



## Reduced Plantar Sole Sensitivity Facilitates Early Adaptation to a Visual Rotation Pointing Task when Standing Upright

by

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*Humans are capable of pointing to a target with accuracy. However, when vision is distorted through a visual rotation or mirror-reversed vision, the performance is initially degraded and thereafter improves with practice. There are suggestions this gradual improvement results from a sensorimotor recalibration involving initial gating of the somatosensory information from the pointing hand. In the present experiment, we examined if this process interfered with balance control by asking participants to point to targets with a visual rotation from a standing posture. This duality in processing sensory information (i.e., gating sensory signals from the hand while processing those arising from the control of balance) could generate initial interference leading to a degraded pointing performance. We hypothesized that if this is the case, the attenuation of plantar sole somatosensory information through cooling could reduce the sensorimotor interference, and facilitate the early adaptation (i.e. improvement in the pointing task). Results supported this hypothesis. These observations suggest that processing sensory information for balance control interferes with the sensorimotor recalibration process imposed by a pointing task when vision is rotated.*

**Key words:** visuomotor adaptation, sensorimotor conflict, proprioception, sensorimotor recalibration.

### Introduction

With normal vision, humans are capable of pointing to a target with accuracy. When vision is distorted through a visual rotation, the performance is initially degraded, but gradually improves with practice (Abeele and Bock, 2001; Krakauer et al., 2000; Piepereit et al., 2006; Prablanc et al., 1975). Similar observations are made when vision is distorted using a mirror-reversed vision paradigm (Bernier et al., 2009; Gagné Lemieux et al., 2014; Lajoie et al., 1992). One hypothesis to explain the initially degraded performance is that when visual feedback is distorted, sensory information from the arm and from the visual system is in conflict. This necessitates strategic and adaptive processes to build a new sensorimotor map (for a review, see

Cressman and Henriques, 2011). There are suggestions that such a conflict can be resolved by an inhibition of proprioceptive information of the arm. It originates from studies showing that subjects without proprioception generally do not show this visuomotor conflict (e.g., Lajoie et al., 1992). In healthy individuals, Balslev et al. (2004) showed that the conflict could be resolved by reducing the inflow of information to the somatosensory areas. In their study, they induced an experimental deafferentation using repetitive transcranial magnetic stimulation over the anterior parietal cortex. The mirror-reversed tracing skills of healthy participants improved immediately. More recently, Bernier et al. (2009) provided additional support to this hypothesis.

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They showed that participants who performed the best upon their initial exposure to a mirror-reversed tracing task were those whose cortical somatosensory evoked potentials were the most reduced (as compared to tracing with direct vision). Altogether, these studies suggest there is a strong possibility that initial gating of the sensory inflow from the arm contributes to resolving the visuomotor conflict.

In the preceding studies, the participants were seated when they performed the hand/arm task and adapted to the distorted visual information. For several activities of daily living, pointing or reaching for an object necessitates cooperation between the movement of the arm and the balance control commands (Massion, 1992). For instance, when a person is standing, anticipatory postural adjustments are observed about 100 ms before the onset of the focal action. This has been observed when lifting an arm, pointing to a target, pushing against an object, lifting, catching, etc. (Aruin and Latash, 1995; Berg et al., 2016; Bouisset and Zattara, 1981; Cordo and Nashner, 1982). Clearly, standing adds a level of complexity and control to the production of an upper-limb movement. Visuomotor adaptation in a standing posture poses an interesting sensory processing problem; while gating of the sensory information from the arm is expected, there is a concurrent inflow of somatosensory information from the lower limbs contributing to balance control that needs to be processed. This duality in processing sensory information could 'generate an initial interference leading to a degraded performance'. If this is the case, reducing the sensory information available from the lower limbs could facilitate the initial adaptive process to a visually distorted context.

This study was designed to test this hypothesis. The plantar sole provides a 'dynamometric map' for balance control (Kavounoudias et al., 1998, 1999, 2001). In this study, we attenuated the sensory information from the plantar sole using a cooling protocol (Billot et al., 2013; Perry et al., 2000). As the attenuation of plantar sole somatosensory information could reduce sensorimotor interference, we hypothesized that reducing plantar sole sensitivity through cooling would facilitate the early adaptation to a visual rotation pointing task.

