present study suggests that an individualized approach can reveal the critical factors determining interlimb transfer. Three main predictors of interlimb transfer were identified in right handed group: variability, peak velocity and laterality quotient. When left handers were tested, interlimb transfer could also be qualitatively and quantitatively predicted with variability and laterality quotient. Taken together these results suggest that beyond the environmental conditions, interlimb transfer is determined by quantitative features of the adaptation phase and by the subjects’ degree of lateralization.

Variability of motor execution and peak velocity are key predictors of interlimb transfer

When considering our results averaged across subjects, they are in line with previous studies which reported significant, but limited, interlimb transfer of sensorimotor adaptation. Our results are also consistent with studies which reported interlimb transfer of adaptation to novel limb dynamics reflecting a central representation of limb dynamics in extrinsic coordinates (Dizio and Lackner 1995; Criscimagna-Hemminger et al. 2003; Malfait and Ostry 2004). However, when we looked at interlimb transfer for each individual, we uncovered a substantial heterogeneity. A classification model revealed that a key predictor of interlimb transfer is the variability of initial movement direction during the last part of the adaptation phase. Recent studies have highlighted how motor variability at the execution level could enhance motor learning, first in songbirds (Ölveczky et al. 2005; Tumer and Brainard 2007) and more recently in humans with arm-reaching tasks (Wu et al. 2014). A direct link
between our study and that of Wu et al. (2014) cannot be firmly established yet since they investigated the link between baseline performance and motor adaptation while we investigated the link between motor adaptation and transfer. However, our results seem to relate to their findings, suggesting that overall, variability may reflect action exploration, which in turn could facilitate sensorimotor adaptation.

There are multiple types of variability and for instance motor variability at the execution level differs from variability in task goal (Ranganathan and Newell, 2013). Increasing the variability in task goal is also well known to improve motor learning (Braun et al. 2009; Kitago and Krakauer 2013) as it stimulates problem-solving capacities. However, adaptation with multiple target directions to a visuomotor rotation (Wang and Sainburg 2004b) and a novel force field (Mattar and Ostry 2007) was not found to facilitate interlimb transfer. These findings raise the question as to why variability of movement execution is so beneficial to adaptation and interlimb transfer.

Although motor variability has often been considered as noise, it is now thought to be beneficial to learning since it would reflect action exploration (Kanai and Rees 2011; Herzfeld and Shadmehr 2014; Wu et al. 2014). Variability presumably allows the nervous system to develop a general knowledge of the relationship between efferent signals and their actual consequences, which in turn would enable the selection of the most appropriate movement strategy. New experiments are necessary to clarify how exactly variability facilitates sensorimotor adaptation and its generalization.

Peak velocity during the adaptation phase also seemed to determine intermanual transfer in our study. Kitazawa et al. (1997) previously showed that the velocity of reaching had a substantial influence on sensorimotor adaptation and our study seems to extend this finding to the interlimb transfer of force-field adaptation. Indeed, we observed a greater peak velocity in so-called ‘Transfer’ subjects compared to ‘No transfer’ subjects. This could be related to the notion that fast movements, with a high peak velocity, are mostly controlled based on feedforward control mechanisms because there is less time to process peripheral sensory feedback during movement execution. Minimizing errors of fast movements thus relies more on the update of motor planning processes, which would facilitate interlimb transfer. One hypothesis to experimentally test is that manipulating movement speed should influence interlimb transfer such that an increased movement speed would result in an increased interlimb transfer.

Laterality quotient influences the interlimb transfer of sensorimotor adaptation

Laterality quotient, a quantitative assessment of handedness in everyday activities (Oldfield 1971), was the second most important predictor of interlimb transfer in our study. Many studies with healthy subjects and stroke patients (Wang and Sainburg 2004a; Mutha et al. 2012; Sainburg 2014) support the idea that, in right handers, the left hemisphere is specialized for the control of limb
dynamics. While the control of dominant hand movements involves greater activation of the contralateral hemisphere compared to the ipsilateral one (Dassonville et al. 1997; Volkmann et al. 1998; Pool et al. 2014), movements of the non-dominant hand are controlled by a more balanced pattern of hemispheric activation (Kawashima et al. 1993; Kim et al. 1993; Ziemann and Hallett 2001). There is also neuropsychological evidence supporting this idea since damage to the dominant left hemisphere can impair the motor function of both right and left hands (Haaland and Harrington 1996; Sainburg 2014). This body of work suggests that, for our right-handed participants, the internal representation of the right hand dynamics was updated during the adaptation phase primarily in the left hemisphere. The contribution of the left hemisphere to the control of the non-dominant arm may be the basis of interlimb transfer in right handers, an idea consistent with a study (Criscimagna-Hemminger et al. 2003) which showed interlimb transfer of force-field adaptation in a split-brain patient. In our study with right handers, the fact that the amount of interlimb transfer increased with the laterality quotient may be explained by a greater activation of the contralateral (left) hemisphere in strongly lateralized subjects when using the dominant (right) hand (Dassonville et al. 1997; Pool et al. 2014) and/or by more involvement of the ipsilateral (left) hemisphere in strongly lateralized subjects when using the non-dominant (left) hand (Verstynen et al. 2004).

One might argue, contrarily, that less neural asymmetry and more bilateral brain activity in general might favor interlimb transfer. When Chase and Seidler (2008) investigated interlimb transfer of adaptation to a visuomotor rotation, they observed in left handers that interlimb transfer increased as the degree of handedness decreased. Also, when they studied whether learning a sequence of finger movements with one hand transferred to the other hand, they found that, in right-handers, interlimb transfer increased as the degree of handedness decreased. We presume that there are differences between adapting arm motor commands to a novel dynamic environment and adapting to a visuomotor rotation (Krakauer et al. 1999; Rabe et al. 2009) or learning a sequence of finger movements. However, these and our findings collectively highlight the importance of handedness for interlimb transfer.

Although all left handers could adapt to the novel force field with their dominant left arm, we did not observe significant interlimb transfer on the non-dominant, right arm, perhaps because of a small effect size. However, a large heterogeneity was found across subjects and a subject-by-subject analysis indicated that transfer was in fact observed in a few subjects. These ‘Transfer’ subjects could be discriminated from so-called ‘No transfer’ subjects based on the laterality quotient as well as variability of initial direction during late adaptation. The fact that peak velocity was not found to be a significant predictor of transfer likely results from the finding that left handers were faster than right handers, which is consistent with previous work (Kilshaw and Annett 1983). Because laterality quotient was found to influence interlimb transfer of all, right- and left-handed individuals, our
findings suggest that it is the extent of handedness which influences intermanual transfer of sensorimotor adaptation.

In summary, laterality quotient and other subjects’ characteristics such as movement kinematics are important for interlimb transfer, which does not result solely from environmental conditions. These individual characteristics should be carefully considered as they could explain the large heterogeneity of results in the literature.

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Chapter 5

Generalization of force-field adaptation in proprioceptively deafferented subjects
I. Forework

In the previous experiment we found that the absence of visual feedback did not have a particular influence on the performance of either adaptation or interlimb transfer of adaptation. Similarly, in the experiment below, we wanted to test whether individuals deprived of proprioception (i.e. GL and IW) would be able to produce interlimb transfer. Although, the absence of proprioception does not preclude adaptation (Sarlegna et al., 2010; Yousif et al., 2015), it was showed to prevent efficient interjoint coordination (Sainburg et al., 1995). Therefore, deafferentation could have negative impacts on other type of behaviors such as interlimb transfer. On the other hand, as stated in the previous experiment, the type of sensory feedback used to build the internal representation of the perturbation may not have any kind of influence on the performance in transfer. In contrast, the individual characteristics may explain the performance of GL and IW in interlimb transfer, even if they are very different to the young healthy individuals tested in the previous study.

There are plenty of experiments that manipulated the visual feedback to observe the consequences on interlimb transfer (Cohen, 1967, 1973; Heuer and Hegele, 2011; Taylor et al., 2011), but none has intended to manipulate the proprioceptive feedback, certainly because of the difficulties to desensitize the proprioceptive inputs or to find deafferented individuals. We had the chance to test GL and IW on interlimb transfer. It gave us valuable insights on the ability to compensate with other available sensory modalities, and also about the capacity of generalization of our classification model.
Chapter 5: Generalization of force-field adaptation in proprioceptively deafferented subjects

II. Article

Generalization of force-field adaptation in proprioceptively-deafferented subjects

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Abstract

Humans have the remarkable ability to adapt their motor behavior to changes in body properties and/or environmental conditions, based on sensory feedback such as vision and proprioception. The role of proprioception has been highlighted for the adaptation to new upper-limb dynamics, which is known to generalize to the opposite, non-adapted limb in healthy individuals. Such interlimb transfer seems to depend on sensory feedback, and the present study assessed whether the chronic loss of proprioception precludes interlimb transfer of dynamic adaptation by testing two well-characterized proprioceptively-deafferented subjects. These had to reach toward visual targets with vision of the limb. For both deafferented subjects, we observed adaptation of the dominant arm to Coriolis forces and after-effects on non-dominant arm movements in different movement directions, thus indicating interlimb transfer. Overall, our findings show that motor learning can generalize across limbs and movement directions despite the loss of proprioceptive afferents
1. Introduction

The properties of the body and the environment change from time to time but sensory feedback such as vision and proprioception help minimizing motor errors via iterative, trial-by-trial corrective mechanisms. A common example is that humans, who wear prisms for instance, can adapt to the novel relationship between a visual input (e.g. an object on a table) and the motor output (Cohen, 1973; Ghahramani and Wolpert, 1997; Bernier et al., 2006; Pipereit et al., 2006; Miall and Cole, 2007). When specifically considering voluntary arm movements, it is well known that humans can restore accurate reaching despite changes in limb dynamics (Dizio and Lackner, 1995; Scheidt et al., 2005; Franklin et al., 2007).

The adaptive control of limb dynamics has been suggested to critically depend on proprioception (Ghez and Sainburg, 1995; Pipereit et al., 2006). Studies of subjects deprived of proprioceptive afferents showed that proprioception is critical for the coordination of daily actions such as walking or arm reaching (Cole and Paillard, 1995; Ghez and Sainburg, 1995; Sarlegna et al., 2006). Ghez and Sainburg (1995) suggested that proprioceptive information is required to update the internal representation of limb dynamic properties. Moreover, studies on healthy subjects deprived of vision showed that proprioception is sufficient to adapt to new limb dynamics (Dizio and Lackner, 1995; DiZio and Lackner, 2000) and that adaptation to a novel force field is similar with or without vision (Scheidt et al., 2005; Franklin et al., 2007; Lefumat et al., 2015). Nevertheless, it has recently been shown that proprioceptively-deafferented subjects could adapt, with visual feedback, to new dynamics of the dominant arm (Sarlegna et al., 2010; Yousif et al., 2015). Both studies thus provided experimental evidence that dynamic adaptation is possible without proprioception as its permanent loss can be compensated by vision. However, it remains unknown whether such adaptation, without proprioception, can generalize to movements that have not been experienced previously. For instance, adaptation of arm movements in a single direction can generalize to movements of the same arm in neighboring directions (Ghahramani and Wolpert, 1997; Lefumat et al., 2015). Adaptation of one arm can also benefit movements of the opposite arm (Criscimagna-Hemminger et al., 2003; Malfait and Ostry, 2004; Wang and Sainburg, 2004a; Lefumat et al., 2015) although such interlimb transfer is generally limited (Galea et al., 2007; Joiner et al., 2013; Stockinger et al., 2015) and sometimes is not observed (Martin et al., 1996). In fact, it remains unclear which factors influence how we transfer what we have learned from one limb to the other.

