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Studying the timescale of perceptual-motor (re)calibration following a change in visual display gain

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Abstract

Experiencing a non-1:1 mapping between perception and action in everyday life is not common. It could be considered as a problem for our perceptual-motor system because of the need to adapt our goal-directed movement to different gains between movement and task spaces. In the Human Computer Interface domain, the main example of such a situation consists in switching from one operating system to another which requires to adapt our movement to different Control Display gains.

The aim of the study was to characterize the perceptual-motor calibration process following a sudden change in control display gain.

Sixteen participants manipulated a mouse computer to move a cursor on the screen. The discrete aiming task consisted on reaching the target from a starting target position as fast and as accurately as possible. Our methodology consisted in suddenly manipulating the gain between both spaces following a three-step adaptation methodology (baseline condition followed by a perturbation and return to baseline condition).

Results demonstrated that not only participants produce adaptive behavior following several types of perturbations, but they were also able to do it at a very short timescale.

As the calibration process described in the present study may play a significant role in the acquisition of accurate perceptual-motor skills involving the use of devices that augment human fine motor capabilities (e.g., telesurgery, mouse and joystick), we conclude that this study could have important implications in the domain of Human-Computer Interaction (HCI) as well as in the domain Human Equipment Interaction.

Keywords : perceptual-motor task, Control display gain, speed-accuracy trade-off, calibration

1. Introduction

We safely navigate in our environment and perform daily tasks accurately thanks to our ability to calibrate our perceptual-motor system to different mappings. The notion of mapping defines the relationship that could exist between our actions and their perceptual consequences.

When writing on paper, for example, humans usually operate with a 1:1 mapping between perception and action. However, one can consider two main examples of situations in which the perception-action coupling is not 1:1, when using an interface for example.

Firstly, when writing on a paper with magnifying glasses, consequences of our writing are perceptually amplified. The mapping is no longer 1:1 but depends on the magnitude of glass amplification, and could be either 1:2, or 1:3, in the case the magnifying glass amplifies 2 or 3 times the environment respectively.

Secondly, in microsurgery, most of the time surgeons have to deal with a non-1:1 mapping. In this case, severe limitations on their movement space can be partly overcome thanks to a laparoscopic camera allowing for the projection of an amplified image on a video monitor. Now, the use of this technology induces a separation between the movement space (or motor space) and the task space and, as a consequence, a need for calibrating the relationship between both spaces. This perceptual-motor calibration allows surgeons to adapt their movement to the non-1:1 mapping between both spaces (Ellis et al., 2004; Ferrel, Leifflén, Orliaguet, & Coello, 2000, Trejo et al., 2007). Surgeons continually adapt their behavior to the ever-changing dynamics of the systems that they control as they use different tools or different display scales. Such adaptation can be thought as a *perceptual-motor calibration* (Rieser et al., 1995; Bingham and Pagano, 1998; Bhalla and Proffitt, 1999; Durgin and Pelah, 1999; Withagen and Michaels, 2004, 2005; Jacobs and Michaels, 2006).

Perceptual-motor calibration has been defined as a mapping between perception and action that is useful in distinguishing between feasible and impossible action opportunities. Thus, perceptual-motor calibration is necessary to establish a relationship between the physical units in which the relevant information is detected and the physical units in which the action is executed (Fajen, 2005).

Following these considerations, any change in the mapping between perception and action requires a need for calibration. This is the case, for example, when a person drives a car that is not their own, an equivalent action on the brake pedal could have different consequences due to differing action capabilities. It is precisely this type of situation that Fajen (2005, 2007, 2008) examined in a series of experiments conducted in a virtual reality environment in which the braking capabilities of the virtual car were manipulated and the participants were asked to stop in front of an obstacle. As a result, in order to complete the collision avoidance task, participants were required to adjust their perception-action loop as quickly as possible in response to changes in braking capabilities. These studies provided convincing results about the ability of the participants to adapt their behavior, even when they had to calibrate their perceptual-motor system to new action capabilities.

The question of measuring the timescale of the perceptual-motor system (re)calibration, even when disturbances occur, is thus of paramount importance to maintain an appropriate behavior. Most of the studies addressing the question of calibration report a really fast timescale. As an example, when the bat weight is changed suddenly in a baseball hitting task, Scott and Gray (2010) observed that calibration to new action capabilities took 5 trials for a lighter bat and 10 trials for a heavier bat. Interestingly, in a similar study, Nakamoto et al. (2012) identified an even shorter timescale as only 3 trials were required to recalibrate the system to a new bat weight.

In accordance with these results, Fajen et al. (2007), using the driving task described in the previous section, showed that participants are capable of rapidly recalibrating to changes in their actions capabilities even when feedback about the outcome of the task is lacking.

The ambition of the current study was to apply the concept of perceptual-motor calibration to the domain of Human-Computer Interface (HCI), with a special emphasis on the identification of the timescale needed to calibrate to a new control display gain using an aiming task which mimics the action of selecting an icon on a desktop computer.

Said differently, we forced participants to recalibrate aiming movements through the manipulation of the control display gain. This is the challenge we potentially face daily when we move our computer mouse to select an icon on the screen and then perform

the same task on a different computer. This concrete situation exemplifies the need for recalibrating the perceptual-motor system to meet the task constraints.

In the domain of Human-Computer Interaction (HCI), *indirect aiming* is indeed highly representative of calibration to a specific mapping. Any computer device involves two different spaces. The *motor space* corresponds to the locus of movement (i.e., mouse manipulation or movement on trackpad). The *task space* corresponds to the space where the consequences of a given movement can be perceived (i.e., computer screen). Consequently, when we use electronic interface technologies, movements are carried out by devices such as a mouse, a stylus or a touchpad and are connected to visual aspects of an ongoing movement on a computer screen.

Today, the massive and increasing use of electronic interfaces orient a large amount of research on understanding how we interact with enhanced visual displays (Casiez et al., 2008 ; Ellis et al., 2004 ; Kovacs et al., 2008). Given the fact that *motor spaces* are highly constrained spatially in comparison with *task spaces*, the common goal pursued is to define the best mapping which allows observing the best performance in terms of movement time and error rate while using these interfaces. In HCI, the term *gain* (and more precisely Control Display gain, i.e., CD gain) is more commonly used rather than the term *mapping* to express the relationship between the input device and the display pointer. The gain could be a function of device velocity (Kovacs et al., 2008; Casiez et al., 2008) or device position (Fernandez et al., 2008).

In this framework, constant gain is the simplest method for manipulating CD gain *via* a constant multiplier regardless of device movement characteristics (Casiez et al., 2008). More recently, gain which increased linearly with motor velocity has also been investigated (Scotto et al., 2020).

All studies comparing different CD gains assume that a CD gain greater than one would allow a better aiming performance in comparison to 1:1 mapping. In an aiming task, where the movement time completion has to be minimized, a frequently and almost classic U-shaped relation between gain and time of movement has been mainly reported (Arnaut & Greenstein, 1986 ; Elliott et al., 1997 ; Jenkins & Connor, 1949 ; Lin et al., 1992 ; Wickens, 1986). To go further, accurate aiming is based on provided visual information process and requires a movement which becomes slower and receives more feedback guidance in low- and high-gain settings (Elliott et al., 1997).

Despite apparent differences between the efficiency of different control display gains, it is also widely accepted that the use of a control display gain function (specific to each operating system used) enhances performance (Casiez et al. 2008; Casiez and Roussel 2011; Scotto et al., 2018). Anyhow, users are very well calibrated to the mapping specific to the interface which they are familiar with. Furthermore, current operating systems are not able to determine the resolution of computer mice, resulting in different cursor behaviors depending on the resolution of the input device (Casiez and Roussel 2011). For example, a computer mouse with a 800 count-per-inch (CPI) resolution will result in cursor movements twice faster compared to a 400 CPI resolution, for the same movements performed in motor space. This can result in large differences in cursor control when switching from one computer to another, as computer mouse resolutions span from 400 to 20,000 CPI.

Given our wish to apply the recalibration issue in the HCI domain, we also considered it relevant to base our research on two well-known motor control paradigms, namely the Fitt's paradigm (Fitts, 1954) and the adaptation paradigm (e.g., Harris, 1963).

Fitts task consists in performing rapid aiming movement operationalized by an Index of Difficulty (ID) with $ID = \log_2(2D/W)$, D representing the distance to be covered and W the target size. When task difficulty increases, the time required to successfully perform the task also increases. This robust empirical relation has come to be known as Fitts' law (see Meyer et al., 1988 and Plamondon et al., 1997 for reviews).

From the kinematics patterns analysis, it has largely been admitted that there are two kinds of perceptual-motor processes involved in Fitts task. While analyzing kinematics patterns, the peak velocity appears as the division point (Huys, Fernandez, Bootsma, & Jirsa, 2010). The acceleration phase, from movement onset to peak velocity results from processes operating in feed-forward (open loop) and reflects central programming of force impulses. The second phase of the movement, usually called deceleration phase results from online adjustments of central commands based on available perceptual feedback (Woodworth, 1899; Elliott et al., 2001, 2010 for reviews). This second phase of movement is lengthened when accuracy constraints increase (e.g., when targets width decreases while distance that has to be covered remains unchanged, Elliott et al., 2001). Further investigations of the deceleration phase lengthening allow authors to observe increase in trajectory irregularities (Ketcham et al., 2002; Meyer et al., 1988) identified as different types of secondary submovement types (Dounskaia et al., 2005): (i)

secondary submovements are used to correct overshoot movements, (ii) submovements are used to correct undershoot movements and (iii) submovements refer to progressive deceleration to stop within the target. In the literature questioning discrete aiming movements' control, it has largely been argued that these submovements take part in corrective processes which ensure spatial accuracy at the expense of longer movement execution (Elliott et al., 2004; Fradet et al., 2008; Lyons et al., 2006).