## **Material and Methods**

### *Participants*

Prior to commencing, participants were briefed about the experiment and provided written informed consent. All forms and procedures were approved by the University Human Research Ethics Committee. Participants were randomly assigned to one of two groups ( $n = 10$  for each group). A first group, hereafter called the UPRIGHT group (age:  $21.9 \pm 0.5$  years, body height:  $174.9 \pm 3.4$  cm, body mass:  $70.4 \pm 4.4$  kg) learned the task while standing with their feet together. The second group, UPRIGHT-COLD (age:  $22.3 \pm 0.3$  years, body height:  $178.5 \pm 2.3$  cm, body mass:  $80.8 \pm 4.2$  kg), went through a specific cooling protocol to attenuate the sensory information available from the plantar sole before performing the visuomotor task also while standing with their feet together. A general health-screening questionnaire was completed prior to testing. All participants were free from any medical conditions that may have compromised their participation, and none was medicated. Vision was normal (20/20).

### *Experimental Procedure*

Participants stood facing a computer monitor and controlled, by moving their right index, a small 1-cm width cursor represented by a <<+>> sign. They moved the arm across the transverse plane and their hand initial position was at the level of the sternum. The cursor represented the real-time position of the tip of the index finger on the screen, and was recorded with an electromagnetic sensor at 100 Hz (Ascension Technology Corporation, Flock of Birds, Burlington, Vermont, USA). For the normal vision condition, moving the finger away from the body, thus along the sagittal plane, resulted in a displacement of the cursor from the bottom to the top of the screen and moving the index from the left to the right of the starting position resulted in an identical displacement of the cursor on the screen (i.e., left to right movement). The visual gain was 1, hence a displacement of the index of 1 cm corresponded to a displacement of 1 cm on the screen. The refresh rate of the position was 60 Hz and there was no feedback about the trajectory. For all conditions, a large cardboard positioned at shoulder height in the transverse plane prevented direct vision of the hand and arm movements. For each participant, data were collected in a single

experimental session lasting about one hour.

At the beginning of each trial, the participant positioned their right index finger at an initial constant position on the sternum and fixated the center of the monitor located 1 m from their head with the center of the monitor at eye-level. Once the participant adopted the starting posture, a visual target (open circle with a radius of 1 cm) appeared at one of five possible orientations, 15 cm from the center of the external referential ( $0^\circ$  corresponding to the forward direction along the sagittal plane, and  $-10^\circ$ ,  $-20^\circ$ ,  $-30^\circ$  and  $-40^\circ$  counter clockwise). Participants were asked to point quickly and precisely to the target as soon as it was presented. They were told, however, that this was not a reaction time task (i.e., they could start their reaching movement within 1-s following the display of the target). The five target orientations were presented randomly in a block of 5 trials with each trial lasting 5 s. When the target was reached in less than 5 s, the participant held the final position until the target disappeared from the screen, and then returned slowly to the initial position.

Before the experimental trials began, the participants received 10 familiarization trials with normal vision (two trials at each target). Then, a short pause ( $\sim 5$  minutes) was given followed by the first two blocks with normal vision (i.e., baseline condition; 10 trials, 2 at each target). Then, participants performed 100 trials (20 blocks) with a  $60^\circ$  visual rotation. For this condition (adaptation), when the target was located at  $0^\circ$ , pointing at  $+60^\circ$  (i.e., clockwise) yielded a forward cursor displacement directly to the target. Hence, with the visual rotation, pointing directly to the target produced a response oriented  $-60^\circ$  (i.e., counter clockwise). An additional 10 trials without rotation (post adaptation) were collected at the end. Between blocks, a rest period of approximately 10 s was given.