Cohen (Cohen, 1973) proposed that interlimb transfer of sensorimotor adaptation depends on sensory feedback, since transfer of prism adaptation was only observed when vision of the moving limb was precluded, i.e. when peripheral feedback control relies only on proprioception. Here we directly tested the hypothesis that proprioception is important for the interlimb transfer of
sensorimotor adaptation (Veldman et al., 2015): specifically, we examined the motor behaviour of two well-characterized deafferented individuals (Cole and Paillard, 1995; Sarlegna et al., 2010) to assess interlimb transfer of adaptation to new Coriolis forces in the absence of limb proprioception. As in similar studies (Dizio and Lackner, 1995; Lefumat et al., 2015), we hypothesized that interlimb transfer would result in a deviation of the first reaching movement of the non-dominant arm after adaptation of the dominant arm.

2. Methods

Subjects

Two subjects deprived of body proprioception (GL and IW, Cole and Paillard, 1995; Forget and Lamarre, 1995) participated in the experiment. GL and IW suffered an acute sensory neuronopathy (when they were 31 and 19 years old, respectively) which resulted in the specific loss of large-diameter, Aβ myelinated afferent fibers: both individuals have thus lost kinesthesia, tendon reflexes, touch, vibration, pressure, as well as position and movement sense of all body parts, from nose down for GL (trigeminal division 3) and from neck down for IW (C3 root level). Both individuals perceive pain and temperature, suggesting that small fibers are intact, as confirmed by a biopsy for GL (Forget and Lamarre, 1995). Examination by an ophthalmologist revealed no visual deficit in either patient. Examination of GL by specialists of the vestibular system revealed no deficit, in line with previous examination (Guillaud et al., 2011). No vestibular deficits have been found for IW (Day and Cole, 2002).

GL, a right-handed woman, was 66 year old at the time of the experiment, and IW, a left-handed man, was 61. The Edinburgh Inventory (10-item version, Oldfield, 1971) revealed a Laterality Quotient of +77% for GL and -100% for IW. Both subjects were naive to the purpose of the experiment. They gave their informed consent prior to the study, which was approved by the institutional review board of the Institute of Movement Sciences and performed in accordance with the ethical standards of the Declaration of Helsinki.

Experimental set-up

Subjects sat at the center of a motorized platform (Figure 25A) which could rotate and thus generate a Coriolis, velocity-dependent force field on the moving limb (Dizio and Lackner, 1995; Guillaud et al., 2011). A bucket seat and a headrest were used to restrain trunk and head motion. On a horizontal board, at waist level, a visual landmark indicated the starting hand position and visual targets were displayed using low-intensity red light-emitting diodes (3 mm in diameter). Three targets were positioned on a 37 cm radius circular array at 0° (straight-ahead), 20° (to the right) and -20°. Full vision of the upper limb and the workspace was available throughout the experiment. The positions of infrared active markers taped on the right and left index fingertips were sampled at 350
Hz using an optical motion tracking system (Codamotion cx1 and MiniHub, Charnwood Dynamics Ltd, Leicestershire, UK).

**Procedure**

Methods were similar in a previous study (Lefumat et al., 2015). Subjects had to position their hand at the starting location (Figure 25A) and to perform unconstrained, forward reaching movements as fast and accurately as possible toward the visual target which was illuminated for 0.3s. No explicit instructions were given with respect to hand movement except ‘reach in one movement’ and ‘avoid correcting after the finger contacted the board’. A 100ms tone informed subjects, 1.6s after trial onset, to go back slowly to the starting location. A 600ms tone signalled trial end 7.4s after trial onset. Peak velocity of the reach was ~10 times greater than that of the backward movement toward the start position. Subjects were familiarized with the task before starting the experimental session, which consisted of 3 phases (Figure 25B):

- **PRE-rotation test**: 30 reaching movements with the dominant arm (DA) then with the non-dominant arm (NDA) toward one of three targets (10 trials per target for each hand, in a pseudorandom order which was similar for both subjects) while the platform remained stationary, providing baseline performance. After the PRE-rotation test, the rotating platform was accelerated in 80s up to a constant velocity of 120 °/s (20rpm).

- **PER-rotation phase**: 100 movements with the DA to the central target. For the right-handed subject GL, the platform rotated counterclockwise at 120°/s, generating tangential clockwise Coriolis forces on the moving limb. For the left-handed subject IW, a clockwise rotation was used to match the biomechanical consequences of the perturbation on the dominant arm. After the PER-rotation phase, the rotating platform decelerated to a stop in 80 s.

- **POST-rotation test**: similar to the PRE-rotation test except that the NDA was tested before the DA. The first presented target was the central one (then left, right...).

A 60s delay between the end of the platform’s acceleration and deceleration phases and the ensuing reach allowed the vestibular semi-circular canals to return to their resting discharge frequency (Goldberg and Fernandez, 1975). Subjects were instructed not to move their opposite arm and their head during the experiment.
Data analysis

Data were analysed with Matlab (Mathworks, Natick, MA, USA). Position data from the markers on the right and left index fingertips were low-pass filtered with a dual-pass, no-lag Butterworth (cut-off frequency: 8Hz; order: 2). Movement onset and end were defined as the first time tangential hand velocity reached above and below 3cm/s.

Initial direction was computed as the angle between the vector start position-target position and the vector start position-hand position at 150ms after movement onset. This early assessment precluded most visuomotor corrections (Sarlegna and Mutha, 2015). For all measures, we assigned positive values to rightward deviations and vice-versa.

We mostly used t-tests comparisons of a single value to a sample (Crawford and Howell, 1998; Sarlegna et al., 2010) with a conservative significance threshold of 0.01 (thus corresponding to a 99% confidence interval) to minimize type I errors. For instance, to assess adaptation, we compared for each subject the DA initial direction of the first movement in the POST-rotation test to the corresponding 10 trials (DA movements toward the central target) from the PRE-rotation test. To assess interlimb transfer, we compared the NDA initial direction in the first trial of the POST-rotation phase to the corresponding trials in the PRE-rotation test.

The magnitude of the perturbation (of the PER-rotation phase) as well as the after-effects (DA) and the transfer value (NDA) were defined by using the formula: \( t_i = \frac{X_i - \mu_i}{SE_i} \), where, for each subject \( i \), \( X \) was the initial direction of the given trial (i.e. first trial of the PER or POST-rotation phase), \( \mu_i \) the initial direction averaged across the movements of the corresponding trials in the PRE-rotation test and \( SE \) the standard error of the PRE-rotation phase.
3. Results

Adaptation of deafferented subjects’ dominant arm (DA) to a novel force field

DA movements of both subjects were fast in PRE-, PER- and POST-rotation phases. On average across these 3 phases, IW and GL’s mean peak velocity (±SD) was 2.8±0.3 and 2.3±0.3 m/s, respectively. IW and GL’s overall movement duration was 447±64 and 600±163 ms while time-to-peak-velocity was 161±20 and 173±35 ms, respectively. As in previous work (Sarlegna et al., 2010), we observed during the PRE-rotation test that DA movements with visual feedback but without proprioception were generally accurate in term of endpoint error but were also quite variable, especially when considering movement trajectory (Figure 25C-D).

The initial direction of the first movement of the PER-rotation phase was substantially shifted by the Coriolis force relative to the PRE-rotation test (GL: +12.7°, t(9)= 6.8; IW: +12.1°, t(9)=5.1; p<0.001 for both; Figure 26A). For both, such shift was similar to that of the healthy subjects in our previous study (GL: t(19)=0.5, p=0.6; IW: t(19)=−1.8, p=0.09). Debriefing at the end of the experiment revealed that IW noticed unusual trajectory errors in the first PER-rotation trials while GL did not consciously perceive that movement trajectory differed from usual.

Analyses of hand path and initial direction during the PER- and POST-rotation trials indicate that both GL and IW adapted to the novel force field (Figure 26B), which also highlights the variability in initial direction across the adaptation phase (mean initial direction across 100 trials: GL=−3.6±6°; IW=−7.9±5.6°). GL adapted in 3 trials and IW in 2 trials, as the healthy subjects from our previous experiment (Lefumat et al., 2015). GL’s and IW’s variability of initial direction was higher at the beginning (10 first trials) than at the end (10 last trials) of the PER-rotation phase (IW: first SD=6, last SD=3.7; GL: first SD= 7.3, last SD=4.3). In the first trial of the POST-rotation test with the DA (performed after the POST-test with the NDA), substantial after-effects were observed in IW (mean shift relative to baseline=−10.2°, t(9)=−3.6, p<0.01) and GL (shift=−4.7°, t(9)=−2.8, p=0.02). Such after-effects were smaller than that of the healthy subjects in our previous study [13] (GL: t(19)=6; IW: t(19)=5.6; p<0.001 for both).

We tested different target directions in PRE- and POST-rotation tests to assess whether the force-field adaptation of DA movements toward the central target generalized to DA movements performed in other directions (+20° and −20°). We observed generalization for IW as the initial direction of the first movement toward the left and right targets was shifted compared to the corresponding trials (left target: mean PRE-rotation test=−2.3±3.3° vs. first POST-rotation trial=−11.8°, t(9)=−9.2, p<0.001; right target: mean PRE-rotation test=−11.3±8.2° vs. first POST-rotation trial=−1.3°, t(9)=−3.9, p<0.01). For GL, generalization across movement direction was marginally significant for the first DA movement of the POST-rotation test toward the right target (mean PRE-rotation test=−
8.0±5.2° vs. first POST-rotation trial=12.5°, t(9)=−2.7, p=0.02) but not for the left target (mean PRE-rotation test=−3.0±4.6° vs. first POST-rotation trial=−5.0°; t(9)=−1.4, p=0.2).

Figure 26: A, Top view of dominant arm (DA) hand paths for GL (left) and IW (right, with the hand paths flipped into a ‘right arm’ coordinate system to facilitate understanding): one representative trial of the PRE-rotation test (black line), the first trial of the PER-rotation phase (pink line) and of the POST-rotation test (green line). Blue asterisks correspond to 150 ms after movement onset. B, Initial direction of the DA across the experiment for GL (orange squares) and IW (blue circles). The inset focuses on the PRE-rotation test and the first 5 trials of the PER-rotation phase. Error bars represent the 99% confidence interval. C, Top view of non-dominant arm (NDA) hand paths: one representative trial of the PRE-rotation test (black line) and the first trial of the POST-rotation test (green line) for GL (left) and IW (right, hand paths flipped in a ‘right arm’ coordinate system). D, NDA initial direction (°) of both subjects (GL left, IW right) in the PRE-rotation test (black) compared to the first trial of the POST-rotation test. Error bars represent the 99% confidence interval.
Interlimb transfer of dynamic adaptation in deafferented subjects

For both subjects, NDA movements were fast in PRE- and POST-rotation phases. On average across these 2 phases, IW and GL’s peak velocity was 2.7±0.3 and 2.2±0.4 m/s, movement duration was 460±60 and 705±90 ms and time-to-peak-velocity was 160±10 and 207±56 ms, respectively. Figure 25E-F shows that baseline NDA movements were fairly accurate but movement trajectory was variable.

When we compared NDA initial direction in the first trial of the POST-rotation test to the NDA initial direction in the 10 PRE-rotation movements toward the central target (Figure 26D), a substantial difference was found (GL=-13.3°, t(9)=-7.9; p<0.001; IW=-8.2°, t(9)=7; p<0.001). This indicates that Coriolis-force adaptation transfers from the DA to NDA.

