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Is visual-based, online control of manual-aiming movements disturbed when adapting to new movement dynamics?

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A R T I C L E I N F O

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A B S T R A C T

Previous research has shown that for goal-directed movements, online visual feedback is not necessary for the adaptation of movement planning to novel movement dynamics. In the present study, we wanted to put this proposition to a stringent test and determine whether the usually dominant role of online visual feedback in movement control is diminished when goal-directed movements are performed in a condition that modifies limb dynamics. Participants performed a video-aiming task while the center of mass of their forearm was experimentally displaced by a 1.5-kg mass attached laterally to its longitudinal axis. A cursor representing the position of the participant's hand was either visible or not visible during the acquisition phase. Then, in a transfer test, the participants performed the task without online visual feedback and either with or without the lateral mass. During the acquisition phase, the participants adapted to the new movement dynamics imposed by the added mass regardless of whether online visual feedback was available. An important new finding of the present study was the observation that the role usually played by online visual feedback in refining movement planning and ensuring control of the initial portion of goal-directed movements was suppressed during adaptation to novel movement dynamics. This resulted in an increase in the role played by visual feedback late in the movement to ensure endpoint accuracy.

1. Introduction

Goal-directed movements require that the central nervous system (CNS) perform a series of operations to transform information about one's hand and the target into appropriate motor commands. To ensure endpoint accuracy, the external forces exerted on one's hand must be taken into account when planning motor commands. For instance, when planning to pick up or move objects, one must anticipate the consequences of biomechanical factors affecting the behavior of the arm, forearm, and hand to adapt his/her motor commands accordingly. These adaptations become finely tuned with practice. Recent research suggests that adapting to external forces is learned by processing proprioceptive feedback with no significant input from visual feedback (Franklin et al., 2007; Krakauer, Ghilardi, & Ghez, 1999; Scheidt et al., 2005; Tong, Wolpert, & Flanagan, 2002).

For example, in Krakauer, Ghilardi, and Ghez (1999), participants were asked to perform serial, straight, and uncorrected out-and-back video-aiming movements between a fixed starting base and eight targets located around it while the center of mass of the their forearm was experimentally displaced by a 1.5-kg mass attached laterally to its longitudinal axis (see Fig. 1). Early in practice, the participants' initial movement trajectory deviated in this added mass condition (Krakauer, Ghilardi, & Ghez, 1999; Sainburg, 2002; Sainburg, Ghez, & Kalakanis, 1999; Wang & Sainburg, 2004), which suggests that feedforward predictions were insufficient to adapt movement planning to counteract for the added mass. However, during movement execution, proprioceptive feedback alone permitted the participants to correct their movement for the large initial deviation caused by the added mass (see also, Scheidt et al., 2005; Shadmehr & Mussa-Ivaldi, 1994). Moreover, through practice either with or without visual feedback of the ongoing movement, the initial direction bias resulting from the added mass decreased to the level of the control condition (i.e., no added mass), suggesting that vision did not contribute to this adaptation.

This is somewhat surprising in light of previous research (Abahnini, Proteau, & Temprado, 1997). For example, in Abahnini, Proteau, and Temprado (1997, exp. 2), participants were asked to perform hand-sweeping movements toward a series of targets located 41.5 cm away. They did not have to stop on the target; they were only required to be directionally accurate. Vision of their

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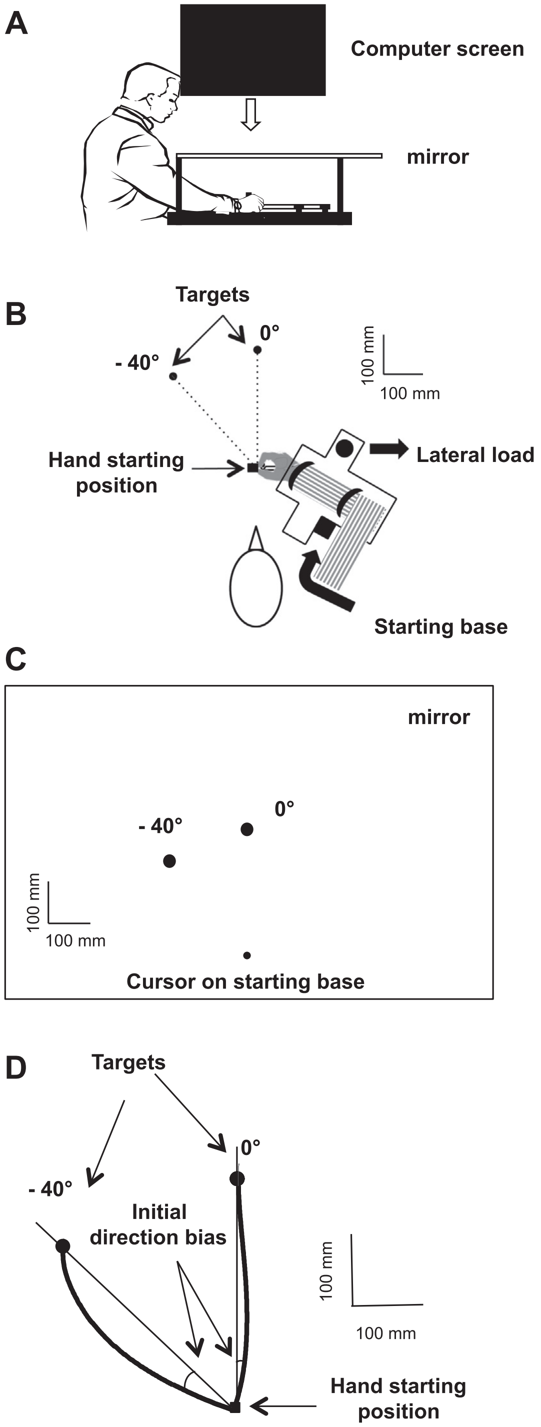