#### **Cooling Protocol**

The cooling protocol was similar to that adopted in two previous studies (Billot et al., 2013, 2015). In those studies, the skin temperature decreased from about  $27$  to  $14^\circ\text{C}$ , and significantly decreased sensitivity for the first and the fifth metatarsus and the heel (monofilament test) and a significant increase in distance for a two-point discrimination test were observed. In the present study, we did not record this information to limit

rewarming of the foot plantar sole before starting the pointing task with a visual rotation. After the movements with normal vision, participants from the UPRIGHT-COLD group immersed their feet in water maintained at  $0\text{-}2^\circ\text{C}$  for 12 min. Water depth was adjusted to obtain a total immersion of toes without immersing the ankle joint. After the 12-min cooling period (in a seated position), the participants adopted the starting posture as quickly as possible to perform the task with the  $60^\circ$  visual rotation. After the first 50 movements (10 pointing blocks), their feet were cooled for an additional period of 3 minutes before completing the last 50 movements. For the UPRIGHT group, two delays similar in duration (12 min and 3 min) to those of the cooling protocol were given.

#### **Data Analysis**

Position data were digitally filtered offline (Butterworth seventh order, 10 Hz low-pass cut-off frequency with dual-pass to remove the phase shift). Because of normal postural oscillations when standing, the initial position was not constant at the beginning of each trial. Thus, the initial position was determined for each trial from the onset of the movement which was defined as the first sample with a velocity greater than  $3\text{ cm}\cdot\text{s}^{-1}$ . This threshold value was selected because finger movements included normal postural oscillations. When this sample occurred less than 100 ms after the target presentation, the trial was removed from the analysis as it indicated an unstable initial posture or a response that anticipated the target presentation. Overall, only 139 such trials were observed (approximately 5% of the trials). The endpoint of the movement was defined from three criteria: (i) the velocity had to be smaller than  $3\text{ cm}\cdot\text{s}^{-1}$ , (ii) the cursor had to be within 1 cm of the center of the target, and (iii) these two conditions had to be fulfilled for at least 250 ms. When these criteria were not achieved within 5 s from the onset of the movement, the last sample of the trial was considered as the endpoint of the movement. Figure 1 illustrates representative trajectories and velocity-time curves (right lower panel) for the same subject. The left upper panel illustrates a movement to the  $-30^\circ$  target with normal vision. The right upper panel shows a movement to the  $-30^\circ$  target with a  $60^\circ$  visual rotation within the first block of trials and the left lower panel depicts a movement to the same target within the last adaptation block.

On each panel, the solid line illustrates the trajectory seen by the participant (from the displacement of the cursor on the screen only as the cursor did not leave a trace of the displacement). To reach the target, however, the participants had to move 60° clockwise; the trajectory produced is illustrated by the dotted line. Movement time (temporal difference between the end and the onset of the movement) and the total distance covered to reach the target were computed. Movement distance was expressed as a percentage of the straight line between the position of the index at the onset of the movement and the target. Hence, movement distance consists of the path length in excess of the shortest possible distance. For each trial, the initial orientation of the movement was calculated from the vector linking the position of the finger at the movement onset and that recorded 150 ms later. The angular error of pointing was calculated from the difference between the initial orientation of the movement and the initial angle (at movement onset) needed to reach the target. Therefore, it represents the error of the planned response (i.e., feedforward control) before any movement corrections took place. Finally, an accuracy measure was calculated for each block (percentage of movement within 1-cm of the target). To summarize, movement time (second), movement distance (% in excess of the shortest distance), angular error (°) and accuracy (% of trials on target) were computed to characterize the pointing movements.

### **Statistical analysis**

All statistical tests were performed with Statistica (version 12.0, StatSoft, Tulsa, Oklahoma, USA). Mean and standard error (SE) are presented throughout the manuscript. Normality of the data was verified using the Kolmogorov–Smirnov test and equality of variances was verified by the Levene test.

## **Results**

A first consideration was to determine that neither group differed in their performance when they were pointing with normal vision (baseline condition). To achieve this goal, each dependent variable for the initial 2 blocks with normal vision was submitted to a 2 (Group) × 2 (Block) analysis of variance (ANOVA) with repeated measures. For all variables, the

ANOVAs (Table 1) showed that the main effects of Group and Block and their interactions were all not significant ( $p > 0.05$ , for all effects). This suggests that the two groups were not different before they were submitted to the condition with a 60 deg. visual rotation (adaptation). For the variable accuracy, all participants were able to point accurately at the target for all trials.