The transfer value of deafferented subjects was greater (GL: t(19)=6.01; IW: t(19)=5.2; p<0.001 for both) than that of the 20 healthy right-handers tested in our previous study (Lefumat et al., 2015). It is worth noting that healthy subjects had similar kinematics (mean peak velocity=2.5±0.9 m/s; mean movement duration=426±16 ms; mean time-to-peak-velocity=152±26 ms) to those of GL and IW in the present study. In Lefumat et al. (2015) we found that interlimb transfer varied with individual characteristics such as laterality quotient and movement kinematics. In particular, the transfer value increased with the laterality quotient (mean=83.7±11%), the variability of initial direction across the last 10 trials of the adaptation phase (mean=3.2±0.9°) and the peak velocity of movements across the PER-rotation phase (mean=2.5±0.3 m/s). A classification model using these 3 variables was trained using the data from the 20 healthy right-handers (Lefumat et al., 2015) and then tested with the dataset from the 2 deafferented subjects. Given that GL and IW were both well lateralized (+77 and -100% respectively) and performed quite rapid DA movements across the PER-rotation phase (2.5 m/s for both subjects), with substantial variability in initial direction across the last 10 learning trials (GL: 5.1°; IW: 3.5°), the model correctly predicted that interlimb transfer of Coriolis force adaptation would be observed for GL and IW with a 99% probability for each.

Considering more quantitative aspects, we used the same 3 variables of the same healthy subjects (n=20) to build a regression model with the transfer value as the dependent variable. Using this model with deafferetned subjects’ data, we found that the predicted transfer value did not significantly differ from the observed value (GL: p=0.20; IW: p=0.15). Second, as some of these variables, in particular variability, were greater for the deafferented subjects compared to the healthy subjects, a greater transfer value was predicted for the deafferented subjects compared to the healthy subjects.

The NDA movements in PRE- and POST-rotation tests allowed us to determine whether Coriolis force adaptation of DA movements toward the central target generalized to NDA movements in
other directions. Our findings revealed generalization across limbs and across movement directions for IW as the first NDA movement toward the left target (initial direction=−13°) differed from the PRE-rotation movements toward the left target (mean=−4.0±8.0°; t(9)=3.5, p<0.01). For IW, generalization was marginally significant for the right target (mean PRE-rotation test=4.4±6.0° vs. first POST-rotation trial=0.2°; t(9)=−2.2, p=0.06). For GL, DA adaptation of movements toward the central target generalized to the NDA movements toward the right target (mean PRE-rotation test=−5.0±7.6° vs. first POST-rotation trial=−15.0°; t(9)=−4.1, p<0.01) and the left target (mean PRE-rotation test=4.8±5.7° vs. first POST-rotation trial=−0.1°; t(9)=−2.7, p<0.01).

4. Discussion

Cohen (Cohen, 1973) proposed that interlimb transfer of sensorimotor adaptation depends on sensory feedback and the present study was designed to directly test the hypothesis that proprioceptive feedback is critical for the interlimb transfer of force-field adaptation. We asked two deafferented subjects to perform reaching movements with both arms, with continuous visual feedback. For both subjects, we observed adaptation of the dominant arm to Coriolis forces, after-effects on the dominant arm movements but also after-effects on the non-dominant arm movements, thus indicating interlimb transfer. Given that adaptation of dominant arm movements influenced subsequent non-dominant arm movements in different directions, this study shows that motor learning can generalize across limbs and movement directions despite the loss of proprioceptive afferences.

Our findings of two deafferented subjects adapting to a novel force field replicate and extend those obtained in previous studies with GL (Sarlegna et al., 2010) and IW (Yousif et al., 2015). The finding of adaptation, interlimb transfer and generalization across movement directions in both subjects highlights the sufficiency of vision to provide information for motor control and learning (Ghez and Sainburg, 1995). The importance of vision in motor learning was also emphasized in other studies which showed that viewing another person adapting to a novel force field can result in improvements in reaching performance in the force field and even to some form of interlimb transfer (Williams and Gribble, 2011). In the present study, comparing the motor commands to their visual consequences was sufficient to result in sensorimotor adaptation, as in Bernier et al. (Bernier et al., 2006), and in generalization across limbs and movement directions.

In our recent study on healthy subjects (Lefumat et al., 2015), force-field adaptation was similar with or without visual feedback, in line with previous studies (DiZio and Lackner, 2000; Scheidt et al., 2005; Franklin et al., 2007). Moreover, interlimb transfer was similar with or without visual feedback: this could be seen as evidence that vision is not necessary for force-field adaptation and interlimb transfer (Dizio and Lackner, 1995). However, the present findings would suggest that proprioception
too is not necessary for force-field adaptation and generalization. Altogether, these findings suggest that neither proprioception nor vision is critical for sensorimotor adaptation and interlimb transfer, as long as one modality is available (Dizio and Lackner, 1995; DiZio and Lackner, 2000; Sarlegna et al., 2010; Melendez-Calderon et al., 2011).

In the present study and our previous study (Lefumat et al., 2015), we observed a shift in the initial direction of the non-dominant arm after dominant arm adaptation. This shift was in the opposite direction of the perturbation in Cartesian space, similar to that of the dominant arm: this is consistent with the idea of a central representation of limb dynamics in extrinsic coordinates (Dizio and Lackner, 1995; Criscimagna-Hemminger et al., 2003; Malfait and Ostry, 2004). In our previous study (Lefumat et al., 2015), three main factors determined interlimb transfer in healthy subjects: laterality quotient (Oldfield, 1971) as well as variability of initial direction and peak velocity during the adaptation phase. Based on these data, we could make qualitative and quantitative predictions of interlimb transfer: these were consistent with our observations on two older subjects with the rare condition of selective proprioceptive deafferentation. This seems to reinforce the general validity, and the predictive ability, of our findings on interlimb transfer. Both deafferented subjects may have benefited from their high motor variability in the adaptation phase, which could facilitate action exploration and thus finding the most efficient movement strategy (Wu et al., 2014). Whether this variability reflects a cognitive strategy or results from difficulties to control limb dynamics after the proprioceptive loss remains unclear and will require additional experiments.

Laterality quotient (Oldfield, 1971) has also been shown to influence interlimb transfer of sensorimotor adaptation (Chase and Seidler, 2008) and both deafferented subjects were strongly lateralized, which in our task appears to facilitate interlimb transfer (Lefumat et al., 2015). Such facilitation may reflect a greater involvement of the dominant left hemisphere (in right handers) when using the right or the left hand, given that the left hemisphere is specialized for the control of limb dynamics (Sainburg, 2014), is activated when using either arm (Kim et al., 1993; Pool et al., 2014) and its damage can impair both right and left hand movements (Sainburg, 2014). Finally, the fact that deafferented subjects performed their reaching movements with a high peak velocity was another factor presumably facilitating interlimb transfer of force-field adaptation. Whether such movement kinematics or laterality quotient influence interlimb transfer in other conditions needs to be tested.

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Chapter 5: Generalization of force-field adaptation in proprioceptively deafferented subjects

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Chapter 6

The contributions of the underlying processes of adaptation in interlimb transfer
I. Forework

In the two previous experiments, interlimb transfer was predicted by individual characteristics. Although the kinematic features during the adaptation phase were contributed efficiently to interlimb transfer, we found no direct link between the level of adaptation and the performance in interlimb transfer. This result was odd since interlimb transfer stems from adaptation. Therefore, instead of resulting directly from the performance in adaptation, we speculated that interlimb transfer may result from the interaction of some sub-components of adaptation. Smith et al. (2006) put forth a model that is quite successful to explain different phenomena resulting from adaptation (see chapter 1). It posits that there are two underlying processes in adaptation: a slow that learns slowly from motor errors but remembers well and a fast that learns quickly from motor errors but forgets quickly too. Such as for interlimb transfer, it was showed that the motor memory (e.g. savings and retention, see chapter 3) cannot be directly does not directly account for the performance in adaptation, but rather by a specific interaction of these two sub-processes. Retention would be better explained by the slow, and savings by the fast process. Therefore, we hypothesized that interlimb would result from either the slow or the fast. Also, we tested in parallel the performance in recalling a previous adaptation with a Coriolis force 24 hours after initial training. We assumed that if interlimb transfer and the performance in motor memory resulted from a similar pattern of sub-processes of adaptation, then we would find correlated performance between these two behaviors.
III. Article

Interlimb transfer of sensorimotor adaptation shares common processes with the motor memory

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In preparation

Keywords: Force-field adaptation – Intermanual transfer - Reaching arm movements — Retention— Savings— Dual-rate model of adaptation

Abstract

When we perform a motor task, such as reaching for an object, under a novel condition, we first make large errors and adapt slowly to perturbations. However, when exposed to the same perturbation after several hours or days, we adapt much faster (i.e. referred to as savings) and/or make initially smaller errors (i.e. referred to as retention)(Krakauer et al., 2005). This increase in performance is thought to stem from the motor memory. The performances in motor memory, savings and retention, are not predicted by the overall performance in adaptation, but by a specific sub-component of adaptation known as the fast and slow process, respectively (Joiner and Smith, 2008; Huberdeau et al., 2015). Moreover, interlimb transfer of adaptation is not either predicted by the overall level of adaptation (Joiner et al., 2013; Lefumat et al., 2015). Therefore, we sought to determine whether interlimb transfer would reflect effective contribution from the slow or the fast process. Also, we hypothesized that if common processes are involved in both motor memory and interlimb transfer, we may observe behavioral links between these two phenomena (i.e. positive correlation between the two performances).

To test this, we designed experiments in which subjects had to reach with their arm for visual targets in a rotating platform producing a velocity-dependent force field. Subjects were right-handed young adults (n=17). They had no visual, only proprioceptive feedback of hand movements. On the first day, there were 3 experimental phases: pre-rotation (right/left hand), training (right hand) and post-rotation (left/right hand). We assessed interlimb transfer by comparing the baseline initial direction of the left hand with the first trial of the post-test. We modeled the fast and slow processes of the subjects producing significant transfer on day 1 and those who did not, in order to compare the contribution of each process according to the performance in transfer. On the second day, we assessed the motor memory of adaptation by testing again the right hand in the force-field.
We observed smaller initial errors on day 2 relative to day 1 on the first trials. This suggests that there was significant retention of motor adaptation. Nevertheless, we did not observe significant interlimb transfer across the participants. But the performances were quite heterogeneous and it allowed us to make two classes of subjects: “transfer” and “no transfer”. As hypothesized, the “transfer” participants were also those that had better performance in motor retention. We also showed that the fast process was the component of adaptation that contributed the most to interlimb transfer.

These results mean that common processes play a role in the formation of motor memory and the performance in interlimb transfer. However, there is a contradiction because motor retention is supposed to result from the slow process, and we observed that transfer was characterized by higher contribution of the fast process. Therefore, further investigation would be required to understand what this discrepancy means.

1. Introduction

Throughout the lifespan, sensorimotor control processes are being optimized by the central nervous system. Such adaptation allows maintaining the most efficient behaviour despite changes in body properties for instance. A body of work indicates that sensorimotor adaptation can be memorized over time, and generalized across other conditions or limbs.

Both retention and savings define the behavioural characteristics of the motor memory. Specifically, retention of sensorimotor adaptation refers to the finding that once a subject has adapted to a perturbation, re-adaptation at a later date is more complete (i.e. smaller errors) (Alahyane and Pelisson, 2005; Krakauer et al., 2005; Joiner and Smith, 2008; Panouillères et al., 2015). While savings refers to the fact that re-adaptation at a later date is faster than during initial training (Brashers-Krug et al., 1996; Shadmehr and Brashers-Krug, 1997; Kojima, 2004; Zarahn et al., 2008; Kitago et al., 2013). Such off-line improvement between practice sessions is thought to rely on the consolidation, with the passage of time, of a fragile motor memory into a stable, and eventually long-term memory (Robertson et al., 2004; Krakauer and Shadmehr, 2006).

Generalization refers to the benefit one can get from previous adaptation in similar circumstances: for example using the opposite limb (interlimb transfer: Dizio and Lackner, 1995; Malfait and Ostry, 2004) or from previous adaptation with the same arm but in different movement directions (intralimb transfer: Gandolfo et al., 1996; Mattar and Ostry, 2007). Although motor memory and transfer of motor learning both directly stem from adaptation, a clear causal link has not been characterized between the degree of adaptation and motor memory (Joiner and Smith, 2008), and the degree of adaptation and transfer (Joiner et al., 2013; Lefumat et al., 2015).