In the present study, we asked participants to produce indirect aiming tasks mimicking the task performed daily thousands of times, consisting of selecting with a mouse or a trackpad a target (icon) on a desktop computer (Casiez & Roussel, 2011). The Fitts paradigm described below provided the tools we need to extract from successive aiming kinematics the signature of perceptual-motor calibration.

The perceptual-motor recalibration process will take place following a sudden change from trial to trial in *control display gain* (CD gain) when performing aiming tasks. We will use a protocol identical to the one used for prism adaptation studies, composed of an initial calibration phase with a given CD gain, a recalibration phase with a different CD gain and finally a return to the initial condition with the CD gain used in the initial phase. This protocol should allow us to precisely assess the timescale of perceptual-motor recalibration process, but also to describe the behavioral changes accompanying the successive recalibration processes.

Based on the literature some predictions can be made. Firstly, changing abruptly CD gain should give rise to an increase in movement time, due to the occurrence of submovements to compensate initial under or over-shoots. Secondly, we expect very fast recalibration to occur (a few trials should be enough) allowing the participants to produce adaptive behavior and to restore initial performance. Finally, we expect post effects to occur during the last phase of the experiment, of the same amplitude but in opposite direction in comparison with those observed following the first perturbation. Once again, a very fast recalibration should be observed.

2. Method

2.1. Participants

Sixteen healthy people (5 women and 11 men, mean age 23.7 years, SD 3.5 years) voluntarily agreed to participate in the experiment. All of them were right-handed, and had no perceptual or motor disorders. All reported normal or corrected vision and were

totally naive about the purpose of the experiment. All subjects gave written informed consent in accordance with the Declaration of Helsinki.

All participants worked most of their time with a computer. Two participants exclusively worked with macOS system, 13 with Microsoft Windows system and 1 participant use equally both. Eleven participants mainly used the mouse, 4 the touchpad of their laptop and one participant uses equally both devices.

2.2. Material

The experiment was executed on a 13-inch MacBook Pro with retina display with a 2.7 GHz Intel Core i5 processor and running macOS version 10.13.4. A 1200 CPI USB corded Logitech mouse was used as an input device to aim at targets.

The experiment was coded in C++ with the Qt framework. The Libpointing library (Casiez & Roussel, 2011) was used to get the raw position of the mouse and to apply different gain functions (i.e., transfer functions) defining the relationship between the horizontal sliding movement of the mouse (i.e., motor space) to the movement of the cursor on the screen (i.e., task space). Cursor position was updated at a sampling frequency equal to 60 Hz on the task space.

2.3. Task

A discrete one-dimensional aiming task was proposed.

Participants sat comfortably at a table facing the MacBook Pro placed in front of them. The position relative to the laptop as well as the position of the mouse were individually chosen in order that the participant could easily move the mouse.

Participants were instructed to move a cursor bar (a thin and white line of 1 pixel or 0.25 mm width) from a starting target to the target (a green bar of 1.75 mm width or 7 pixels) depicted on a black background screen of the MacBook's display (Fig. 1).

Before to start each trial, participants were instructed to reach the gray starting position and hold on the cursor 1000 ms on it. After this imposed delay, starting position turned green and a green target (25 mm width) appeared at a fixed distance of 80 mm from the center of the starting target. From this moment, participants were instructed to start moving when they want and to move the cursor bar from the starting position to the

target “as smooth, fast and accurate as possible” by sliding the mouse without lifting it up and repositioning it (also called clutching).

Participants were required to click on the mouse when they were inside the boundaries of the target to validate the aiming and hold stationary for about 500 ms after clicking. Then the final current target turned gray and became the starting position for the next trial.

Aiming was not validated if participants clicked on the mouse outside the target boundaries and they thus had to come back inside the target and click again on the mouse and hold stationary for about 500ms.

Participants performed, thus, each specific aiming in the opposite direction of the previous one. Each trial ended while selecting the target (i.e., clicking on the target).

- Insert Figure 1 about here -

2.4. Experimental design

Participants performed the task under three Control Display (CD) gain conditions. A CD gain represents the mathematical function transforming a displacement of the mouse on the motor space into a displacement of the cursor on the visual space.

The three CD gain conditions were the following: (1) the *constant gain 1*, abbreviated CG1, corresponded to 1:1 mapping for which displacement on motor space mapped identically to the displacement in task space (i.e., the speed of the mouse cursor is identical to the speed of the mouse, using the same units). (2) The *constant gain 3*, abbreviated CG3, corresponded to a gain between mouse speed in motor space and cursor speed in task space equal to 3 whatever the speed in motor space. (3) The *increasing gain*, abbreviated IG, corresponded to a gain 1 at the beginning of the movement when the speed in motor space is null and linearly increased up to 3 when the motor speed reached 10 cm.s^{-1} (Fig.2) following the procedure proposed by Scotto et al. (2020). The maximum gain and the associated motor speed at which it could be reached has been determined empirically before the experiment began (see Scotto et al. for more details).

Participants were introduced to the task and had about 10 aimings to get used to it in the Constant Gain 1 (CG1) condition.

Then, they completed three Blocks of 60 aimings each.

Each block consisted of 3 sessions of 20 aimings each in a row. The 1st session (first 20 aimings) was performed with a CG1, the 2nd session (aimings 21 to 40) was performed with a specific gain depending on the block (i.e., either CG1, CG3 or IG) and the 3rd session, corresponding to the last 20 aimings was performed with CG1.

The condition CG1 was considered as the reference condition.

Under the Block CG1-CG1-CG1, the three sessions of 20 aimings performed in a row were performed with a constant gain of 1. Under the Block CG1-CG3-CG1, the 2nd session was performed with a constant gain of 3 (CG3) (Fig. 2). Under the Block CG1-IG-CG1, the 2nd session was performed with the Increasing Gain (IG) (Fig. 2).

The order of presentation of the 3 Blocks was randomized across subjects whereas the order of the session inside each session was fixed and similar for all participants.

In summary, the experimental design was: 16 participants X 3 Blocks X 3 sessions (3 X 20 trials). Each participant performed 3 Block X 60 trials = 180 trials.

And in total 2880 trials were analyzed (16 participants X 180 trials).

- Insert Figure 2 about here -

2.5. Data analysis

The position time series from the mouse in motor space and from the cursor in task space were filtered with a dual-pass, second-order Butterworth filter, with a cut-off frequency of 6 Hz. Velocity and acceleration were subsequently derived using a 3-point central difference technique.

During the first part of the analysis, three dependent variables were used: the movement time, the peak velocity and the percentage of acceleration phase.

The second phase of data analysis concerned the analysis of sub-movement types as well as some characteristics of the primary submovement.

Movement time was computed as the elapsed time between the movement onset and the movement offset. Movement onset and offset were determined on the basis of velocity profiles. The onset of the movement corresponded to the time the mouse

velocity was superior to 5% of the peak velocity. Movement offset was identified from the mouse click time corresponding to the target selection; more precisely it corresponds to the first time mouse velocity signal value was below 5% of the peak velocity (see Botzer & Kamiel, 2019 for a review, Donchin et al., Georgopoulos et al., [1982](#); Moran and Schwartz, [1999](#); Roby-Brami et al., [2000](#); Scott et al., [2001](#)).

Peak velocity was obtained from the maximum value of the velocity signal.

Due to the presence of a gain other than 1 in some conditions, motion of the cursor between the targets (task space) differed from motion of the mouse (motor space). We therefore separately analyzed peak velocity in motor space and task space and reported both for reasons of completeness.

The percentage of acceleration time was defined as the time to peak velocity divided by the movement time.

Then, following a similar procedure as those previously used by Poletti et al. (2015; 2016) the movement was decomposed into either primary and secondary submovements. The primary submovement was characterized by a rapid movement that brings the limb near the target and the optional secondary submovement corresponded to an online control phase during which the target is approached (Woodworth, 1899). Thus, in the case of Type 1, secondary submovements are used to correct overshoots. We identified overshoots when at the end of the primary submovement, i.e., after the velocity reached its peak, the velocity crossed zero, changing from positive to negative.

In the case of Type 2, secondary submovements are used to correct undershoots. We identified undershoots, when at the end of the primary submovement, the acceleration crossed zero, changing from negative to positive.

In the case of Type 3, secondary submovements are used to correct progressive deceleration movements ; at the end of the primary submovement, the jerk crossed zero, changing from positive to negative.

This procedure allowed us to determine first the type of submovements but we also analyzed some kinematics variables from the primary submovement.

While the type of submovement has been identified, we then analyzed the distance that remained to be covered after the primary submovement to reach the center of the

target. For the overshoot type of movement, this value is negative, and corresponds to the distance that has to be covered by the secondary reversal movement to reach the center of the target.