### **Adaptation to a new visual mapping**

Figure 2 shows movement time for both groups for all blocks of trials (Baseline, Adaptation, Post Adaptation). As expected, pointing to a target with a 60° visual rotation initially disturbed the pointing performance of both groups; movement time of curved reaching trajectories lasted longer. The UPRIGHT-COLD group, however, showed shorter movement times than the UPRIGHT group during the early adaptation period (first two blocks). This difference vanished rapidly and no difference was observed between both groups at the end of the adaptation period. Also, there was no difference between groups during the Post adaptation period. It is worth noting that shorter movement times did not lead to less accurate movements (see below).

The main hypothesis of this study was that cooling the feet would contribute to facilitating visuomotor recalibration because attenuation of somatosensory information from the lower limbs could reduce sensorimotor interference. To test this hypothesis, we submitted each dependent variable to a Group (2; UPRIGHT, UPRIGHT-COLD) × Period (3, Early adaptation [i.e., first two blocks], Late adaptation [i.e., last two blocks], Post adaptation) × Block (2) ANOVA with repeated measures on the last two factors. Figure 3a presents data for movement time (s) for the Early, Late, and Post adaptation blocks. For comparison purposes, movement times for the baseline condition are also presented. The ANOVA for movement time showed significant interactions of Period × Group and Period × Block (Table 2). The decomposition of the interaction of Period × Group (a-priori contrast) confirmed that the UPRIGHT-COLD group showed shorter movement times than the UPRIGHT group during the Early adaptation period and that this difference vanished in the Late adaptation period ( $F(1,18) = 5.31, p = 0.031$ ). A similar pattern of results was noted for the distance error and

accuracy (Table 2; for the decomposition of the interaction of Period x Group,  $F(1,18) = 9.99$ ,  $p = 0.005$  for the distance error, and  $F(1,18) = 12.6$ ,  $p = 0.002$  for accuracy).

The angular error (Figure 4) is thought to represent the initial motor command (i.e., feedforward control) prior to any corrections based on visual or proprioceptive feedback. Interestingly, the ANOVA for the angular error showed that the two groups were not different. The main effect of Group ( $p = 0.12$ ) and the interactions of Period x Group ( $p = 0.65$ ) and

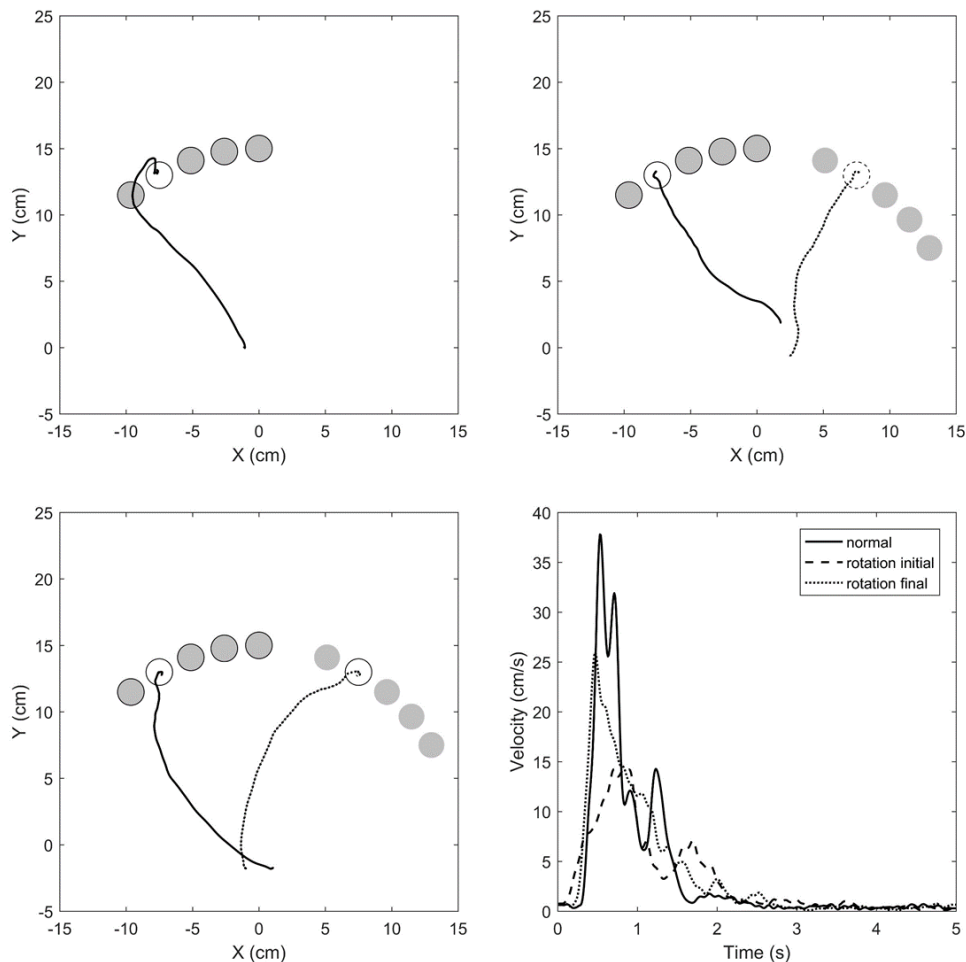
Period x Block x Group ( $p = 0.87$ ) were not significant. Both groups showed large positive angular errors during the Early adaptation period (Figure 4). The angular error decreased slowly, but was still more than  $20^\circ$  at the end of the adaptation period. The ANOVA showed a significant main effect of Period ( $F(2,36) = 167.78$ ,  $p = 0.00$ ,  $\eta^2 = 0.90$ ) and a significant interaction of Period x Block ( $F(2,36) = 15.47$ ,  $p = 0.00$ ,  $\eta^2 = 0.46$ ). This suggests that participants in both groups had not fully recalibrated to the  $60^\circ$  visual rotation.