Recently, adaptation has been described as a process emerging from the interaction between two components with different timescales, a fast process which learns quickly from motor errors but also
forgets quickly, and a slow process which, on the other hand, learns slowly but retains well motor information (Smith et al., 2006; Wolpert et al., 2011). In this framework, Joiner and Smith (2008) have demonstrated that the amount motor retention is predicted by the level of the slow process achieved at the end of training, i.e. the higher the slow process, the better the retention. On the other hand, a number of recent studies showed that the formation of motor savings is attributable to a strong contribution of the fast component (Haith et al., 2015; Huberdeau et al., 2015; McDougle et al., 2015; Orban de Xivry and Lefèvre, 2015). As for transfer of sensorimotor adaptation, it has been suggested that to be linked to the fast process (Malfait and Ostry, 2004; Keisler and Shadmehr, 2010; Heuer and Hegele, 2011), although an analytical and computational study indicated that generalization across movement direction derives from the slow process (Tanaka et al., 2012).

Similarly to motor memory, we hypothesized that interlimb transfer would result from a specific interaction of the slow and fast processes. In addition, we speculated that interlimb transfer and motor memory would be correlated, if they reflected similar underlying mechanisms. Therefore, our study was twofold: first with behavioural analysis, we tested whether the performance in interlimb transfer would be related to that in motor memory; second with modelling, we tested the contribution of the fast and slow processes according to the performance in interlimb transfer.

2. Methods

Subjects. Seventeen subjects with no known sensorimotor impairment participated (12 males, 5 females, mean age: 22.9 years). They had no visual feedback, only proprioceptive feedback of hand movement as the room was completely dark. All subjects were right handed, as assessed with the Edinburgh handedness inventory (Oldfield, 1971): laterality quotient was 80±10% on average. All subjects were naive to the purpose of the experiment. Participants gave their informed consent prior to the study, which was approved by the institutional review board of the Institute of Movement Sciences and performed in accordance with the ethical standards of the Declaration of Helsinki.

Experimental set-up. Participants sat in a bucket seat at the center of a motorized rotating platform and were asked to reach toward flashed visual targets (Figure 27A). On a horizontal board, at waist level, a visual and tactile landmark indicated the starting hand position. Visual targets were low-intensity red light-emitting diodes (3 mm in diameter). Two targets were positioned on a 37 cm radius circular array at 0° (straight-ahead) and -30° (to the left) with respect to start position. Infrared active markers were taped to the right and left index fingertips whose positions were sampled at 350 Hz using an optical motion tracking system (Codamotion cx1 and MiniHub, Charnwood Dynamics Ltd, Leicestershire, UK). The experimenter controlled the tracking system, the motorized platform and the presentation of the visual targets from an adjacent room by using a customized software
Chapter 6: The contributions of the underlying processes of adaptation in interlimb transfer

(Docometre) governing a real-time acquisition system ADwin-Pro (Jäger, Germany) (Lefumat et al. 2015).

**Procedure.** At the beginning of each trial, participants had to actively position their hand at the starting location (Figure 27A). They were asked to reach as fast and accurately as possible with their hand toward the visual target which was illuminated for 0.3 s. No explicit instructions were given with respect to hand path. However, participants were required to ‘reach in one movement’ and not to correct after their finger contacted the horizontal board. 1.6 s after trial onset, an auditory 100-ms tone informed the subject to go back slowly to the starting location. 7.4 s after trial onset, a 600-ms tone signaled to the participant that the trial had ended and that the next trial would start immediately. Peak velocity of the targeted, outward reaching movement was “10 times greater than that of the backward arm movement toward the start position. All participants were familiarized with the task during a preliminary phase. They were instructed not to move any body part.

The experimental session consisted of 3 phases (Figure 27B) on day 1 and day 2:

Day 1:

- **PRE-rotation test (baseline):** as the platform was stationary, participants executed 30 reaching movements with the dominant arm (DA) toward the central and lateral targets (15 trials per target, in a pseudorandom order) then 15 with the non-dominant arm (NDA) toward the central target. After the PRE-test, the rotating platform was accelerated in 80 s up to a constant velocity of 120 °/s, i.e., 20 rpm.

- **PER-rotation (adaptation) phase:** Participants performed 80 movements with the DA to the central and left targets while the platform was rotating counterclockwise at 120°/s, generating clockwise Coriolis forces on the moving limb. Coriolis forces \( F_{\text{cor}} \) (see DiZio and Lackner, 1995) are the product of the arm mass \( m \), platform’s angular velocity \( \alpha_v \) and tangential arm velocity \( \nu_t \) according to the equation: \( F_{\text{cor}} = -2m\alpha_v\nu_t \). During that phase, participants wore 2 weight bands of 750 grams each on the dominant forearm. This was done to further alter limb dynamics. After the adaptation phase, the rotating platform was slowed to a stop within 80 s.

- **POST-rotation test (transfer test):** Once the platform was stopped, participants executed 1 reaching movement with the non-exposed NDA toward the central target.

Day 2:

- **PER-rotation (adaptation) phase:** Same as on day 1.

- **POST-rotation test (transfer and after-effects on the DA):** Once the platform was stationary, participants executed 1 reaching movement with the non-exposed NDA toward the central target followed by 15 movements with the DA toward the central and lateral targets.
A 60 s delay was used between the end of the platform’s acceleration and deceleration phases and the first reach trial to allow the vestibular semi-circular canals to return to their resting discharge frequency. The PER-rotation test lasted approximately 15 min, the complete reaching task lasting approximately 40 min.

**Kinematic data analysis.** Data were analysed using Matlab (Mathworks, Natick, MA, USA). Position data from the markers on the right and left index fingertips were low-pass filtered with a dual-pass, no-lag Butterworth (cut-off frequency: 15Hz; order: 2). Movement onset was defined as the first time tangential hand velocity reached 3 cm/s and movement offset as the first time hand velocity dropped below 3 cm/s.

The main dependent variable we considered was initial movement direction, computed as the angle between the vector from the start position to the target position and the vector from the start position to the hand position at peak velocity (PV) of the arm movement. Besides, to assess adaptation and retention, we computed the error made on each trial at PV direction by subtracting from each trial its corresponding baseline (of the left or central target). Also, we computed the lateral endpoint error, i.e. the perpendicular deviation (in cm) between the index fingertip at movement end and the straight line connecting the starting point (i.e., movement onset) to the target (DiZio and Lackner 1995). For all the measures, we assigned positive values to rightward deviations and negative values to leftward deviations.

The level of adaptation was assessed using the formula (First adaptation trial – Final adaptation)/(First adaptation trial --Baseline) with Final adaptation referring to the mean of the last 10 trials of the adaptation phase and Baseline referring to the mean of the 15 trials towards the central target in the pre-adaptation phase.

The transfer value of each subject was defined using the formula: \( transfer_i = \frac{|X_i - \mu_i|}{S_i} \), where, for each subject \( i \), \( X \) was the initial direction of the first POST-test NDA trial, \( \mu \), the initial direction averaged across NDA baseline movements, \( S \) was the standard error of the baseline. This value allowed us to classify subjects as “Transfer” or “No transfer”. Indeed, the formula used to assess the transfer value is similar to the Student’s t-value which is used for hypothesis testing with a normal distribution. In other words, if the transfer value was outside the 99% confidence interval of the corresponding baseline, the null hypothesis was rejected and the subject was classified a ‘Transfer’ subject. Note that significant transfer could be positive or negative. Positive values indicate that the transfer is in extrinsic coordinates (e.g. clockwise, regardless of the limb used) and negative values indicate transfer in intrinsic coordinates (e.g. towards adduction regardless of the limb).
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**Statistical analysis.** To compare DA adaptation on day 1 and day 2, and thus assess retention, we used a repeated-measures analysis of variance: a 2x2 [Day (1, 2) x Adaptation phase (First two trials, last ten trials)] ANOVA.

We investigated whether the transfer classification of the subjects could be revealed by the variables describing adaptation and retention. For this purpose, we used clustering which is an unsupervised technique that groups a set of observations in such a way that the observations in the same cluster are more similar to each other than to those in another cluster. Specifically, we chose a k-means clustering method with a city-block distance to partition the observations. We specified a number of 2 clusters to compare the results with the classes “Transfer” and “No transfer”.

All data had a normal distribution as verified with the Kolmogorov-Smirnov method. Newman-Keuls tests were used for post-hoc analysis. For all tests, the significance threshold was set at 0.05.

**Model simulations.** To assess the effect of adaptation on retention and interlimb transfer, we chose to model the adaptation phase of day 1 with the dual-rate model of sensorimotor adaptation first proposed by Smith et al. (2006). In this model, the movement output is updated at each adaptation trial and combines two underlying processes: the fast process that responds quickly to movement errors but does not retain well information, and a slow process that retains well the information but responds slowly to movement errors. Consequently, the model assumes for each process separate retention factors and learning rates as follow:

\[
\begin{align*}
    x_f(n+1) &= A_f \cdot x_n - B_f \cdot e_n \\
    x_s(n+1) &= A_s \cdot x_n - B_s \cdot e_n \\
    x_n &= x_f n + x_s n \\
    B_f &> B_s, A_s > A_f
\end{align*}
\]

where, \( x_n \) is the motor output on trial \( n \), \( x_f \) the fast component, \( x_s \) the slow component of adaptation, \( e(n) \) the error on trial \( n \), \( B \) the learning rate, \( A \) the retention factor. The error \( e(n) \) is the sum of the force field \( F \) and the motor output \( x(n) \) such that:

\[
e_n = x_n + F
\]

We estimated the parameters \( A \) and \( B \) as well as the strength of the force-field \( F \) to fit the initial learning data. Here, we included the strength of the force field as a free parameter in the equation. For the simulation of the model, the parameters \( A, B \) and \( F \) were derived from a least-squares fit to the initial learning data using the `fmincon` function in MATLAB.

We built the model on the mean of each subject groups (Lee and Schweighofer, 2009). To find confidence intervals of model parameters estimates, we used the bootstrap method with case resampling. Bootstraping is a statistical technique that approximates the sampling distribution several times by selecting randomly observations from the original data set. So a particular data point from the original data set could appear multiple times in a given bootstrap sample. In our
study, we generated 500 bootstrap samples of the original data and considered averages of the resampled data sets. These new samples were used to iteratively solve the equation of the model. The results of the model for each sample were used to obtain a mean and standard deviation of each component of the equation, which allowed use to make group comparisons. The model was estimated using this bootstrap procedure for the “Transfer” and “No transfer” subjects. Then, we compared the value of the different parameters (A, B and F) and processes (fast and slow) at different time of the adaptation course (beginning and end).

Figure 27: A) Representation of the experimental setup. The counterclockwise rotation was applying a rightward deviation on the moving limb. B) Experimental protocol on day 1 and day 2. The right arm had to adapt to the Coriolis force on day 1 and was tested again on day 2 to see whether or not there was a beneficial impact of motor memory on the performance. Initial transfer was tested on day 1 outside the rotation and on day 2 to see if there was any effect of retention of transfer.