The absolute time corresponding to the end of the primary movement was analyzed as well as the percentage of time at which this submovement occurs.

2.6. Statistics analysis

Data was analyzed using R. The effects of Blocks and Sessions were examined first using a mixed effects repeated measures ANOVA with Sessions nested within Blocks. When significance level ($p < .05$) was reached, effects were further characterized through a Tukey post-hoc tests.

One of the main objectives of the current experiment being to identify the timescale of the calibration process, a separate statistical analysis was then conducted at the level of specific aimings for the sessions 2 and 3. Each single aiming was analyzed by analysis of variance (ANOVA) and compared with the average of the consecutive aimings with Helmert contrasts in order to quantify the numbers of trials needed to calibrate the system and thus reach a stabilized level of performance.

3. Results

3.1. Movement Time (MT)

3.1.1. Analysis at the level of the Blocks

The repeated-measures ANOVA based on Movement Time was performed with Blocks and Sessions as within factors.

The analysis of variance revealed a significant main effect of Blocks ($F(2,143) = 3.16, p < .05$), while Sessions (nested in blocks) almost reach the significance threshold ($F(6,143) = 2.14, p = .05$). The post-hoc demonstrated that MT was lower in Block CG1-CG1-CG1 (1.12 ± 0.17 sec) in comparison with Block CG1-CG3-CG1 (1.15 ± 0.19 sec) ($p < .05$) (see Fig.3 upper panel).

3.1.2. Analysis at the level of single aiming following the perturbations

3.1.2.1. Block CG1-CG3-CG1

During Session 2, the repeated-measures ANOVA with Helmert contrast revealed that MT were longer during the first and the second aiming (with an average MT of 1.56 ± 0.39 s and 1.50 ± 0.56 s respectively) in comparison with the average MT of the remaining aimings (MT = 1.06 ± 0.25 s) (see Table 1 for detailed statistical results).

During Session 3, the repeated-measures ANOVA with Helmert contrast revealed that MT were longer during the first aiming (with an average MT of 1.65 ± 0.33 s) in comparison with the average MT of the remaining aimings (MT = 1.16 ± 0.24) (see Table 1 for detailed statistical results). The calibration process took either 1 or 2 aimings after perturbation (see Fig.3 lower panel).

3.1.2.2. Block CG1-ICG-CG1

The repeated-measures ANOVA with Helmert contrasts on MT revealed that during Session 2 MT were significantly longer for aimings 1 (1.69 ± 0.38), 2 (1.38 ± 0.45), 3 (1.49 ± 0.37) and 4 (1.37 ± 0.34) in comparison to the average MT of the consecutive remaining aimings (MT = 1.10 ± 0.22). During Session 3, the MT was longer for the first aiming following the change (1.46 ± 0.26) in comparison with the average MT of the remaining aimings (MT = 1.10 ± 0.20) (see Table 1 for detailed statistical results). The calibration process took either 1 to 4 aimings after perturbation (see Fig.3 lower panel).

- Insert Figure 3 about here -

3.2. Peak of velocity (PV)

3.2.1. Peak of velocity (PV) in motor space

3.2.1.1 Analysis at the level of the Blocks

The repeated-measures ANOVA on Peak velocity was performed with Blocks and Sessions as within factors. It revealed a significant effect of Blocks ($F(2,143) = 84.39$, $p < .001$). A posteriori comparisons demonstrated that Peak velocity was higher in Blocks CG1-CG1-CG1 (28.74 ± 6.46 cm.s⁻¹) in comparison with the two other Blocks ($p < .001$ & $p < .001$), whereas Peak velocity was not different in Block CG1-CG3-CG1 (23.35 ± 8.71 cm.s⁻¹) and Block CG1-IG-CG1 (23.98 ± 7.99 cm.s⁻¹) ($p = .35$).

The factor Sessions (nested in blocks) also reach the significance threshold ($F(6,143) = 119.82, p < .001$). Tukey post-hoc test revealed that under the Session 1, the 3 Blocks did not significantly differ. Under the Session 3, only Block CG1-CG1-CG1 significantly differed from Block CG1-IG-CG1 ($p < .05$).

Due to the sudden change of the CD gain under Session 2, Block CG1-CG3-CG1 and Block CG1-IG-CG1 both significantly differed to Block CG1-CG1-CG1 ($p < .001$ and $p < .001$ respectively). Then, Block CG1-CG3-CG1 and Block CG1-IG-CG1 did not differ under Session 2 ($p = .12$). Under the session 2, on average PV was equal to $28.97 \pm 6.41 \text{ cm.s}^{-1}$ for the Block CG1-CG1-CG1, to $14.07 \pm 4.90 \text{ cm.s}^{-1}$ for the Block CG1-CG3-CG1 and $16.29 \pm 4.99 \text{ cm.s}^{-1}$ for the Block CG1-IG-CG1 (see Fig.4 upper panel).

3.2.1.2. Analysis at the level of single aimings following perturbations

3.2.1.2.1. Block CG1-IG-CG1 and Block CG1-CG3-CG1

The repeated-measures ANOVA with Helmert contrasts revealed that whatever the block condition (CG1-IG-CG1 and CG1-CG3-CG1), PV on motor space was significantly higher for the first and the second aiming following the first perturbation (from CG1 to CG3 or from CG1 to IG) in comparison with the following trials. On average, under the Block CG1-CG3-CG1, PV was equal to $24.50 \pm 7.65 \text{ cm.s}^{-1}$ and $17.02 \pm 6.83 \text{ cm.s}^{-1}$ for the 1st and the 2nd aiming respectively and equal to $13.44 \pm 4.99 \text{ cm.s}^{-1}$ for the remaining aimings. For the Block CG1-IG-CG1, PV was equal to $26.15 \pm 7.98 \text{ cm.s}^{-1}$ and $17.85 \pm 7.16 \text{ cm.s}^{-1}$ for the 1st and the 2nd aiming following the perturbation respectively and equal to $15.61 \pm 4.84 \text{ cm.s}^{-1}$ for the remaining aimings.

When focusing on the second perturbation (i.e. from CG3 to CG1 or from IG to CG1), PV on motor space was significantly lower for the first aiming following the perturbation ($13.94 \pm 5.27 \text{ cm.s}^{-1}$ and $15.93 \pm 4.59 \text{ cm.s}^{-1}$ for Block CG1-CG3-CG1 and Block CG1-IG-CG1 respectively) than for the following aimings ($28.56 \pm 5.98 \text{ cm.s}^{-1}$ and $27.85 \pm 6.11 \text{ cm.s}^{-1}$ for Block CG1-CG3-CG1 and Block CG1-IG-CG1 respectively) (see Table 1 for detailed statistical results).

One can note that under the Block CG1-IG-CG1, the third aiming under the Session 3 was slightly but significantly lower than the average PV across aims 6 to 20 (see Fig. 4 lower panel).

The calibration process took either 1 to 3 aimings after perturbation (see Fig. 4 lower panel).

- Insert Figure 4 about here -

3.2.2. Peak of velocity (PV) on Task space

3.2.2.1. Analysis at the level of the sessions

The repeated-measures ANOVA based on Peak velocity on Task Space was performed with Blocks and Sessions as within factors.

It revealed a significant effect of Blocks on PV ($F(2,143) = 18.50, p < .001$). A posteriori comparisons revealed that PV was lower in Blocks CG1-CG1-CG1 ($28.74 \pm 6.46 \text{ cm.s}^{-1}$) compared to the two other Blocks ($p < .001$ & $p < .001$). Conversely PV was not statistically different in Blocks CG1-CG3-CG1 ($32.74 \pm 11.79 \text{ cm.s}^{-1}$) and CG1-IG-CG1 ($34.70 \pm 14.04 \text{ cm.s}^{-1}$) ($p = .12$).

The main effect of Sessions (nested in blocks) also reached the significance threshold ($F(6,143) = 47.19, p < .001$). Tukey post-hoc test revealed that under the Session 1, the 3 Blocks did not significantly differ, similarly to what can be observed in Session 3.

Due to the sudden change of the CD gain under Session 2, Block CG1-CG3-CG1 and Block CG1-IG-CG1 both significantly differed to Block CG1-CG1-CG1 ($p < .001$ and $p < .001$ respectively). Then, Block CG1-CG3-CG1 and Block CG1-IG-CG1 differed under Session 2 ($p < .05$). Under the session 2, on average PV was equal to $28.97 \pm 6.41 \text{ cm.s}^{-1}$ for the Block CG1-CG1-CG1, to $42.23 \pm 14.68 \text{ cm.s}^{-1}$ for the Block CG1-CG3-CG1 and $48.46 \pm 15.31 \text{ cm.s}^{-1}$ for the Block CG1-ICG-CG1 (see Fig. 5 upper panel).

3.2.2.2. Analysis at the level of single aimings following the perturbations

3.2.2.2.1. Block CG1-ICG-CG1 and Block CG1-CG3-CG1

The repeated-measures ANOVA with Helmert contrasts revealed that whatever the block conditions (CG1-ICG-CG1 and CG1-CG3-CG1), PV was significantly higher during the first two aimings following the perturbation (i.e., from CG1 to CG3 or from CG1 to IG) in comparison with the remaining trials. On average, during the Block CG1-CG3-CG1, PV was equal to $73.50 \pm 22.96 \text{ cm.s}^{-1}$ and $51.05 \pm 20.50 \text{ cm.s}^{-1}$ for the 1st and the 2nd aiming respectively and equal to $40.37 \pm 14.95 \text{ cm.s}^{-1}$ for the remaining aimings. For the Block CG1-IG-CG1, PV was equal to $78.51 \pm 23.91 \text{ cm.s}^{-1}$ and $52.00 \pm 24.48 \text{ cm.s}^{-1}$ for the 1st and the 2nd aiming respectively and equal to $46.47 \pm 14.99 \text{ cm.s}^{-1}$ for the remaining aimings.