**Table 1**  
*Summary of results for the Group x Block analysis of variance for each dependent variable for the baseline condition (normal vision).*

Variable			Group			Group x Block		
	Upright M (SE)	Upright-cold M (SE)	F (1,18)	p	$\eta^2$	F (1,18)	p	$\eta^2$
Movement Time (s)	1.482(.065)	1.225(.065)	0.06	0.8	0.003	0.26	0.88	0.001
Distance (%)	19.7(2.7)	12.8(2.7)	3.34	0.08	0.156	2.16	0.15	0.107
Angular error (deg)	-4.7(3.1)	-5.8(3.1)	0.06	0.79	0	0.44	0.51	0.024
Accuracy (%)	100	100						

**Table 2**  
*Summary of results for the Group x Adaptation (Early adaptation, Late Adaptation, Post adaptation) x Block analysis of variance for each dependent variable*

Variable	Group			Period x Group			Period x Block		
	F (1,18)	p	$\eta^2$	F (3,54)	p	$\eta^2$	F (3,54)	p	$\eta^2$
Movement Time (s)	2.65	0.12	0.12	4.54	0.006	0.20	14.45	0.00	0.44
Distance (%)	7.18	0.01	0.28	8.90	0.000	0.33	22.28	0.00	0.55
Angular error (deg)	1.80	0.19	0.09	0.56	0.63	0.03	10.53	0.00	0.36
Accuracy (%)	5.84	0.03	0.24	10.42	0.00	0.36	11.33	0.00	0.38



**Figure 1**

*Representative trajectory and velocity-time curves from one participant.*

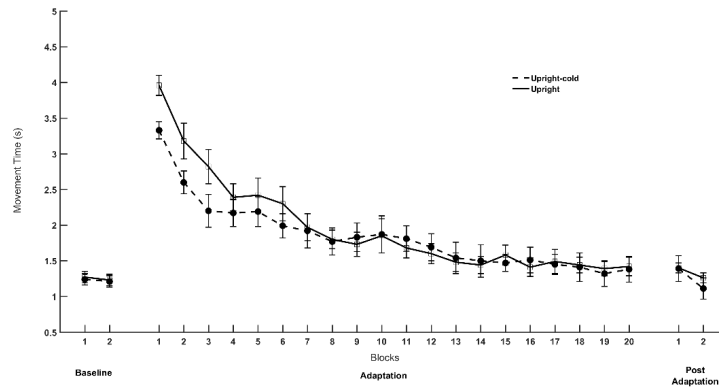
*A) A movement to the  $-30^\circ$  target with normal vision is presented.*

*The shaded circles are presented for illustrative purposes only as for each pointing only the target (open circle) and a "+" cursor indicating the real-time position of the index finger (without any feedback about the trajectory) were seen by the participant.*