3. Results

Adaptation and retention of Coriolis force

Figure 28A-B show that during baseline, hand paths were generally straight and accurate (mean initial direction error of movements toward the central target = -2.7±3.7°, endpoint error= -0.73±1.1cm). Movements were fairly accurate despite the high requested speed (results across all experimental phases: mean peak velocity=2.6±0.5m/s; mean movement time=364±50ms). As expected, the counter-clockwise rotation of the experimental platform generated Coriolis forces which clearly perturbed, clockwise, the hand path on the initial trial of the adaptation phase on Day 1 (Figure 28A). Figure 28C-D shows that the initial direction error of the first trial was less perturbed on Day 2 compared to Day 1, consistent with the idea of a formation of a motor memory developed on Day 1. Adaptation was substantial on both Day 1 and Day 2 as subjects were able to eventually compensate for the novel force-field to restore straight and accurate hand paths (Figure 28A-D). These findings were statistically significant. A 2x2 [Day (1, 2) x Trial (First 2, Last 10)] ANOVA on initial movement direction error revealed a significant interaction ($F(1,16)=12.3, p<0.01, \eta^2=0.2$). As
illustrated on Figure 28E, post-hoc analysis showed that on Day 1 and Day 2, initial direction error during the first trials of the adaptation phase was greater than that in the last 10 trials \((p<0.001\) for both days), consistent with the idea of a sensorimotor adaptation. The retention of motor learning was seen as the initial direction error during the first trials was smaller on Day 2 than on Day 1 (Day1=11\(^\circ\), Day2=6\(^\circ\), \(p<0.01\)). By comparing each trial mean with the 95\%CI of the mean baseline across subjects, we found that participants adapted to the force-field in 3 trials on both day 1 and day 2. Thus, we didn’t observe an effect of savings. Similar findings were found on the lateral endpoint error. Indeed, a 2x2 [Day (1,2) x Trials (First 2, Last 10)] ANOVA on the endpoint errors (relative to baseline) revealed an interaction \((F(1,16)=41, p<0.001, \eta^2=0.1)\) showing that initial errors decreased from the first to the last trials on Day 1 \((p<0.001, \text{error difference}=2.8\text{cm})\) but not on Day 2 \((p=0.6, \text{error difference}=-0.3\text{cm})\). More precisely, we did not observe an effect of savings on day 2 because the first trial was already quite accurate. Also, there was a significant reduction of endpoint errors in the first adaptation trials between Day 1 (mean=4.1±2.8cm) and Day 2 (mean=1.5±1.6cm; \(p<0.001\)). In summary, these results suggest that sensorimotor adaptation was observed on Day 1 and Day 2 and that formation of a motor memory resulted in retention on Day 2.

**Interlimb transfer of Coriolis force adaptation toward the non-dominant, left arm**

Interlimb transfer of force-field adaptation was assessed on Day 1 and Day 2. We recently reported a large heterogeneity in interlimb transfer of Coriolis force adaptation across individuals and developed a method to assess transfer toward the non-dominant arm for each individual (Lefumat et al. 2015). In the present study, interlimb transfer was not significant when considering all participants as initial direction error of the left arm movements did not differ between the PRE-test and the POST-test, both on Day 1 \((p=0.7; \text{PRE- and POST-test difference}=0.57±5.7°)\) and on Day 2 \((p=0.09; \text{PRE- and POST-test difference}=-1.8±4.2°)\). However, we again found a large inter-subject heterogeneity and could distinguish 2 classes of subjects, ‘Transfer’ and ‘No transfer’ subjects (see Methods). Our analysis of data from Day 1 revealed
that 11 subjects could be classified as ‘Transfer’ and 6 subjects as ‘No transfer’. Given that the goal of the current study was to investigate the link between transfer and retention, we assessed whether the amount of retention between Day 1 and Day 2 differed between ‘Transfer’ and ‘No transfer’ classes of subjects. We performed two separate 2x2 [Day (1, 2), Class (‘Transfer’, ‘No transfer’)] ANOVAs on initial direction error of the first and last trials. Both analyses revealed an interaction (First trial: $F(1,15)=66, \eta^2=0.06$; Last trials: $F(1,15)=66, \eta^2=0.7; p<0.05$ for both, Figure 29A-B). Decomposition of the interaction revealed that the change of initial direction error between Day 1 and Day 2 was significant for the ‘Transfer’ subjects (mean difference=$6.0\pm6^\circ$; $p<0.01$) but not for the ‘No transfer’ subjects (mean difference=$0.16\pm3.6^\circ$; $p=1$). We also found that in the last adaptation trials, only ‘No transfer’ subjects improved their performance from Day 1 to Day 2 ($p<0.05$, error reduction=$-5.53\pm6.2^\circ$) as ‘Transfer’ subjects’ errors already were very small on Day 1 ($p<0.05$, error reduction=$0.51\pm2.6^\circ$).

We investigated whether the existence of two distinct groups of subjects could be distinguished by the amount of retention per se. The goal was to test whether a similar partition of the subjects, as in the ‘transfer’ and ‘no transfer’ group, would be observed. We plotted the transfer value as a function of the difference in initial direction error between Day 1 and Day 2 in the first and last trials of the adaptation phase of Day 1. The correlation was significant for the errors in the last trials of the adaptation phase ($r=0.61, p<0.01$), but not for the errors in the first trials ($p=0.2$). Then, we applied a k-means clustering method for these 2 plots (Figure 29C-D) to group the subjects according to their similarities in term of transfer and savings. The silhouette index are quite low (First errors=0.4, Last errors=0.5) which means that the clusters are not very well separated. However, we observed that the resulting clusters are very close to our predefined classes (Transfer and No Transfer). Indeed, for the first errors we obtained 94% (i.e. 16 subjects out of 17) and for the last errors 77% (i.e. 13 subjects out of 17) of good discriminations. These classification similarities support the idea of a relation between interlimb transfer and retention.

To determine whether the amount of transfer could be predicted by the variables describing adaptation, we conducted a forward multiple regression on the initial direction errors during the first and last trials on Day 1 and Day 2 as a function of the transfer value. The selected variables to predict transfer, sorted by importance, were the last trials’ errors on Day 2, those on Day 1 and the first trials’ errors on day 1 ($r=0.66,r^2=0.44,adj \ r^2=0.31; p<0.05$). Specifically, the transfer value increased as the last trials’ errors on day 2 decreased, while the last trial errors on day 1 increased, as did the first trials on day 1. It suggests that generalization was sensitive to large
errors in initial adaptation on day 1. Regarding the last’ trials errors, we observed a difference in the direction of the regression between day 1 and day 2. This may be due to the subjects’ performance. Indeed, on day 1 subjects tended to over-compensate the force field (-2.5±4.5°), thus a positive relation between transfer and the errors meant that the subjects with better transfer value had smaller initial direction errors (i.e. closer to 0). On day 2, subjects were closer to straight hand path (-0.8±4°) but it is the subjects that over-compensated the most the force-field who had higher transfer values.

Multi-rate model of adaptation
To investigate whether the slow or the fast processes differed according to the performance in generalization, we ran the multi-rate model of adaptation separately on the classes of ‘Transfer’ and ‘No transfer’ subjects (Figure 29). The variable used for the model was the initial movement direction in the adaptation trials on Day 1. We applied 500 bootstrap samples of this variable. Then, for each trial, data were averaged across subjects before estimating the equation parameters (see Methods). Figure 30A-C show that the states of both the slow and fast processes were higher in the ‘Transfer’ class in the beginning (i.e. mean of the first 10 trials) of the adaptation phase (slow: $t(998)=5.6$, $d=0.3$; fast: $t(998)=10.3$, $d=0.6$ ; $p<0.001$ for both). At the end of the adaptation phase (i.e. mean of the last 10 trials), the fast process was higher in the ‘Transfer’ class while the output of the slow process was higher in the ‘No transfer’ class (Figure
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30A-C. **slow**: \( t(998)=-9.3, \ d=0.6; \) **fast**: \( t(998)=10.5, \ d=0.7; \ p<0.001 \) for both). To get a more detailed measure of the processes, we compared the fitted values of the retention factors \( A_f \) and \( A_s \) and the learning rate \( B_f \) and \( B_s \) in the 2 classes. The learning rates were higher in the ‘Transfer’ class \( (B_s; \ t(998)=14, \ d=0.9; \ B_f; \ t(998)=20, \ d=1.3; \ p<0.001 \) for both) whereas the retention factors were higher in the ‘No transfer’ class \( (A_s; \ t(998)=-7.7, \ d=0.5; \ A_f; \ t(998)=-3.7, \ d=0.2; \ p<0.001 \) for both). These findings suggest that interlimb transfer results predominantly from a high contribution of the fast process throughout adaptation with lower contribution of the slow process at the end of the adaptation phase. Also, early adaptation occurs at a higher rate among the ‘Transfer’ subjects, as supported by the finding that the effect size of the learning rates was strong for the slow process and very strong for the fast process (As and Af). While the difference in retention factors was significant, its influence was modest as indicated by the effect size (e.g. medium for As and small for Af).

![Figure 30: Results of the dual-rate model. A-B) Output of the model for the “transfer” (A) and No “Transfer” class (B). The black represents the motor compensation (the adaptation curve) and is the result of the sum of the slow (blue) and fast (red) process. C) Histograms of the mean and standard error of the 10 first trials (left) and of the last 10 trials (right) of the fast and slow processes. D) Confidence intervals of the difference between the “transfer” and “No transfer” class for the comparisons represented by the histograms. E) Histograms of the mean and standard error of the parameters of the model. F) Confidence intervals of the difference between the “transfer” and “No transfer” class for the parameters of the model.](image)

4. **Discussion**

This study aimed at investigating whether generalization and retention of motor adaptation reflect similar underlying mechanisms. Specifically, we first set out on to observe if participants with better performance in generalization stood out in their retention performance. Then, we investigated how generalization and retention are...
influenced by the sub-components of adaptation, the fast and slow processes put forth by Smith et al. (2006). One of our key finding is that the participants who elicited significant generalization were also those with better retention on day 2. These subjects also had straighter movements at the end of the adaptation phase on day 1 than subjects who did not elicit generalization of sensorimotor adaptation.

As we analysed the contribution of the fast and slow processes underlying adaptation, striking similarities were found between the subjects showing generalization and those showing high retention of sensorimotor adaptation. Indeed they were characterized by a high contribution of the fast process throughout adaptation, a low contribution of the slow process at the end of the adaptation phase and a high impact of the learning rates (both fast and slow).

**The contribution of the fast and slow processes in retention and generalization**

Our results corroborate previous studies showing retention of visuomotor adaptation over 24 hours (Joiner and Smith 2008; Criscimagna 2010; Krakauer 2005; Alahyane and Pelisson, 2005) and extend it to the paradigm of Coriolis force-field adaptation. Moreover, our results are in line with recent studies showing that the formation of long-term motor memory is attributable to a high contribution of the fast process (Huberdeau et al. 2015; Haith et al. 2015; Keisler and Shadmehr, 2010) and also agree with the hypothesis that generalization stems from the fast process (Keisler and Shadmehr, 2010 ; Huberdeau et al. 2015). It has been proposed that the fast process engages the explicit/declarative motor memory (Keisler and Shadmehr, 2010), which is most commonly entailed by large and unexpected errors that are sensitive to reward (Orban de Xivry et al. 2015; Huang et al. 2011; Stockinger et al. 2014). This form of learning lays down a memory that is effector-independent as it relies on higher cognitive representations (Keisler and Shadmehr, 2008). By contrast, the slow process encompasses an implicit and procedural form of learning that is sensitive to movement errors and does not result in retention of motor memory (Huberneau et al. 2015). According to this body of work, in our study participants showing generalization and retention seemingly relied more on higher-order strategies and less on lower-level sensorimotor policies (see Figure 16).

The participants exhibiting significant interlimb transfer were showing better retention but also more rectilinear trajectories at the end of the adaptation phase,
whereas the other participants tended to over-compensate the force-field. It has been shown that by applying a curved path in a velocity-dependent force-field, the participants may use a strategy of re-optimization so that the motor plan minimizes the motor costs and maximizes rewards (Izawa et al. 2008). However, here this over-compensation seemed to be counterproductive to generalization and retention of adaptation. Instead, there may be a local threshold above which over-compensation is not beneficial anymore. Or in our study the better kinematic strategy would appear to be to produce smooth and straight paths movements as postulated by the minimum-jerk model (Todorov, 2004).