Fig. 1. (A) View of the apparatus. (B) The participant's forearm was attached to a sled on which a 1.5-kg mass could be secured 25 cm laterally to the forearm. (C) Information visible to the participant (only one target was visible for each trial). (D) Initial direction biases (see main text) were computed for each target.

hand was available throughout movement execution (normal vision), it was not visible at all (target-only), or it was restricted to a small area around the target (1 cm; terminal vision). Each trial was followed by verbal knowledge of results (KR) informing the participants of their direction error. The results showed that the terminal vision condition resulted in significantly lower direction error and variability than the target-only condition, indicating that seeing one's hand around the target even for a very brief period of time resulted in better movement planning than the target-only condition. This position was further supported by the results of a transfer test performed by all participants in the target-only condition during which they received no KR. In this transfer test, withdrawing vision and KR from the terminal vision group and the normal vision group resulted in a significant increase in direction error whereas withdrawing KR from the target-only group did not. Therefore, the results of the above study indicate that seeing the terminal accuracy of one's movement is an important source of visual information for movement planning, whereas the results of movement adaptation studies indicate that it is not (see also, Abahnini & Proteau, 1999; Bédard & Proteau, 2003, 2004; Proteau et al., 2000). Because of these contradictory findings, our first goal was to perform a stringent test of the hypothesis that vision does not contribute to or refine movement planning during adaptation to novel movement dynamic constraints.

Although there is no evidence that visual inputs contribute to movement planning or trajectory formation under novel dynamic constraints, in other force-field adaptation studies (Franklin et al., 2007; Scheidt et al., 2005), it was shown that when participants were given sufficient time to complete their movements using visual feedback for online control, performing the task under normal visual feedback resulted in straighter movements with better endpoint accuracy and lower endpoint variability than when online visual feedback was not permitted. By itself, this result is not surprising because it is well documented that the latter part of goal directed movements is under visual control (Carlton, 1981; see also Paillard, 1996 for a review of early work). However, what is not known is whether the putative dominant role played by proprioceptive feedback in movement planning when adapting to new constraints in movement dynamics modifies the dominant role usually played by visual feedback for online movement control. In the previous work from our laboratory that we have reviewed above, withdrawing visual feedback in the transfer test always resulted in a large and significant increase in endpoint error and variability. In fact, these increases were so large that endpoint error and variability for the participants who had trained in the normal vision condition became larger than that noted for the participants who trained in the target-only condition. This underlined the dominance of visual feedback for movement control. The second goal of the present study was to determine whether visual feedback remains as dominant in movement control when one adapts to new movement dynamics, as has been shown in our previous work. It could be that the hypothesized dominant role of proprioceptive feedback in movement planning and, thus, feedforward control processes (Desmurget & Grafton, 2000) is such that it diminishes the importance of visual feedback for movement control.

To reach our goals, participants aimed at visual targets while a 1.5-kg mass attached 25 cm laterally from the longitudinal axis of the forearm altered its inertial configuration (i.e., "loaded condition" Krakauer, Ghilardi, & Ghez, 1999; Sainburg, 2002; Sainburg, Ghez, & Kalakanis, 1999). This task required participants to adapt their movement planning and control to take into account the new limb dynamics imposed by the added load. The participants practiced this task in either a normal vision condition or a target-only condition (only the starting base and target were visible); each trial was followed with KR. Then, they all took part in two transfer tests conducted in the target-only condition, but with no KR. One transfer test was performed in the loaded condition whereas the other transfer test was performed in the no-load condition. Concerning our first goal, if visual feedback plays no role in movement planning when adapting to new dynamics constraints, then the direction bias created by the added load during practice and the after-effect resulting from the withdrawal of the added load in the transfer phase (Lackner & Dizio, 1994; Shadmehr & Mussa-Ivaldi, 1994) should not differ soon after movement initiation between the normal vision and the target-only groups. On the contrary, if vision plays a significant role in movement plan-