When one focus on the second perturbation (i.e., from CG3 to CG1 or from IG to CG1) PV was significantly lower for the first aiming following the perturbation (see Table 1 for detailed statistical results). Under the first aiming, PV was equal to $13.94 \pm 5.27 \text{ cm.s}^{-1}$ and to $15.93 \pm 4.59 \text{ cm.s}^{-1}$ (for Block CG1-CG3-CG1 and Block CG1-IG-CG1 respectively) whereas the average PV for the remaining aimings was equal to $28.56 \pm 5.98 \text{ cm.s}^{-1}$ and $27.85 \pm 6.11 \text{ cm.s}^{-1}$ (for Block CG1-CG3-CG1 and Block CG1-IG-CG1 respectively) (see Fig.5 lower panel).

The calibration process took either 1 or 2 aimings after perturbation (see Fig.5 lower panel).

- Insert Figure 5 about here -

3.3. Percentage of Acceleration Time (%AT)

3.3.1. Analysis at the level of the Blocks

The repeated-measures ANOVA on Percentage of Acceleration Time (%AT) was performed with Blocks and Sessions as within factors. It revealed a significant effect of Block on %AT ($F(2,143) = 9.21, p < .001$). A posteriori comparisons revealed that %AT was higher in Block CG1-CG1-CG1 ($17.10 \pm 4.81 \%$) in comparison with the two other Blocks ($p < .001$ & $p < .05$). Conversely, Block CG1-CG3-CG1 ($15.29 \pm 3.88 \%$) and Block CG1-IG-CG1 ($15.81 \pm 4.55 \%$) were not statistically different ($p = .45$).

The main effect of Sessions (nested in blocks) also reach the significance threshold ($F(6,143) = 8.32, p < .001$). Tukey post-hoc test revealed that under the Session 1, the 3 Blocks did not significantly differ as well as under the Session 3.

Due to the sudden change of the CD gain under Session 2, % AT under both Block CG1-CG3-CG1 and Block CG1-IG-CG1 was significantly lower than under Block CG1-CG1-CG1 ($p < .001$ and $p < .001$ respectively). Then, Block CG1-CG3-CG1 and Block CG1-IG-CG1 did not differ under Session 2 ($p = .99$). Under the session 2, on average % AT was equal to $17.47 \pm 4.53 \%$ for the Block CG1-CG1-CG1, to $13.37 \pm 3.63 \%$ for the Block CG1-CG3-CG1 and $13.65 \pm 4.37 \%$ for the Block CG1-IG-CG1.

3.3.2. Analysis at the level of single aimings following perturbations

3.3.2.1. Block CG1-CG3-CG1

Following the first perturbation (CG1-CG3) the %AT did not change. Conversely, after the second perturbation (CG3-CG1) the %AT was higher (23.17 ± 15.10 %) in the first aiming in comparison with the remaining aimings (16.77 ± 3.91 %) (see Table 1 for detailed statistical results).

3.3.2.2. Block CG1-IG-CG1

Following the first perturbation (CG1-IG) the %AT was lower during the first aiming (10.09 ± 3.52 %) in comparison with the remaining aimings (13.82 ± 4.20 %). After the second perturbation (IG-CG1), the %AT was higher (21.34 ± 16.82 %) in the first aiming in comparison with the remaining aimings (16.90 ± 3.73 %) (see Table 1 for detailed statistical results).

According to the block session and the perturbation, the calibration process took maximum 1 aiming after perturbation. One can note that under Block CG1-CG3, there is no calibration on %AT following the first perturbation (see Fig.6 lower panel).

- Insert Figure 6 about here -

3.4. Remaining distance after primary submovement (RD-SM)

We remind at this point that when RD-SM is negative, participants overshoot the target. RD-SM corresponds to the distance they have to reverse to reach the center of the target. Inversely, when RD-SM is positive, participants undershoot the target and RD-SM corresponds to the distance they have to fill out in order to reach the target.

3.4.1. Analysis at the level of the Blocks

RD-SM is on average positive under each block and sessions prescribed indicating that on average over 20 aimings per sessions and across blocks, participants undershoot the target.

The repeated-measures ANOVA based on remaining Distance after primary submovement (RD-SM) was performed with Blocks and Sessions as within factors. It revealed a significant effect of block on RD-SM ($F(2,143) = 10.20, p < .001$).

A posteriori comparisons revealed that RD-SM under Block CG1-CG1-CG1 was significantly higher (13.65 ± 6.75 mm) than under Block CG1-IG-CG1 (9.58 ± 11.14 mm)

($p < .001$). RD-SM was significantly lower under Block CG1-IG-CG1 (9.58 ± 11.14 mm) than Block CG1-CG3-CG1 12.31 ± 9.82 mm ($p < .05$). Finally, RD-SM was not statistically different in blocks CG1-CG1-CG1 and CG1-CG3-CG1 ($p = .31$).

There was also a main effect of Sessions (nested in blocks) ($F(6,143) = 28.26, p < .001$). The Tukey post-hoc test revealed that under the Session 1, the 3 Blocks did not significantly differ as well as under the Session 3.

Due to the CD gain added under Session 2, RD-SM under Block CG1-CG1-CG1 and Block CG1-IG-CG1 was significantly higher than under Block CG1-CG3-CG1 and Block CG1-IG-CG1 ($p < .001$ and $p < .001$). Then, under Session 2, RD-SM was significantly higher under Block CG1-CG3-CG1 than under Block CG1-IG-CG1 ($p < .05$). On average and under the session 2, RD-SM was equal to 13.04 ± 5.85 mm for the Block CG1-CG1-CG1, to 5.68 ± 9.36 mm for the Block CG1-CG3-CG1 and -0.11 ± 10.47 mm for the Block CG1-IG-CG1 (see Fig.7 upper panel).

3.4.2. Analysis at the level of single aimings following the perturbation

3.4.2.1. Block CG1-CG3-CG1

Helmert contrasts revealed that the RD-SM is higher in the first 2 aimings following the first perturbation (CG1-CG3), with negative values indicating overshoots ($-69.85.11 \pm 34.61$ mm and -14.45 ± 19.83 mm for the 1st and the 2nd aiming respectively) (see Table 1 for detailed statistical results) in comparison with the remaining aimings (12.16 ± 8.43 mm). Following the second perturbation (CG3-CG1), RD-SM significantly increase (positive values indicate undershoots) during the first 3 aimings (41.42 ± 17.16 mm, 26.35 ± 17.24 mm, and 25.80 ± 17.07 mm for the 1st, 2nd and 3rd aimings) in comparison with the remaining aimings (13.10 ± 7.43 mm) (see Fig.7 lower panel).

3.4.2.2. Block CG1-IG-CG1

Helmert contrasts revealed that the RD-SM is higher in the first 3 aimings following the first perturbation (CG1-IG), with negative values indicating overshoots (-77.82 ± 39.79 mm, -22.35 ± 24.30 mm and -12.38 ± 24.95 mm for aiming 1, 2 and 3 respectively) (see Table 1 for detailed statistical results) in comparison with the remaining aimings (7.36 ± 8.77 mm) Following the second perturbation (IG-CG1), RD-SM significantly increase

(positive values indicate undershoots) during the first aiming (36.92 ± 23.64 mm) in comparison with the remaining aimings (14.48 ± 6.53 mm) (see Fig.7 lower panel).

RD-SM with the MT is the kinematic parameter for which the calibration process is the longest comparing all parameters analyzed in the current study.

- Insert Figure 7 about here -

4. Discussion

Switching from one operating system to another (for example from windows to macOS) is likely to be a problem for our perceptual-motor system because of the need to adapt our goal-directed movement to different CD gain between motor and task spaces.

The aim of the present study was to characterize the perceptual-motor calibration process following a sudden change in CD gain, but also to identify the underlying timescale of the calibration process. We mainly hypothesized that changes in CD gain should give rise to functional kinematics changes on a very short timescale.

This study could have important implications in the domain of Human-Computer Interaction (HCI). Indeed, although several studies have already identified the CD gains most prone to allow users to reach a good performance in aiming tasks (e.g., Casiez et al., 2008; Scotto et al., 2020), to our knowledge the ability of users to adapt to a change in CD gain has never been addressed.

Our methodology consisted in examining the perceptual-motor adjustments accompanying changes in CD gain following a three-step adaptation methodology (baseline condition followed by a perturbation and return to baseline condition). More precisely, based on the results of Scotto et al. (2020), a constant gain of 3 and a linear increasing CD gain have been used to study the recalibration process following exposure to the baseline condition (cf., Scotto et al., 2020 for more details).

