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Sensory Integration in the Learning of Aiming Toward "Self-Defined" Targets

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This study aimed at supporting the specificity of learning hypothesis, when aiming was based on internal cues, as directing the hand toward a "self-defined" target location. Participants practiced modest (20 trials) or intensive (720 trials) training with visual and proprioceptive information or proprioceptive information only. Pretests and posttests were performed in sensory conditions that did or did not match the training condition. Results showed that dynamic visual cues played a dominant role at the beginning of the task, and an intensive practice resulted in increased accuracy of kinesthetic information and efferent mechanisms of motor responses. These results have implications with regard to motor learning conceptions and training as a function of the task constraints.

Key words: motor learning, pointing, sensorimotor representation, specificity of practice

The role of afferent information in motor control and learning has been debated over the years. Some researchers have found that the importance of sensory information decreases as motor practice develops (Schmidt, 1975), whereas others found it to increase (Adams, Gopher, & Lintern, 1977; Elliott & Jaeger, 1988; Proteau, 1992). In the latter case, the role played by different sensory information in controlling ongoing movement can be investigated. A recent point of view has suggested that learning is specific to the sources of afferent information used during practice (Tremblay & Proteau, 1998). More specifically, it has been proposed that early in practice participants are able to determine the source(s) of afferent information that are more likely to ensure optimal accuracy. Participants process this source of information to the detriment of all others (Coull, Tremblay & Elliott, 2001; Proteau & Carnahan, 2001; Soucy & Proteau, 2001; Tremblay & Proteau, 1998). In the context of manual aiming toward a visual target, it has been shown that withdrawing visual information after its dominance has been established can result in the same increase of errors for either short or intensive practice. Thus, vision appears to be a more important source of feedback than proprioception, whatever the amount of practice. According to that view, however, withdrawing this source of afferent information before its dominance has been established would be less detrimental than doing so later (Proteau, 1992).

Although aiming toward visual targets is probably the most frequent movement in our repertoire, aiming can also be directed toward remembered target locations. In the present experiment, the specificity of motor learning hypothesis—previously tested almost exclusively with aiming based on visual cues—was tested with aiming toward "self-defined" targets. Neurophysiological studies have demonstrated that two separate neural systems may contribute to motor responses toward either visual or remembered target locations (Mushiake & Strick, 1993, 1995; Van Donkelaar, Stein, Passingham, & Miall, 1999). The cerebellothalamocortical system appears to be preferentially involved in controlling visually triggered movements, while the basal gangliothalamocortical system appears to be preferentially involved in controlling internally generated movements. Others studies have demonstrated that actions toward remembered targets (or pantomimed actions) are controlled differently from actions toward visual targets (or natural actions; Goodale, Jakobson, & Keillor, 1994; Milner & Goodale, 1995; Westwood, Chapman, & Roy, 2000). Researchers have proposed that the ventral visual processing stream mediates pantomimed actions, while natural actions depend on the dorsal stream. These suggestions called for investigation of the role of afferent

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information in learning and controlling movements toward remembered or self-defined targets. More particularly, it is important to examine the viability of the specificity of learning hypothesis, when aiming movements are based on internal cues, such as when the hand is directed toward a "self-defined" target location.

In the present experiment, learning the "self-defined" target locations occurred either with proprioceptive information (P condition) or with both dynamic visual and proprioceptive information (VP condition), with visual cues delivered by a fiber optic on a stylus. If the dynamic visual cues are the most efficient source of sensory information, as observed in aiming toward a visual target, then its withdrawal in a P condition posttest should induce a performance decrement. This decrement will be a function of the time needed to integrate vision into the movement representation developed during learning. If vision is quickly integrated, the performance decrement should appear after just a few practice trials (i.e., 20 in the present experiment). If more practice is needed to integrate vision, then performance decrement should appear only after an extensive practice (i.e., 720 trials). The question of adding dynamic visual information in a VP condition posttest after practice without it (P condition) is also of main interest. If visual cues constitute the most important source of information, their addition in a posttest should lead to the elaboration of a new sensorimotor representation that integrates both visual and proprioceptive information. Consequently, performance decrement should be observed, with a further acquisition phase necessary to develop the new intermodal representation.

Comparing pretest and posttest performances can provide relevant information about the role of the sensory context during practice (VP vs. P condition). If the sensory context remains identical throughout the pretest, practice session, and posttest, a significant improvement of movement accuracy can be expected. A VP condition should lead to improvement of the VP sensorimotor representation, and a P condition should lead to improvement of the P sensorimotor representation. When the sensory context during the practice session differs from the one used in pretest and posttest, we may ask whether positive transfer can occur (i.e., whether performance can improve from pretest to posttest VP or P when practice is conducted in the P or VP conditions, respectively).