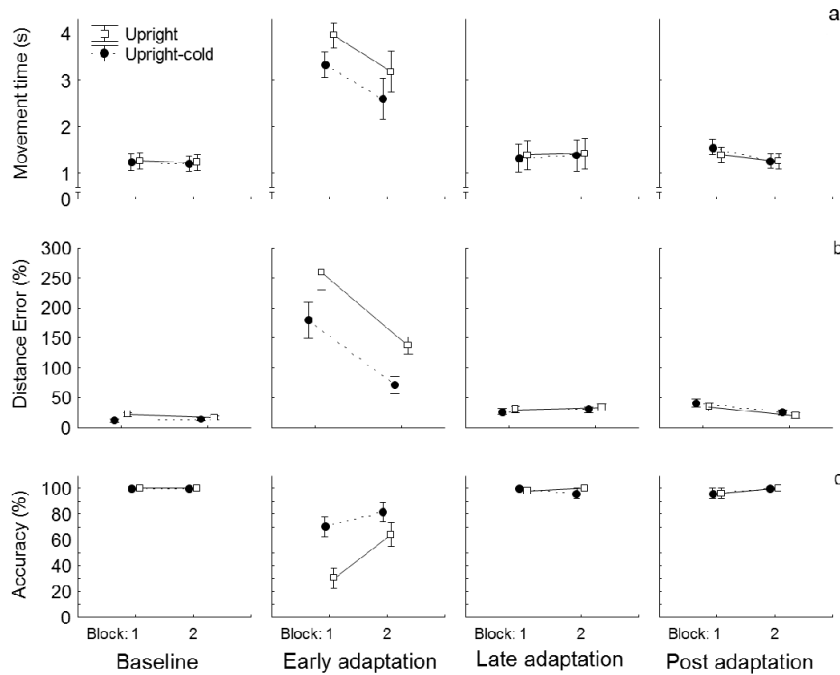
*B) A movement to the  $-30^\circ$  target with a  $60^\circ$  visual rotation within the first block of trials is illustrated. The target seen by the participant is illustrated by the open circle. The solid curve illustrates the trajectory seen by the participant (from the displacement of the cursor on the screen). To reach the target, however, the participants had to move  $60^\circ$  clockwise; the trajectory produced by the participant is illustrated by the dotted line. The difference observed in the starting position arises from an initial position distant from the center of the external referential.*

*C) A movement to the  $-30^\circ$  target with a  $60^\circ$  visual rotation within the last block of trials is illustrated. D) Velocity-time curves for the three trials are presented.*

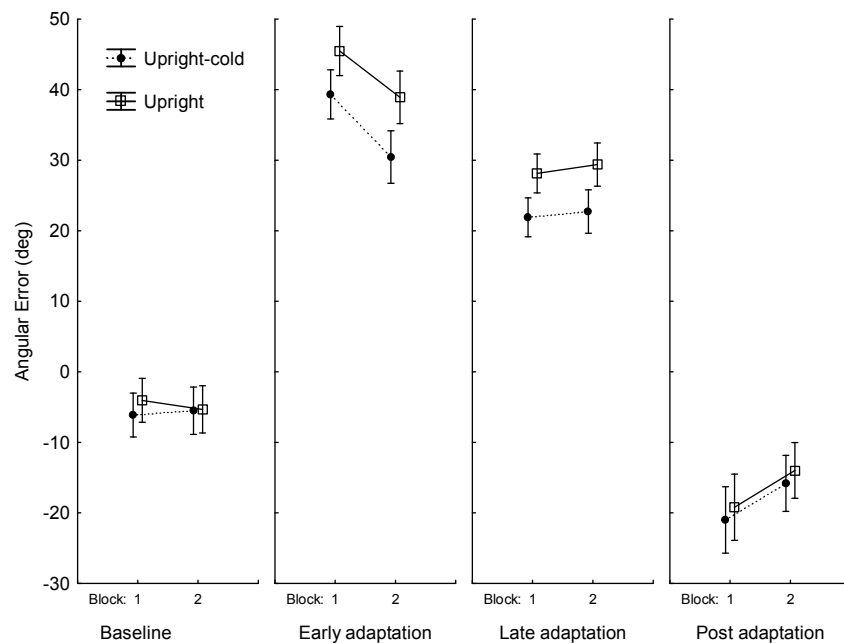
*All trials are synchronized on the movement onset.*