Before discussing our results, one can take into account a particularity of the current study regarding the status of performance achieved and success criteria of the task. Reading different studies on perceptual-motor calibration leads us to conclude that in most of the cases, the performance is analyzed as “the task has been successful or not”. For example, the ball has been intercepted/or not in a study where the characteristics of the baseball bat were manipulated (Scott & Gray, 2010), an approaching ball has been hit/or not with a released pendulum (Smith et al., 2001), or else participants performing a simulated braking task stopped as close as possible to a target or collided it (Fajen, 2008).

Inversely, in the current study, participants could not miss the target because the only way to validate and end up each trial was to click on the target. In that sense, we cannot conclude that participants have successfully completed the task or not. In the following sections, we will discuss the calibration process in terms of adaptation timescale to the different kinematics parameters (MT, PV, % AT) to new CD gain and not in terms of the numbers of aimings necessary to pass the task. As we were not able to conclude that participants were calibrated once they successfully complete the task, we made the choice to talk about a calibration state achieved once kinematics parameters were stable in between successive aiming's meaning that participants were not exploring the different endpoint kinematics solutions but they had instead stabilized their behavior. Repeated measures of ANOVA with Helmert contrast was, according to us, the best statistical method to investigate this stabilization concept.

We will first discuss the results across Blocks and independently of the sessions. Then, we will discuss the consequence of changing the CD gain in two different ways. As the last part of the discussion, we will present the limits of the current study as the perspectives.

4.1. Comparison between Blocks independently of the Sessions

A main effect of block factor on each kinematics parameter analyzed has been observed and allowed us to conclude that behavior is impacted by changing the CD gain between motor and task space. Thus, it does make sense to talk about and analyze a calibration process through a close inspection of the dependent variables recorded.

On average, MT was longer for the two blocks including a sudden change of CD gain (Figure 3, upper panel). Without taking into account the timescale of the calibration process, a longer MT can be analyzed in parallel with a lower peak velocity on motor space (Figure 4, upper panel) and a shorter relative acceleration phase (Figure 5, upper panel). PV was on average lower for the blocks with a change than the control block (Block CG1-CG1-CG1). Our results are consistent with the results from Scotto et al. (2020) and showed that overall, participants take advantage of the CD gain added by decreasing their PV on motor space. Moreover, they also reached it earlier for the Block with change as a significative lower % Acc was observed.

Finally, remaining distance after primary sub-movement was significantly lower overall for the two blocks when CD gain was suddenly changed. This is the consequence of the observed overshoot trials following the change and discussed hereafter. An overshoot is quantified with a negative RD-SM and thus decrease the average RD-SM for the Session 2 of the two blocks were a CD gain change occurred.

4.2. Calibration process timescale analysis

Remember that our three steps adaptation methodology allowed us to examine the perceptual-motor calibration process when changing the CD gain (second session) and when restoring the initial CD gain (third session).

How the change in gain (from CG1 to either CG3 or IG) disrupts the aiming movement

A close inspection of the very first aiming movement following the disturbance is necessary to provide a good understanding of the function of the calibration phase. Whatever the change in gain, this first aiming gave rise to large overshoots of the target (of the order of 60 cm) and could be related to the fact that the first part of the pointing movement (up to peak velocity), is performed in open-loop and remained unchanged. The final pointing accuracy was kept unchanged thanks to the appearance of corrective submovements at the expense of movement time. The same pattern of results emerges whatever the change in gain ; in both cases (CG3 or IG) the gain increases in comparison with the baseline condition (CG1).

4.3. Analyzing the calibration process following the perturbation

It is worth noting that our analyses allowed us to describe several functional adaptations operating at a very short timescale. The increases in CD gain were compensated through a decrease in peak velocity, giving rise to the disappearance of particularly time consuming overshoots. These adaptations allow the participants to adopt a more standard kinematics pattern with an initial phase allowing bringing the cursor just before the target (i.e., undershoots), followed by functional adjustments to meet the target.

In addition to the ability of participants to produce a perceptual-motor behavior adapted to new execution conditions, our most striking result concerns the timescale of the recalibration process, as very few repetitions were necessary before a new stable adaptive behavior emerged. Taken together our results indicate that a couple of repetitions were sufficient to induce a calibration to a new CD gain.

Interestingly, comparable calibration timescale has been reported in studies in which either baseball players were asked to hit balls while bat weight was manipulated (Scott & Gray, 2010) or drivers had to brake in front of an obstacle while brake strength of a virtual vehicle was changed (Fajen, 2007).

One can hypothesize that in these studies (including in the present study) the calibration process has been facilitated by the fact that the tasks investigated preserve the links between perception and action. It has clearly been demonstrated that during a judgment task (Mark, 1987 & Wagman et al., 2014) there is a less perfect match between the explored source of information and the skill to be judged so that recalibration takes a longer period of time. To pursue, in a judgment task of maximal reaching height, Wagman et al. (2014) observed that judgment accuracy improves when participants were allowed to perform the actual reaching task instead of simply judging without feedback and without manipulation of action capabilities.

Thus, van Andel et al. (2017) state that “the time required for calibration is mainly dependent on the aptness of the information explored for calibration. When the movement itself is explored, calibration occurs rapidly (Fajen 2007 ; Nakamoto et al., 2012 ; Franchak & Adolph, 2014 ; Wagman et al., 2014) but when exploration occurs using less relevant information movement calibration takes longer (Mark, 1987)”.

4.4. Do different perturbations (CD3 vs., IG) have an influence on the recalibration process ?

Even if not central in the present study, we also compared the specific kinematics changes and the timescale of the calibration process, following the two perturbations (i.e., CG 3 and IG). Overall, we observed a similar calibration process to a sudden change of CD gain, either when a CG3 or an IG was added. However, it has been observed that the two variables, Movement Time and Remaining Distance after the primary submovement, take two more aimings to be calibrated under the Block CG1-IG-CG1 than the Block CG1-CG3-CG1 in Session 2 and inversely for the RD-SM in Session 3. This slight difference on calibration time scale could be explained by previous work showing a better performance under CG3 than IG for high levels of task difficulty (Scotto et al., 2020).

Now, even if the mapping between perception and action was different depending on the perturbation (i.e., CG3 vs., IG), the two CD gains gave rise to a perceptual amplification (i.e., on the task space) of the movement produced in the movement space. In these circumstances, it is not really surprising that, at least from a qualitative point of view, the kinematics changes accompanying the calibration process were similar. Participants only performed the task for an ID 6 which can be considered as a very constraining task which limits the plausible difference between these two CD gains. As demonstrated by Scotto et al. (2020), one can conclude that the task is so constraining from the accuracy point of view that motion variability is very weak.

4.5. Analyzing the calibration process following the return to the baseline condition (CG1)

From a qualitative point of view now, the return to initial conditions acts logically as a perturbation participants have to deal with, given the fact that CD gain changes from either CG3 or IG to CG1. The first trial following the return to initial conditions mirrors a very nice aftereffect. The movement being calibrated to the previous CD gain (either CG3 or IG), a large undershoot is observed for the first trial and demonstrates a consequence of insufficient velocity to bring the cursor close to the target to be pointed. The subsequent adjustments allowed the cursor to reach the target at the expense of time. The results also revealed, irrespective of the CD gain used in the second session (i.e., either CG3 or IG), that participants were able to recalibrate to the baseline condition within the time frame of one aiming. While revealing once again the impressive adaptive

capacities of the participants to different mappings, these results also show that calibration to a one-to-one (1:1) mapping could be faster than a calibration to a non-1:1 one. Moving with a 1:1 mapping is consistent with what we daily do and correspond to what we experienced the more since we are able to perform perceptual-motor tasks as writing, for example. We can easily argue that calibration to such a 1:1 mapping is less time and probably attentional consuming.

4.6. Limitations and perspectives

The results of the present study suggest that calibration of the perceptual-motor system is a very fast process which needs a few trials to be carried out. However, following this study, many questions remain to be addressed.

Scott and Gray (2010), in a study designed to test different baseball bat weights evoke the possibility for an agent to develop stored calibration states that can be immediately recalled so that no re-calibration would be needed. In the current HCI context, it could be interesting to investigate this notion of calibration state storage. Do users store calibration process for the CD gain they experience every day, facilitating the transition from one to the other? Does this storage can facilitate calibration to new CD gain never experienced or to other devices (i.e., mouse, trackpad, joystick) and does this benefit performance?

It could also be interesting to test this hypothesis when users face new CD gain but also when they have to perform the task with different levels of difficulty. In the present study, the level of difficulty was high (ID6) and it would be interesting to assess to what extent task difficulty could act as a mediating factor in the calibration process.

Finally, we would also like to advocate in the next studies for the usefulness of a multi-level analysis framework, i.e., combining neuro-musculoskeletal levels of analysis, in order to provide a more comprehensive picture of how movement is organized and calibrated. This more integrated approach could be used to avoid pathologies or injuries such as musculoskeletal disorder or put in another way to reduce fatigue for example for users who use these devices daily and all day long.

The same framework could also be used to investigate the calibration process for a similar task for specific populations, for example elderly people or patients suffering

from Parkinson disease, which specifically impaired fine motor skill and for video games users or people manipulating devices very often such as tele-surgeon.

5. Conclusion

To the best of our knowledge, the present study is the first to investigate the recalibration process in the HCI domain. The main result is that not only participants produce adaptive behavior following different types of perturbations, but they are also able to do it at a very short timescale which is in perfect agreement with the results provided by other researchers in other domains.