**The putative neural substrates of the processes underlying sensorimotor adaptation**

Adaptation to a visual or mechanic perturbation is attributable to distinct mechanisms operating simultaneously and in parallel. The implicit learning stemming from the slow process is thought to reflect updating of an internal forward model which would be cerebellum-dependent (Taylor et al. 2014; Izawa et al. 2012). However other findings contradict the fact that the slow process would account for this unique neural substrate. Indeed, in patients with cerebellar degeneration, adaptation to gradual perturbation which results from the slow process (Orban de Xivry et al. 2011) was shown to be preserved while adaptation to abrupt perturbation leading to large errors and resulting thus from the fast process was damaged (Criscimagna et al. 2010). This would suggest that the slow process is not entirely cerebellar-dependent, and that the fast process also results from interactions involving the cerebellum as pointed out in a TMS study (Schlerf et al. 2012). Presently, the neural basis of the fast process, allowing the formation of a long-term memory, likely relies on a wide network and includes the primary motor cortex (Orban de Xivry et al. 2011, 2013; Richardson et al. 2006) and some other areas relative to executive and attentional functions such as the frontal and temporal cortex (Keisler and Shadmehr. 2010; Anguera et al. 2010; Taylor et al. 2014). There appear to be multiple components within the slow process (McDougle et al. 2015; Inoue et al. 2015; Lee & Schweighofer, 2011) which may be supported by both subcortical and neocortical substrates, and probably the cerebellar nuclei (Orban de Xivry et al. 2011; Medina et al. 2011).

Interlimb transfer seems to share common cortical activities with the areas allowing long-term motor memory. Indeed, some studies suggest that it relies on
the cerebellum, the parietal (Seidler and Noll, 2008), the motor cortex (Anguera et al. 2007; Seidler and Noll, 2008; Perez et al. 2007), and the supplementary motor area that has been shown to encode a memory trace that can be accessed by both hands (Perez et al. 2007, 2008).

The dual-rate model of adaptation is quite successful in explaining several phenomena. But it is still an approximation of sensorimotor adaptation and it remains elusive on certain mechanisms. The putative neural substrates underlying the slow and the fast processes and leading to the formation of a long-term memory and generalization may rely on a wide and complex network that remains to be determined.
Discussion
Chapter 7

Interlimb transfer of sensorimotor adaptation: an intricate process
Interlimb transfer has been identified for decades, and yet there is not an unified view on the factors and underlying processes that lead to it. Diverse tasks and experimental conditions have been used to investigate interlimb transfer so that it is difficult to draw a general conclusion. For instance, some experiments use motor tasks such as catching balls (Morton et al., 2001), sequence learning of key presses (Perez et al., 2007b), skill learning (Kantak et al., 2011) or, in our case, sensorimotor adaptation tasks (Dizio and Lackner, 1995; Lefumat et al., 2015, 2016). These different tasks involve different mechanisms and in particular different degrees of cognition and implicit learning (Masters, 1992; Mazzoni and Krakauer, 2006). Therefore, direct comparisons are thorny. Even among sensorimotor tasks which seem similar, some discrepancies remain. Consider the example of a reaching task: Prisms, visuomotor rotations and dynamic perturbations are the most common paradigms which have been used to assess interlimb transfer of reach adaptation, and the findings on these studies are sometimes used indifferently to make hypotheses or interpretations. Nevertheless, it can be hazardous to lump together these paradigms because they do not involve the exact same processes (Krakauer et al., 1999; Rabe et al., 2009; Donchin et al., 2012) and may thus lead to different behavioral consequences (Krakauer et al., 2000; Mattar and Ostry, 2007). Moreover, other phenomena seem to play a role in the heterogeneity of the findings in interlimb transfer: the positions of targets, the awareness of the perturbation, the estimation of the source(s) of the errors, the direction of transfer, the manner transfer is assessed etc.

The goal of our first two experiments was mainly to test new hypotheses based on a critical review of the discrepant findings in the literature. Although most of our hypotheses, most notably on the importance of sensory conditions or of conscious strategies, were not necessarily relevant to clarify the processes underlying interlimb transfer, we ended up characterizing some factors mostly related to individual characteristics such as movement kinematics and laterality quotient (Oldfield 1971). The goal of the third experiment was to provide some more insights on the processes underlying interlimb transfer by using the well-known dual-rate model of sensorimotor adaptation put forth by Smith et al. (2006). Our approach was thus to try to tackle both the paradigmatic and the idiosyncratic factors which influence interlimb transfer as well as the processes of interlimb transfer, hoping that this could prove relevant to understand interlimb transfer as a whole.

We first hypothesized that the paradigmatic conditions, and more precisely the type of feedback used during adaptation could account for the performance in transfer. This began with the observation that most studies reporting significant interlimb transfer were performed while direct vision of the limb was prevented, either as no visual information was available or as only a visual cursor could be seen. This hypothesis also echoed one suggestion of Cohen (1967, 1973) who studied interlimb transfer of prism adaptation. We also thought that this hypothesis could be consistent with the credit assignment theory (Berniker and Kording 2008) that postulates that the nervous system
assigns the consequences of our actions either to internal factors or to external factors (the environment). Adaptation would more likely generalize to another effector if an error is due to the environment. Thus we hypothesized that vision of the limb would be associated to an assignment of errors expected in the first trials of the adaptation phase to internal factors (as one would see himself missing the target), while without vision of the limb errors would more likely be associated to external factors, which in turn would lead to interlimb transfer. The first two experiments showed that interlimb transfer does not seem to be related to the type of sensory feedback used during adaptation. Considering that adaptation occurred under all type of sensory conditions, with vision or without vision (Lefumat et al. 2015) and even without proprioception (but with vision, Lefumat et al. 2016), it may not be surprising that interlimb transfer was also observed, since the task was similar to that of Dizio and Lackner (1995). In fact, it was previously shown that adaptation can be similar with or without vision of the limb, even in unstable environments which are more difficult to adapt to (Scheidt et al., 2005; Franklin et al., 2007; Arce et al., 2009). Also the absence of proprioception was shown not to preclude adaptation to a novel force field (Sarlegna et al., 2010; Yousif et al., 2015) despite its well documented effect on the compensation of intersegmental dynamics in multi-joint arm movements (Sainburg et al., 1995). We thus conclude that a sensory modality could compensate for the loss or the absence of another modality, at least for force-field adaptation and generalization of such adaptation. This latter case is a natural result of sensory substitution that is allowed by the plasticity of our nervous system (Bach-y-Rita, 1987).

The second goal of our first study was to identify whether, instead of paradigmatic features, the individual characteristics could account for the heterogeneity of the performance in interlimb transfer. To this end, among a set of variables describing mainly the kinematic features of the dominant arm, we selected the most discriminant variables to separate the participants in term of interlimb transfer to the opposite arm. The variables which could distinguish the participants that produced interlimb transfer from those who did not were the variability of initial direction at the end of the adaptation phase, the peak velocity of movements across the adaptation phase and the laterality quotient (i.e. the extent of handedness; Oldfield, 1971). Not only could these variables explain in a qualitative manner interlimb transfer, but they could also quantitatively describe the amount of interlimb transfer. It is an increase of each of these variables that described better a high performance in interlimb transfer. These results suggest that inter-individual differences influence motor performance and in particular interlimb transfer. This is a first step before designing new experiments and specific manipulations in order to establish a causal relationship between movement kinematics and interlimb transfer. Interestingly, Kanai and Rees (2011) revealed how inter-individual differences can be used as a source of information to link human behavior and
cognition to brain anatomy. This supports the idea that not only invariant features of the motor repertoire are interesting to better understand motor behavior.

In the third experimental chapter, we focused on the processes underlying interlimb transfer and we used the dual-rate model of adaptation (Smith et al. 2006) to describe the pattern of the subprocesses during dominant arm adaptation that may lead to significant interlimb transfer from the dominant to the nondominant arm. We found that interlimb transfer was better characterized by a high contribution of the fast and a low contribution of the slow process. Interestingly, we also found that the subjects with better performance in interlimb transfer were those with better performance in retention of adaptation when tested on the same task 24 hours later with the dominant arm. These different findings are discussed further in the following sections.

I. Inter-individual differences

1. The role of the trajectory’s variability

In the first experimental chapter we reported a positive correlation between the variability of initial movement direction at the end of the adaptation phase (i.e. last 10 trials) and the extent of interlimb transfer. However the influence of variability was not only restricted to the last trials of the adaptation phase, since a correlation was also observed when variability was computed across all the trials of the adaptation phase. Even if late variability was selected in the classification and regression models, all the variables regarding variability (e.g. early, late, all trials) were highly correlated to the performance in interlimb transfer. Therefore, rather than solely the late variability, it seems that variability overall has a significant influence on subsequent movements with the opposite arm.

Variability has been shown to be beneficial in many contexts such as in motor skill learning (Shea and Morgan, 1979; Ranganathan and Newell, 2013), sensorimotor adaptation and reinforcement learning (Wu et al., 2014). For example, Shea and Morgan (1979) trained subjects to acquire different motor sequence in two different conditions, either with each sequence experienced repeatedly within a block of trials or with the sequence randomly changing from trial to trial. The random group experienced larger errors during training but performed better in a retention test and generalized better to more complex motor sequences. Similarly Kantak et al. (2011) showed that variable practice promotes better transfer of performance to other tasks than constant practice. Considering the variability of the movements per se rather than the variability of the schedule, Wu and colleagues (2014) studied the effect of baseline task-relevant variability on the rate of learning. In a reinforcement learning task in which participants had to guess the shape of the rewarded trajectory, higher level of task-relevant variability in the baseline predicted faster learning. The authors concluded that motor variability is a form of action exploration that through its active regulation
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facilitates motor learning. In this condition, motor variability can be equated with action exploration where the exploration necessary to gather knowledge must be balanced with exploitation of the knowledge that has been accrued. Herzfeld and Shadmehr (2014) used a meaningful illustration to explain the trade-off between exploration and exploitation (Figure 31).

![Image](image.png)

**Figure 31:** Motor variability in trying to find the piñata (Illustration from Herzfeld and Shadmehr, 2014) during the exploration of the environment. Once contact is made, the child switches to a strategy of exploitation, in which the same movement is repeated on subsequent swings.

In this illustration we see a child trying to hit a piñata. In the first trials, the child explores randomly its environment with a large amount of variability, and this behavior gives him some information about the possible location of the piñata. Once the bat finds the piñata, he switches to a strategy of exploitation whereby he exclusively attempts to strikes the rewarded location. Wu and colleagues (2014) also reported a positive relationship between variability and learning in a force-field adaptation task in which participants had to counter a velocity-dependent force field while performing reaching arm movements (thus there was no prerequisite on the shape of movement trajectories). In this condition, the task relied on error-based learning, thus participants had the ability to adjust motor outputs based on motor errors without the requirement of any additional information. Therefore it was somewhat surprising to find that variability was beneficial to error-based learning just like it was forward-based, reinforcement learning. The authors stated that action exploration provides useful information for improving the internal representation of the gradient function between the motor errors and the motor commands. In line with this study, recent evidence coming from structural learning proposes that varying the structure of a sensorimotor task (e.g. random perturbations for the same targets) allows facilitation to subsequent tasks within this range because it requires the learning of fewer parameters than if the structure was not known.
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Transitioning between two tasks conforming to the structure leads to less interference, because fewer parameters have to be changed (Braun et al., 2009; Turnham et al., 2012).