**Figure 2**  
*Movement time (mean  $\pm$  SE; ms) for the UPRIGHT and UPRIGHT-COLD groups for the baseline, adaptation and post adaptation conditions. All five targets were presented within each block.*



**Figure 3**  
*Movement time (mean  $\pm$  SE; ms), distance error (mean  $\pm$  SE; % in excess of the shortest distance), and accuracy (mean  $\pm$  SE; %) for the UPRIGHT and UPRIGHT-COLD groups for the baseline, early adaptation (first two blocks), late adaptation (last two blocks), and post adaptation conditions. All five targets were presented within each block.*



**Figure 4**

*Angular error (mean  $\pm$  SE; deg) for the UPRIGHT and UPRIGHT-COLD groups for the baseline, early adaptation (first two blocks), late adaptation (last two blocks), and post adaptation conditions. All five targets were presented within each block*

## Discussion

The goal of the present study was to test if, when standing, attenuating plantar sole somatosensory input through a cooling protocol would facilitate the sensorimotor recalibration process when pointing to a visually rotated target. As expected, we observed that participants submitted to the cooling protocol showed shorter movement times, shorter movement paths and greater accuracy than those in the control group. These differences, however, were short lasting and vanished after the first few blocks of trials. Nevertheless, these observations suggest that processing sensory information for controlling body sway interferes with the sensorimotor recalibration process imposed by a pointing task when vision is rotated.

Taking into account the important role of

the plantar sole for balance control (Kavounoudias et al., 1998), this could be considered as a counterintuitive hypothesis (and result) as one could suggest that decreased sensory information for balance control would increase body sway and hence contribute to a deterioration of the performance of any associated upper arm pointing movements. However, we showed in previous studies that although cooling the plantar sole of the feet yielded a significant reduction in plantar sensation, perturbations to balance control were limited because of recalibration of the contribution of the various sources of sensory information available and compensatory strategies (e.g., Billot et al., 2015). Hence, in the present study we postulated that cooling the plantar sole of the feet would facilitate the sensorimotor recalibration of the hand by reducing possible interference resulting from the



differential processing of sensory information from the lower limbs (necessary to control balance) and the hand (initial gating to facilitate the recalibration).

Partial support for this hypothesis also comes from a learning study with older participants (Gagné Lemieux et al., 2015). In this study, participants were exposed to a mirror-reversed vision tracing task when seated or when standing. After three practice sessions (over three different days), all participants were compared when standing. Hence, participants that initially practiced the tracing task seated transferred to a standing condition. According to a transfer-appropriate practice hypothesis (Lee, 1988), the group that practiced standing was expected to perform better because they previously experienced this condition and presumably learned to integrate balance control commands with the tracing movements. This was not the case. Participants initially exposed to the standing condition were much slower to trace the template. This slowness persisted even when these participants transferred to a seated condition. This observation did not result from baseline general slowness, but from genuine interference between the sensorimotor processes involved in balance control and for the mechanisms resolving the visuomotor conflict arising from the mirror-reversed vision. Participants that were first exposed to the visuomotor conflict in a seated

posture could resolve the conflict while disregarding sensorimotor information related to balance control. As observed by Bernier et al. (2009) the initial exposure to a visuomotor conflict involves gating of the sensory inflow to the anterior parietal cortex. Movement-related sensory gating is known to specifically target the moving limb (Rushton et al., 1981; Tapia et al., 1987). There is a possibility that standing, because it requires processing of sensorimotor information for balance control, interferes with this gating process of the sensory information from the hand resulting in initial interference. Additional studies are needed to explore more specifically the specific interactions between mechanisms responsible for balance control and those necessary to facilitate adaptation to a new visuomotor context.

In conclusion, this experiment shows that reducing plantar sole sensitivity benefited early visuomotor recalibration. It suggests that processing of sensorimotor information for balance control interferes with the initial visuomotor recalibration processes required when first exposed to a visually rotated environment. This suggests the potential for interference between the sensorimotor mechanisms for balance control and accurate reaching movements.

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