The calibration process described in the present study may play an important role in the acquisition of accurate perceptual-motor skills involving the use of devices that augment human fine motor capabilities (e.g., telesurgery, mouse and joystick). Most of the time, these devices required users to move with a non-1:1 mapping which does not correspond to the 1:1 mapping experienced every day. Movements performed with such non-linear mapping is accompanied by changes in the available information and the dynamics of the controlled system. We are convinced that the ability to rapidly calibrate the system to novel non-1:1 mapping between perception and action is also at work whenever people use a new device or a new operating system or when a surgeon discovers a new telesurgery device.

6. References

Table 1

	TM			
	Block CG1-CG3-CG1		Block CG1- IG-CG1	
	Session 2	Session3	Session 2	Session3
Aiming 1	p<.001	p<.001	p<.001	p<.001
Aiming 2	p<.001	p=.093	p<.01	p=.232
Aiming 3	p=.340	p=.472	p<.001	p=.201
Aiming 4	p=.524	p=.209	p<.005	p=.552
Aiming 5	p=.125	p=.374	p=.264	p=.371

	PV Visual Space			
	Block CG1-CG3-CG1		Block CG1- IG-CG1	
	Session 2	Session3	Session 2	Session3
Aiming 1	p<.001	p<.001	p<.001	p<.001
Aiming 2	p<.05	p=.139	p<.05	p=.223
Aiming 3	p=.886	p=.213	p=.536	p<.05
Aiming 4	p=.452	p=.224	p=.953	p=.534
Aiming 5	p=.461	p=.07	p=.559	p=.510

	PV Motor Space			
	Block CG1-CG3-CG1		Block CG1- IG-CG1	
	Session 2	Session3	Session 2	Session3
Aiming 1	p<.001	p<.001	p<.001	p<.001
Aiming 2	p<.05	p=.139	p=.177	p=.223
Aiming 3	p=.954	p=.213	p=.438	p<.05
Aiming 4	p=.519	p=.224	p=.897	p=.534
Aiming 5	p=.531	p=.07	p=.703	p=.510

	Percentage Acceleration			
	Block CG1-CG3-CG1		Block CG1- IG-CG1	
	Session 2	Session3	Session 2	Session3
Aiming 1	p=.147	p<.001	p<.05	p<.05
Aiming 2	p=.239	p=.100	p=.478	p=.766
Aiming 3	p=.807	p=.244	p=.295	p=.818
Aiming 4	p=.853	p=.304	p=.413	p=.945
Aiming 5	p=.693	p=.922	p=.321	p=.555

Remaining distance after primary submovement

	Block CG1-CG3-CG1		Block CG1- IG-CG1	
	Session 2	Session3	Session 2	Session3
Aiming 1	p<.001	p<.001	p<.001	p<.001
Aiming 2	p<.05	p<.005	p<.001	p=.461
Aiming 3	p=.484	p<.005	p<.001	p=.123
Aiming 4	p=.114	p=.989	p<.05	p=.868
Aiming 5	p=.392	p=.197	p=.402	p=.997