In our experiments it is not the variability of the baseline that predicted interlimb transfer, but the variability of the adaptation phase. In line with the ideas developed earlier, we could think that in our experiment variability may help the participants to explore the workspace during the adaptation phase and develop better strategies that can transfer to other effectors. We initially thought that variability helped enhancing the internal representation of the perturbation, but we did not find direct evidence between the rate of learning or the general performance in adaptation and the variability. It is worth noting that all the participants adapted fully and very quickly to the Coriolis force. Thus our analysis may suffer from a potential ceiling effect that prevented us from assessing the effect of variability on the level of adaptation.

Also, if we consider the exploration-exploitation idea in our adaptation experiment, one should expect to observe less variability at the end of the adaptation phase, as a result of an exploitation strategy. However, variability at the end of adaptation differed from baseline variability (it was higher) despite participants were adapted to the perturbation. Thus variability was deliberately modulated by the participants. This may suggest that adaptation was not complete and exploration was still active. In fact, it has been shown that behaving in an unusual, variable, or unpredictable manner is sometimes functional (Neuringer, 2002). In decision-making studies, the overall variability of an individual’s choice can be beneficial to adaptive inference (Cohen et al., 2007). Adaptive inference is the process of drawing conclusions from uncertain data in a dynamic environment. In a typical paradigm to study this process, participants must infer a future state based on the statistics of past experiences. Critically, however, these statistics are unstable, so the inference process must be adjusted accordingly (Cohen et al., 2007; Gold and Shadlen, 2007; Tervo et al., 2014). Interestingly, unlike in reinforcement learning, variability of decision does not lead to relevant information in solving a problem. Instead, variability seems as an outcome of uncertain environment in helping adaptive behavior. Behaviors with high variability are more likely to detect a change of rule in the environment than behaviors that exploit always the same solution. In other words, variability allows keeping track of the uncertainty of the environment associated with the relevant data and their possible interpretations. In the context of motor adaptation, this adjustment process can be thought of as changes in an inferred, probabilistic (uncertain) model of the force-field perturbations that must be overcome to produce an appropriate arm trajectory. The uncertainty in this model has two competing effects: higher uncertainty gives rise to more movement variability (because each movement is based on the model’s estimate of the force-field perturbation), but also can promote adaptation (because a model with no uncertainty about the current force field would be unable to account for the possibility that the force field has changed). Thus, this idea posits that motor
variability is beneficial for motor adaptation because it reflects the flexibility inherent to sufficient uncertainty in a learned model of an unpredictable world. This type of strategy may promote interlimb transfer because the learned model is not specific to the effector (i.e., the trained arm) and thus can also be applied to the other arm. However the reason to why variability is beneficial to interlimb transfer remains unclear and additional studies, which directly manipulate variability and assess its effect on transfer, would be required.

2. The role of movement velocity

Peak velocity of reaching movements during the adaptation phase was another predictor of interlimb transfer in our first two studies. However its role is quite uncertain and different hypotheses are possible.

Peak velocity may be an important factor because in the task, we used a velocity-dependent force field. Naturally, greater peak velocity induced greater trajectory errors. Initially, we thought that these large errors may have induced greater compensation and may thus have led to a more refined internal representation of limb dynamics, resulting in greater transfer of sensorimotor adaptation. However, as for variability, the level of adaptation was not impacted by peak velocity. Using a visuomotor, non-velocity-dependent perturbation may help clarifying the influence of peak velocity on interlimb transfer.

One alternative explanation is that fast movements may rely more on feedforward control mechanisms than slower movements. Therefore, minimizing errors may rely more on motor planning processes and that would be reflected in our assessment of interlimb transfer which was done early in the movement, before most feedback loops could substantially influence movement trajectory. Therefore peak velocity would be a good predictor not because it enhances mechanisms allowing interlimb transfer, but because it enhances the visibility of the after-effects by minimizing the influence of online control processes. Similarly to that hypothesis, high peak velocities may reflect lower reliance on impedance strategies, which would in turn promote larger after-effects on the opposite arm movement. To unravel this issue we could use either visual channel in visuomotor rotations, or force-field channel (error-clamps) in dynamic learning. These two methods project the actual hand trajectory onto the straight line passing from starting to end target. Hence it allows minimizing most sensory feedback control mechanisms based on vision and proprioception.

3. The role of the laterality quotient and its putative influence on the hemispheres

It has been suggested that interlimb transfer stems from the bilateral increase in corticospinal excitability (Criscimagna-Hemminger et al., 2003; Anguera et al., 2007; Joiner et al., 2013; Ruddy and Carson, 2013; Sainburg, 2014). We suggest that the laterality quotient was a relevant predictor of
transfer in our first study because it has an influence on the interhemispheric communications and thus on the level of bilateral activation. For the sake of simplicity we will develop this issue by only referring to the case of right-handers and of transfer from the dominant to the non-dominant arm as in our experiments.

Many studies of healthy subjects (Sainburg, 2002; Schambra et al., 2011; Mutha et al., 2012) and stroke patients (Schaefer et al., 2007, 2009; Mani et al., 2013) showed that, in right-handers, the dominant left hemisphere is specialized in the control of limb dynamics and entails greater dynamic representations than the non-dominant right hemisphere (Kawashima et al., 1993; Dassonville et al., 1997; Gazzaniga, 2000; Goble and Brown, 2008) For instance, Schambra et al. (2011) found that applying tDCS over the left hemisphere motor cortex but not the right hemisphere induced greater skill learning than sham during unilateral pinch force modulation of both the right and left hand. Thereby, it reveals that the left hemisphere is able to influence motor learning in the left hand. Also, the contributions of the two hemispheres are not symmetrical. The movements of the dominant hand involves greater contralateral than ipsilateral activations of the hemispheres, whereas the movements of the non-dominant hand result in a more balanced pattern of activation between the hemisphere with substantial recruitment of ipsilateral motor areas (Kawashima et al., 1993; Kim et al., 1993; Dassonville et al., 1997; Callaert et al., 2011) Taken together, it may suggest that motor skills require important activation of the left dominant hemisphere when using both right and left arm movement because it is proficient for controlling limb dynamics (Sainburg, 2014). Therefore, in our study with right handers, the fact that the amount of interlimb transfer was linked to the laterality quotient may be explained by 1) a greater activation of the contralateral (left) hemisphere when using the dominant (right) hand and/or 2) by more involvement of the ipsilateral (left) hemisphere in strongly lateralized subjects when using the non-dominant (left) hand. There is some evidence consistent with these two possibilities. During movements with the dominant arm, it was shown that strong lateralization leads to higher contribution of the contralateral dominant hemisphere in both right and left handers (Dassonville et al., 1997). Therefore, the predominant encoding of the adaptation state in the dominant hemisphere may have been accessible through the ipsilateral projections when the left arm was used. Regarding the second possibility, one study revealed that among participants who had a low proficiency on the motor task with their non-preferred hand, the amount of activity elicited in the ipsilateral motor region of the non-preferred hand was significantly higher than in individuals with comparable performance between the hands (Verstynen et al., 2004). A lower proficiency with the non-dominant arm may refer to individuals with

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3 Transcranial Direct Current Stimulation
a higher laterality quotient, even if in the former study the authors could not link directly these two features.

Our hypothesis is slightly different to what classically the cross-activation model stands for (Chapter 2 - IV). That is, distributed cerebral activity, during unilateral movement with the right arm, leads to adaptations in neural circuits that project to the muscles of the untrained left limb, thus facilitating subsequent performance of the task with the untrained left limb (Ruddy and Carson, 2013). We can difficultly make a similar hypothesis, namely that strong lateralization enhances the ipsilateral activations of the trained right arm (i.e. right hemisphere in right handers) because, as stated earlier, the amount of activation ipsilateral of the dominant arm is less important in strongly lateralized individuals (Dassonville et al., 1997). In fact, the cross-activation model is most likely to predict that interlimb transfer would be enhanced in ambidextrous individuals due to high symmetry in the brain activation when using the dominant arm (Chase and Seidler, 2008).

As for right-handers, we found that the laterality quotient in left-handers was a good predictor of transfer. In left-handers some studies describe a mirror pattern of activation as stated above: a right dominant hemisphere specialized in control of limb dynamics (Wang and Sainburg, 2006; Przybyla et al., 2011), and high contralateral activation when using either arm (Dassonville et al., 1997). But there are fewer studies on left-handers and unfortunately findings are conflicting so it is difficult to be conclusive on whether interlimb transfer from dominant to non-dominant arm in strongly left-handed individuals is due to the same reason as for strongly right-handed individuals. Although it would be tempting to draw similar conclusions for right-handers and left-handers, distinct underlying mechanisms are likely to occur. We have to take into account the substantial heterogeneity of handedness’s degree among left-handers, and more symmetry compared to right-handers (Oldfield, 1971; Chase and Seidler, 2008). Indeed, left-handers live in environments mostly made for right-handers, who represent 90% of the population, and hence they are forced to use more frequently their non-dominant arm in daily activities compared to right-handers (Oldfield, 1971). This may explain why they coordinate more efficiently their non-dominant arm than right-handers (Przybyla et al., 2011).

Prospective studies would be needed to explore further the contribution of the dominant hemisphere, and of the laterality quotient in interlimb transfer. One way to investigate the influence of the hemispheres would be to use tDCS or TMS\(^4\) over the left and right motor cortex hemispheres during training with the dominant arm or transfer with the non-dominant arm.

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\(^4\) Transcranial Magnetic Stimulation
II. Similarities between retention, savings and interlimb transfer

In our third experiment we found that the subjects with better performance in transfer were also those with better performance in motor retention when tested on the same adaptation task 24 hours later. We suggested that this may be because similar processes underlie these two behaviours. Intriguingly, we found that interlimb transfer is attributable to a high contribution of the fast process that has previously been associated with savings, another form of motor memory, but not retention that has associated with the slow process. Hence, many questions arise: What do the differences between retention and savings teach us about interlimb transfer? And why do we observe this conflicting result?

1. Characteristics of the motor memory and its implication for interlimb transfer

In motor adaptation studies, two types of behaviours result from the formation of motor memory: savings (i.e. faster relearning the second time) and retention (i.e. smaller errors the second time). According to the literature, savings are associated with a memory that is sensitive to explicit knowledge and reward-based learning such as encountered in reinforcement learning (Haith et al., 2015; McDougle et al., 2015; Orban de Xivry and Lefèvre, 2015). A sudden introduction of a perturbation, leading to large errors, is thus more likely to induce savings (Stockinger et al., 2014; Orban de Xivry and Lefèvre, 2015), probably because it enhances awareness of the environment that is linked to the declarative memory (Malfait and Ostry, 2004; Keisler and Shadmehr, 2010). This form of memory is subject to consolidation, namely it can resist to interference and become permanent (Krakauer et al., 2005). In contrast, retention engages an implicit form of memory that is driven by sensory prediction errors and generally does not lead to consolidation of motor memory (Huberdeau et al., 2015). It is commonly assumed that savings stem from the fast process, and retention from the slow process (Joiner and Smith, 2008; Keisler and Shadmehr, 2010; McDougle et al., 2015). It was also shown that these two processes engage different neural networks (Kim et al., 2015). Thereby, retention and savings are considered as two distinct processes.