Figure 1

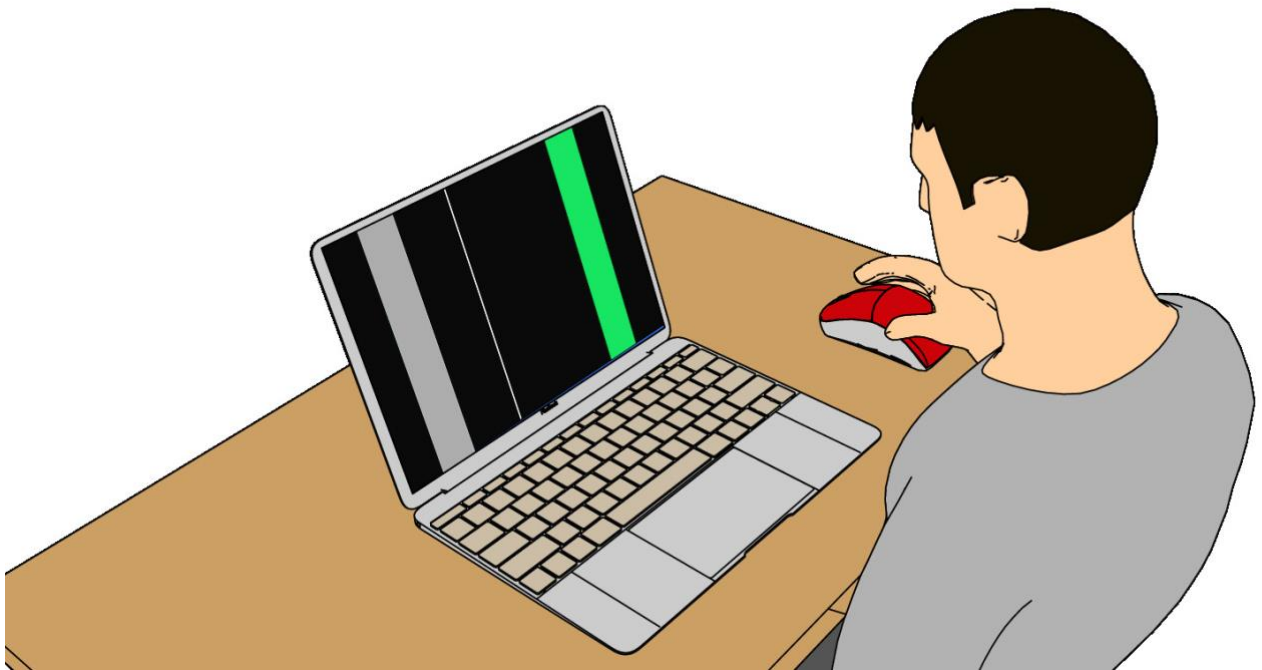


Figure 2

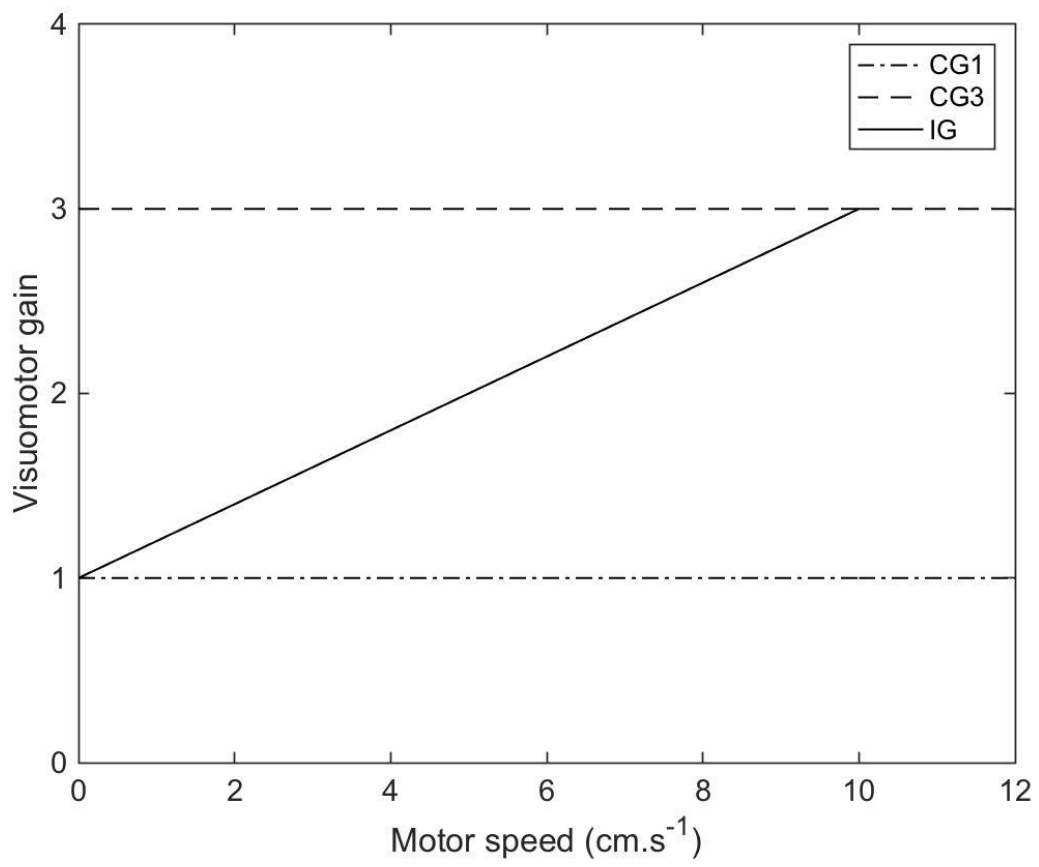


Figure 3

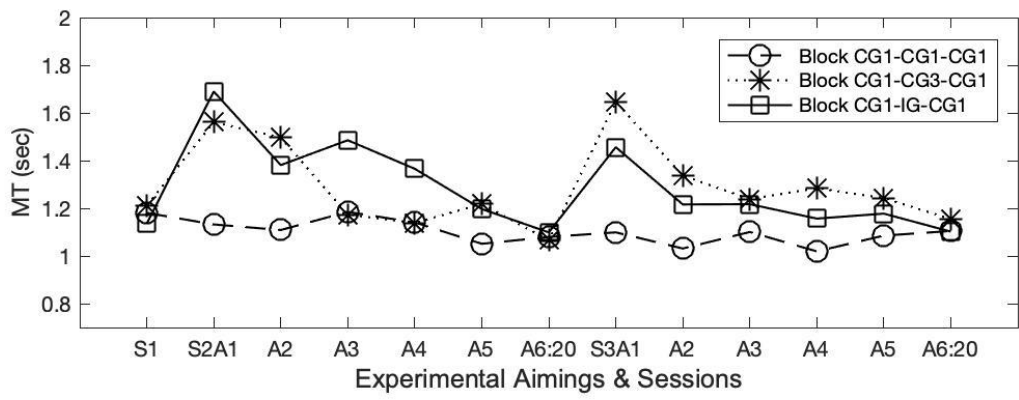
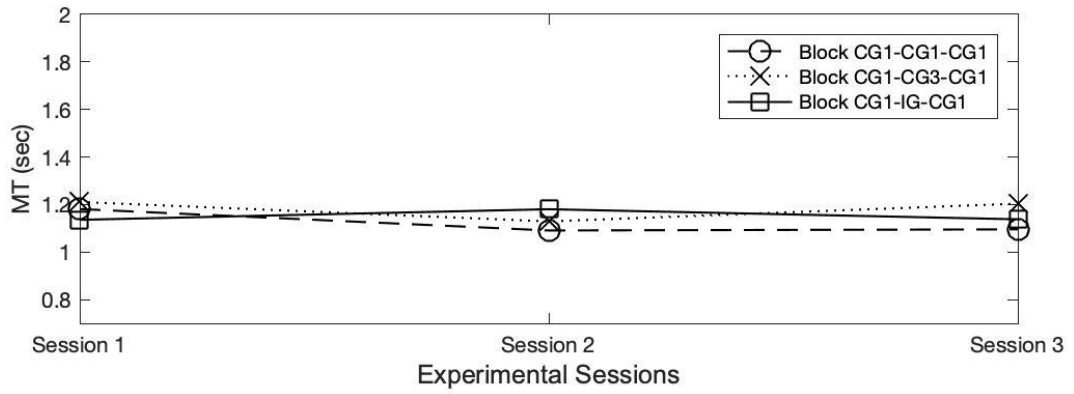


Figure 4

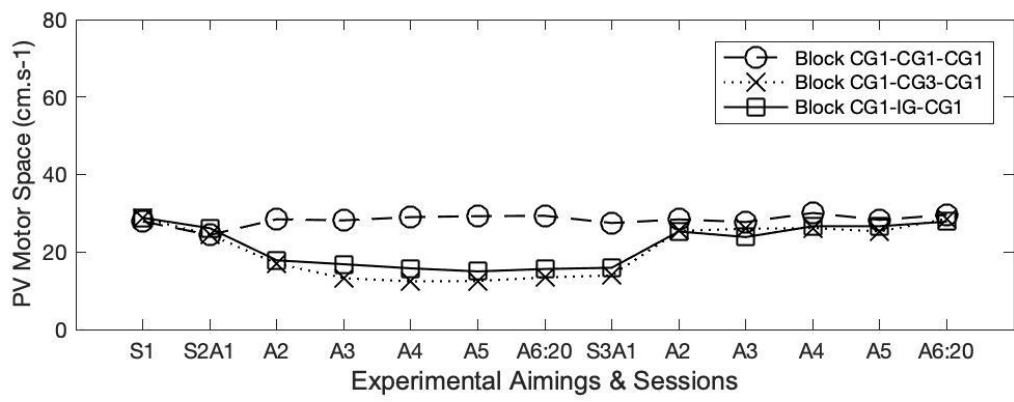
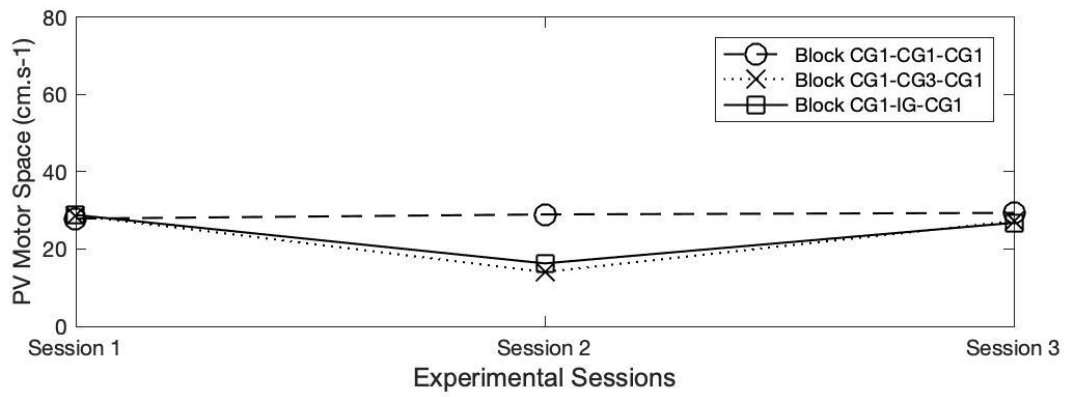


Figure 5

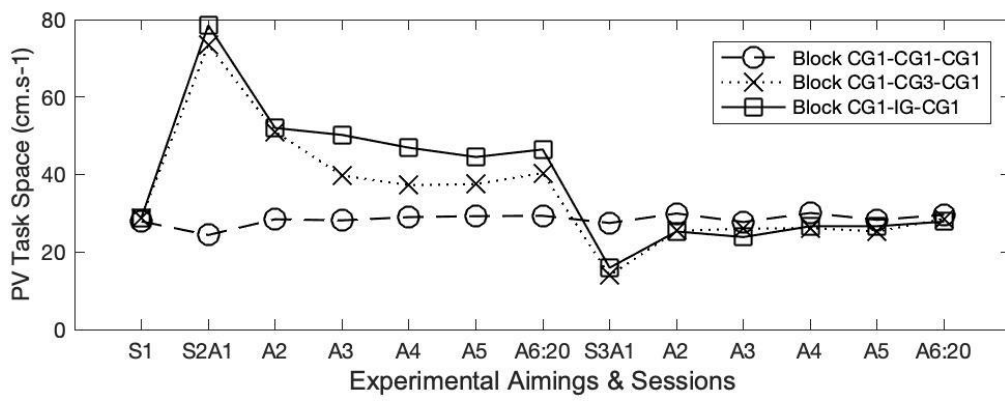
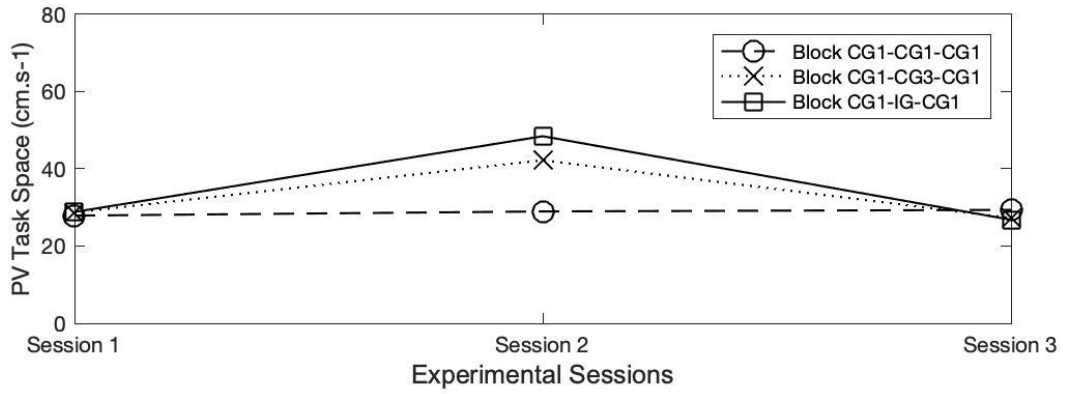