According to this body of work, we could conclude that interlimb transfer relies more on higher-order strategies and less on lower-level sensorimotor policies as initially suggested by Malfait and Ostry (2004). Interestingly, in our experiment cognitive strategies may have precluded the observation of after-effects and interlimb transfer since subjects were verbally informed that the rotation was stopped: subjects thus could have switched back to a “normal” control mode. Yet after-effects were observed both on the dominant and non-dominant arms, and they most likely reflect unintentional, implicit adaptive processes. This is in line with Mazzoni and Krakauer (2006) statement that sensorimotor tasks are bound to sensorimotor strategies that are implicit. Moreover, during
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our first experiment, the debriefing questionnaire we used at the end of the experiment informed us that the participants did not systematically felt the perturbation, and almost all of them reported going straight to the target when tested for transfer in the post-adaptation phase. Although interlimb transfer is characterized by a high contribution of the fast process, and thus may share resources with some cognitive mechanisms (e.g. attention, strategies elaboration, planification etc.), we cannot conclude without further evidence that interlimb transfer is solely a cognitive process in the sense that it implies awareness of the environment and the motor commands. Keisler and Shadmehr (2010) tested the role of the declarative memory in the formation of motor memory by adding cognitive and non-cognitive tasks between training and recall. They found that motor memory can be disrupted only by tasks that engage declarative memory; therefore they concluded that the motor memory shares critical resources with the declarative memory system. Similarly, we could introduce different cognitive tasks involving memory, attention or executive functions between training and testing for transfer to investigate whether as suggested by our findings, cognition contributes to interlimb transfer. Another possibility would be to try interfering with the fast process during training, for instance by using a dual-task paradigm (Redding and Wallace, 1985; Ingram et al., 2000).

Another interesting idea is that the fast process is induced by large and unexpected errors. This statement is consistent with the observation of our first experiment whereby high peak velocities that lead to big errors correspond to large interlimb transfer. Orban de Xivry and Levèfre (2015) stated that large errors early in the adaptation phase are critical for the formation of model-free motor memory (i.e. reward-based learning). Moreover in skill learning studies, challenging conditions during practice facilitate memory formation as this might lead to deeper cognitive processing and therefore more refined motor memory representations (Kantak and Weinstein, 2012). The implication of large errors in interlimb transfer has been first identified by Malfait and Ostry (2004) who observed that an abrupt, but not a gradual, introduction of a perturbation resulted in significant interlimb transfer. However, several studies conflict with this study (Taylor et al., 2011; Wang et al., 2011; Joiner et al., 2013) and it would be interesting to find out why large errors may have an impact on interlimb transfer: does it enhance contribution of cognitive awareness? One possibility uncovered by our first study is that larger errors imply more exploration which, as discussed when addressing the influence of variability, seems to facilitate the updating of the relationship between the motor commands and its consequences on the environment and the body.

Interestingly, variable practice seems more beneficial to retention, consolidation and intralimb transfer than constant practice in motor skill learning (Shea and Morgan, 1979; Kantak et al., 2010, 2011; Ranganathan and Newell, 2010). Although interlimb transfer seems distinct to the formation of a motor memory, variability appears as an important feature that guides conjointly these behaviors. Besides, variable and constant practice account for different pattern of neural activation. Kantak and
colleagues (2010,2011) found that, for consolidation and intralimb transfer, variable practice promotes reliance on the dorsolateral-prefrontal cortex (DLPC) which is engaged preferentially in cognitively-challenging tasks, whereas constant practice promotes reliance on the primary motor cortex (M1). This observation is an additional argument to the hypothesis that interlimb transfer may result from cognitively-related functions rather than implicit and automatic motor policies.

2. The underlying processes of adaptation responsible for transfer and motor memory

Previous studies showed that the neural substrates for retention of motor memory and intralimb transfer partially overlap (Seidler and Noll, 2008; Kantak et al., 2010, 2011; Seidler, 2010). In our last experiment, we found that interlimb transfer and motor retention were behaviourally connected. Despite these two behaviours share similar neural substrates, the underlying processes that we identified seem to conflict, since we observed that motor retention that is typically associated with the slow process, was better in subjects producing significant interlimb transfer, behaviour that we identified as resulting predominantly from the fast process. So what are the different possibilities that may explain this surprising difference?

First, perhaps savings (that is characterized by faster re-learning) was not totally absent from re-adaptation. Indeed, the task was very easy to learn, thus the participants may have benefit from a ceiling effect that preventing us from detecting any difference of performance between day 1 and day 2. One way to solve this issue would be to run the same experiment with visuomotor rotations or a robotic device to slow down adaptation and thus increase the possibility to identify whether or not savings of adaptation can occur. If savings that is perceived as a fast process is present during re-adaptation then it would be easier to understand why the performances in interlimb transfer and in motor memory are related.

There may be an alternative hypothesis. The dichotomy between savings and retention is theoretical and often relies on the dual-rate model of adaptation. This model is quite successful in explaining several phenomena but it is still an approximation of sensorimotor adaptation and it remains elusive on certain mechanisms. Notably, some findings are in conflict with the actual view of savings and retention. For instance, the presence of reward during learning, that is typically associated with savings, also promotes retention better than equivalent punishment (Galea et al., 2015). Similarly, another study showed that binary feedback of task success after learning enhanced better retention than sensory errors (Shmuelof et al., 2012). Therefore, it is possible that both processes may be partitioned into distinct sub-processes. Some studies revealed that the slow process may be decomposed into two (Brennan and Smith, 2015b; McDougle et al., 2015) or multiple components (Lee and Schweighofer, 2009), and the fast process into two components (Kim et al.,
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2015). One possibility is that in our last study, the fast process that seemingly characterized the performance in interlimb transfer may share common processes with the retention of motor memory. A more precise knowledge of the sub-processes of adaptation may give better insights on the behavioural consequences of the different processes.

III. Prospective studies

Our studies allowed us to identify multiple features that seem to play a role in interlimb transfer. However we were only able to extrapolate their roles in light of the actual literature and did not establish a causal relationship between these features and interlimb transfer. It would be interesting to manipulate these features to understand further why it impacts interlimb transfer. the ideas that we addressed earlier.

To investigate the effect of variability and velocity on interlimb transfer, it would be appropriate to manipulate these kinematic features in different experimental conditions by varying their magnitude. It would also be interesting to further test the idea that movement velocity is an important feature determining interlimb transfer because it leads to large errors. One possibility would be to test different force-field perturbations with a robotic device for instance: by testing perturbations with varying sensibilities to the arm velocity, we could distinguish the effect of movement velocity and error size on interlimb transfer. One other possibility that we are currently testing is to assess interlimb transfer in an adaptation task using a perturbation which is non-velocity dependent, i.e. with prisms which produce similar initial errors.

Something that we did not take into account in our studies is the stiffness of subjects’ arm during the task, and the goal of new projects may be to test the influence of stiffness on interlimb transfer by manipulating it and assessing it by means of EMG (Franklin et al., 2003) or mechanical perturbations using a robotic device (Darainy et al., 2004).

One major factor influencing interlimb transfer was variability of motion, and future projects may address this issue by asking participants to follow specific trajectories indicated by via points. We could make different groups: one with random trajectories (e.g. from -50° to +50°), one with similar trajectories but organized in an incremental manner (e.g. from -50° to +50° with a step of -5°), and one control condition in which trajectories would be directed so that it accurately reaches the target. If we assume that variability is beneficial to transfer because it is more challenging cognitively (Kantak et al., 2011) or because it is a reflection of the adaptive properties of the participants we may observe better performance in the random group. Or if what matters is the elaboration of a complex map between the motor errors and the motor commands (Joiner et al., 2013), then the first
two conditions would probably elicit similar performance in transfer but better than in a control group.

To assess further the influence of handedness, one way to proceed is to test individuals with various laterality quotients. One way to investigate the influence of the distinct hemispheres would be to use tDCS or TMS stimulation over the left and right motor cortex hemispheres during adaptation with the dominant arm or transfer with the non-dominant arm as the laterality quotient seems to modulate the hemispheres’ activation (Dassonville et al., 1997). For instance, in the case where participants are right-handers, if inhibition of the dominant left hemisphere during movements with the untrained left arm leads to no transfer or smaller interlimb transfer than a sham condition, it would lend credence to our hypothesis that ipsilateral activations of the dominant left hemisphere contribute to interlimb transfer. Imaging brain activity would be useful to assess whether stronger lateralization allows stronger involvement of the left dominant hemisphere during motor adaptation and interlimb transfer. Another way of investigation would be to assess the level of interhemispheric inhibition before and after adaptation, using TMS (Duque et al., 2007; Perez et al., 2007b). The reason is that the level of ipsilateral activation when using the left arm may be due to lower degree of interhemispheric inhibition from the right to the left hemisphere. Interestingly, Kobayashi et al., (2003) found that among the participants with substantial amount of ipsilateral activation of the motor cortex during nondominant hand movement, interhemispheric inhibition of the left motor cortex to the right motor cortex was very low. In summary, it would be interesting to assess the link between brain activations, interhemispheric inhibition, interlimb transfer and laterality quotient.

Despite the ecological qualities of the rotating platform, it would be convenient to run sensorimotor tasks with a robotic device or visuomotor rotations. First, it would alleviate the ceiling effect that we observed in all our experiments and that prevented us from making some relevant conclusions regarding the level of adaptation. Secondly, it would enable us to build a more flexible protocol with for instance catch-trials and error clamp trials, and also it would enable us to switch easily between different perturbations. Particularly, it would be interesting to use such a set-up to test the conjoint effect of interlimb transfer and motor memory. If it allows us to slow down adaptation, we could compare more easily the adaptation curves of day 1 and day 2, and tell whether or not we observe savings.

At last, study of the role of cognition remains an interesting line of work. To address that, we could test the opposite arm within the force-field so that if transfer actually results from a cognitive process, interlimb transfer would be greater and performance may be similar to that of naive movements. As stated in the previous sections, it would be interesting to interfere with the transfer performance by adding cognitive tasks (e.g. declarative memory tasks, attentional tasks etc.)
between training and test for transfer to identify which cognitive functions presumably play a role in interlimb transfer. Other possibilities would be to use a dual-task paradigm during training or test individuals with cognitive impairments, resulting from stroke or Alzheimer’s disease for example.
Conclusion
Adaptation is an inherent feature of each human being that allows interacting properly with the environment. The abilities to generalize experience to other conditions or limbs and to retain in memory acquired knowledge are some fundamental characteristics stemming from adaptation and learning.

This doctoral thesis aimed at investigating the processes underlying interlimb transfer of sensorimotor adaptation as well as the factors that could influence it. We were able to identify different predictors of interlimb transfer of force-field adaptation such as the variability and the peak velocity of movements during adaptation, as well as the laterality quotient. However, further research is required to better understand the role of each of these features. We also tested the influence of the sensory feedback conditions on interlimb transfer: whether vision was available or not, interlimb transfer was observed. Interestingly, two older individuals deprived of proprioception, were able to adapt and even to transfer such as healthy young individuals. These findings support the idea that sensorimotor integration is a flexible process. Overall, the thesis suggests that in addition to paradigmatic conditions which can influence interlimb transfer, inter-individual differences also greatly influence adaptive processes of motor control. Indeed, adaptation and transfer are influenced by the way individuals move, with different speed and variability, but also by the types of processes underlying adaptation.

Knowledge about interlimb transfer is not only interesting because it provides evidence about the global and local nature of underlying processes of adaptation, but it is also potentially important in applications regarding functional rehabilitation of patients with movement disorders and sports performance (Lee and Carroll, 2012; Issurin, 2013; Calabro and Perez, 2016). In patients with hemiparesis, therapeutic options are limited due to severe control deficiency. But interlimb training or also called cross-limb education could be an alternative since it may improve the affected limb by training the opposite unaffected limb (Hendy et al., 2012; Lee and Carroll, 2012). With this method, even restoring a limited degree of mobility could help before switching to more conventional rehabilitation therapies. Stinear and Byblow (2004) showed that patients who suffered from stroke can improve their paretic limb by practicing passive flexion-extension of the paretic wrist driven by the active movements of the unaffected wrist. Interestingly, they found that cortical excitability was modified after this passive-active training. The knowledge about the neural substrates and the interhemispheric communications underpinning interlimb transfer may allow developing alternative therapies. For example, some studies use non-invasive brain stimulation (e.g., TMS or tDCS) to enhance motor learning (Panouillères et al., 2015) and its consolidation (Tecchio et al., 2010) beyond that achieved through practice alone. Similar methods can be used to enhance the paretic limb of people suffering from control impairments (Teo et al., 2015).
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