Figure 6

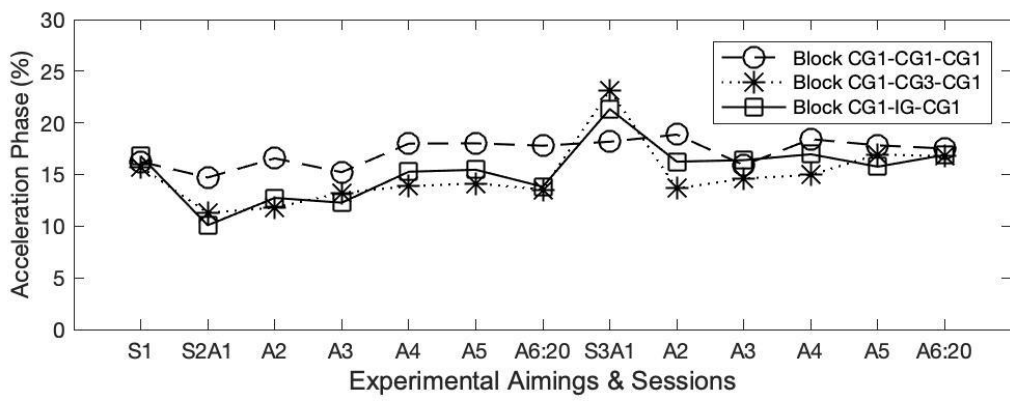
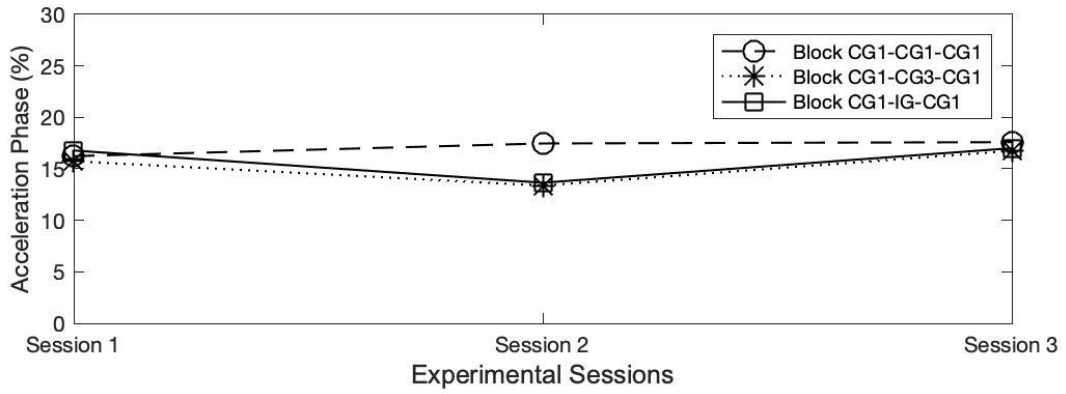


Figure 7

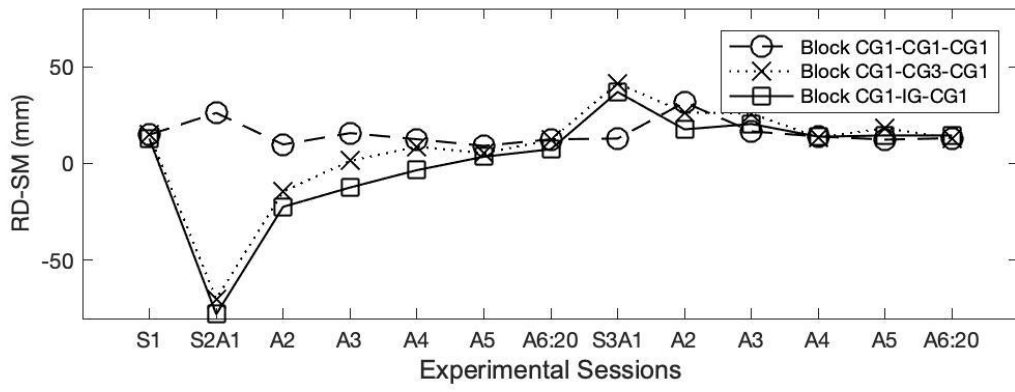
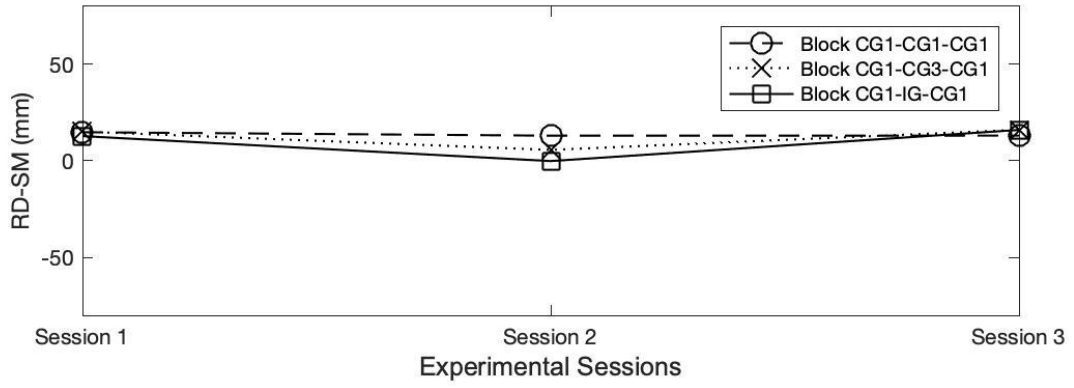


Table caption

Table 1 : P value Results from the repeated measures ANOVA with Helmert contrast performed on MT, PV Motor Space, PV Task Space, % Accel and RD-SM under Session 2 and 3 for the Block CG1-CG3-CG1 and Block CG1-IG-CG1. When reach the significant threshold i.e. $p < .05$, p-value was written in bold.

Figures captions

Figure 1 : Experimental setup. Participants have to move a cursor bar, (a thin and white line) corresponding to the mouse position from a gray starting target to the green target.

Figure 2 : Control Display (CD) gains as a function of motor speed. CG1: Constant Gain of 1; CG3 : Constant Gain of 3; IG : Increasing Gain.

Figure 3 : Upper panel : Average Movement Time (sec) for the three experimental blocks (Block CG1-CG1-CG1, Block CG1-CG3-CG1 and Block CG1-IG-CG1) and the three experimental sessions. Session 1 corresponds to the trials 1-20, Session 2 to the trials 21-40 and Session 3 to the trials 41-60 (Upper panel).

Lower panel : Average Movement Time (sec) for the three experimental blocks (Block CG1-CG1-CG1, Block CG1-CG3-CG1 and Block CG1-IG-CG1). For the Session 1 the average MT across the first 20 trials is represented. For the Sessions 2 and 3, average MT for aiming 1, 2, 3, 4, and 5 (notes as S2 A1 or S3 A1 for Session 2 and 3 respectively, A2, A3, A4, & A5) as well as the average across trials 6 to 20 (noted A6:20) are represented.

Figure 4 : Upper panel : Average Peak velocity (cm.s^{-1}) on Motor Space for the three experimental blocks (Block CG1-CG1-CG1, Block CG1-CG3-CG1 and Block CG1-IG-CG1) and the three experimental sessions. Session 1 corresponds to the trials 1-20, Session 2 to the trials 21-40 and Session 3 to the trials 41-60 (Upper panel).

Lower panel : Average Peak velocity on Motor Space (cm.s^{-1}) for the three experimental blocks (Block CG1-CG1-CG1, Block CG1-CG3-CG1 and Block CG1-IG-CG1). For the Session 1 the average PV across the first 20 trials is represented. For the Sessions 2 and 3, average PV for aiming 1, 2, 3, 4, and 5 (notes as S2 A1 or S3 A1 for Session 2 and 3 respectively, A2, A3, A4, & A5) as well as the average across trials 6 to 20 (noted A6:20) are represented.

Figure 5 : Upper panel : Average Peak velocity (cm.s^{-1}) on Task Space for the three experimental blocks (Block CG1-CG1-CG1, Block CG1-CG3-CG1 and Block CG1-IG-CG1) and the three experimental sessions. Session 1 corresponds to the trials 1-20, Session 2 to the trials 21-40 and Session 3 to the trials 41-60 (Upper panel).

Lower panel : Average Peak velocity on Motor Space (cm.s^{-1}) for the three experimental blocks (Block CG1-CG1-CG1, Block CG1-CG3-CG1 and Block CG1-IG-CG1). For the Session 1 the average PV across the first 20 trials is represented. For the Sessions 2 and 3, average PV for aiming 1, 2, 3, 4, and 5 (notes as S2 A1 or S3 A1 for Session 2 and 3 respectively, A2, A3, A4, & A5) as well as the average across trials 6 to 20 (noted A6:20) are represented.

Figure 6 : Upper panel : Percentage of Acceleration (%) for the three experimental blocks (Block CG1-CG1-CG1, Block CG1-CG3-CG1 and Block CG1-IG-CG1) and the three experimental sessions. Session 1 corresponds to the trials 1-20, Session 2 to the trials 21-40 and Session 3 to the trials 41-60 (Upper panel).

Lower panel : Percentage of Acceleration (%) for the three experimental blocks (Block CG1-CG1-CG1, Block CG1-CG3-CG1 and Block CG1-IG-CG1). For the Session 1 the average % Accel across the first 20 trials is represented. For the Sessions 2 and 3, average % Accel for aiming 1, 2, 3, 4, and 5 (notes as S2 A1 or S3 A1 for Session 2 and 3 respectively, A2, A3, A4, & A5) as well as the average across trials 6 to 20 (noted A6:20) are represented.

Figure 7 : Upper panel : Remaining distance to be covered after primary submovement (cm) (RD-SM) for the three experimental blocks (Block CG1-CG1-CG1, Block CG1-CG3-CG1 and Block CG1-IG-CG1) and the three experimental sessions. Session 1 corresponds to the trials 1-20, Session 2 to the trials 21-40 and Session 3 to the trials 41-60 (Upper panel).

Lower panel : Remaining distance to be covered after primary submovement (cm) (RD-SM) for the three experimental blocks (Block CG1-CG1-CG1, Block CG1-CG3-CG1 and Block CG1-IG-CG1). For the Session 1 the average % Accel across the first 20 trials is represented. For the Sessions 2 and 3, average % Accel for aiming 1, 2, 3, 4, and 5 (notes as S2 A1 or S3 A1 for Session 2 and 3 respectively, A2, A3, A4, & A5) as well as the average across trials 6 to 20 (noted A6:20) are represented. Note that positive values signify an undershoot and negative values signify an overshoot.