Method

Participants

Thirty-six self-proclaimed right-handed students with normal or corrected-to-normal vision participated in the experiment. Their mean age was 23 years (*SD* = 3.2 years). All were naive to the experimental task and conditions. All participants participated on a volunteer basis and gave their informed consent prior the beginning the experiment.

Task and Apparatus

The experiment took place in a dark room. Participants performed an aiming task that consisted of moving a hand-held stylus from a predefined starting base to an aiming area of 304 x 304 mm, located 35 cm in front of them on a digitizing tablet surface (model UD1212R, Wacom Technology Corporation, Vancouver, Canada). This apparatus allowed movement to vary from 38.5 to 66.5 cm with a 22° variation to the left or to the right of the starting base.

For each participant, an aiming trial was composed of two successive phases. In the encoding phase, participants had to reach a self-chosen target position in the aiming area, maintain the position for about 1 s, and then return the stylus to the starting base. At the end of this encoding phase, in the recall phase, participants were asked to point as accurately as possible toward the memorized target position. Less than 1 s separated the end of the encoding phase and the beginning of the recall phase. Participants were required to vary the self-chosen target position in the aiming area from trial to trial and explore the entire aiming area in each experimental session. For both the encoding and recall phases, participants completed each aiming in a movement time of 1,000–1,300 ms, which allowed ongoing control to be based on afferent information. Moreover, this time bandwidth corresponded to the spontaneous movement time as defined in a pilot study. Movement time was defined as the delay between the moment the stylus left the starting base and the point it contacted the aiming area. The difference between the aiming positions recorded during the encoding and the recall phase was computed.

Procedure

Prior to the experiment, participants performed practice trials to become familiar with the movement time (MT) constraints. They received knowledge of results (KR) on MT concerning responses that were too long or too short. The familiarization session, performed in a VP or P condition without KR on spatial error, ended when participants performed six successful MT trials successively. Following this preliminary session, students participated in pretests under two feedback conditions. In the VP condition, a fiber optic on the stylus provided visual cues of ongoing movements. In the P condition, participants could rely only on proprioceptive feedback. Participants performed 15 trials under each of the two feedback conditions. The order of conditions was counterbalanced among participants.

After a 2-min break, participants were randomly divided into four experimental groups of 9 participants each. Two groups practiced the experimental task for 20 trials (modest practice), and the remaining two groups practiced for 720 trials (intensive practice). For each level of practice, one group of participants was assigned to the VP condition and one group to the P condition. Each acquisition trial was followed by verbal KR on the spatial deviation amplitude between the encoding and recall aiming.

One day after the end of practice[1], participants performed posttests (15 trials) under sensory conditions identical to those described in pretests (VP and P conditions). No KR on spatial accuracy was provided during the pre- and posttests. Whatever the experimental phases (pretest, acquisition, posttest), participants were informed of their movement time when it fell outside the prescribed range. Trials not completed within this time range were discarded and run again later (23% average across groups, experimental phases, and sensory conditions).

Data Analysis

Spatial localization of aiming (for the encoding and recall phases) and MT (in ms) were computer-recorded throughout the experiment. The radial error of aiming $(\text{horizontal errors}^2 + \text{vertical errors}^2)^{1/2}$, taking into account the difference between aiming positions (in mm) recorded during the encoding and recall phases, was computed and used as an index of spatial accuracy[2]. Statistical analyses were carried out on MT, within-participant variability on MT, and the radial error of aiming. Newman-Keuls tests were used for post hoc comparisons when necessary.

Results

Acquisition

We examined improved aiming accuracy as a function of feedback conditions (VP vs. P). For the first 20 practice trials, the dependent variables were submitted to a 2 Level of Practice (modest vs. intensive) x 2 Feedback Condition (VP vs. P) x 2 Block analysis of variance (ANOVA) with repeated measures on the last factor. The following 700 practice trials were grouped into 70 blocks of 10 trials. The dependent variables were submitted to a 2 Feedback Condition (VP vs. P) x 35 Block ANOVA. Every two blocks (even-numbered blocks) were retained for analysis. The statistical analyses on MT and within-participant MT variability revealed no significant main effects or interactions. MT averaged 1,143 ms (± 27.2 ms) across acquisition blocks and feedback conditions.

For the first 20 trials, the ANOVA performed on the radial error revealed no significant main effect or interaction. For the following 700 trials, the ANOVA revealed a significant Block x Feedback Condition interaction, $F(34, 544) = 1.51, p < .05$. As illustrated in Figure 1, the radial error decreased from Block 52 (i.e., after 520 trials of practice) under the VP condition only, while it remained stable in the P condition. At the end of practice (from Block 66), aiming accuracy was significantly better in the VP condition than in the P condition, $p < .05$.

End of Acquisition Versus Posttest Analyses

Only the results for the last 15 trials of the acquisition phases were retained as representative of participants' performance at the end of practice. The sensory condi-

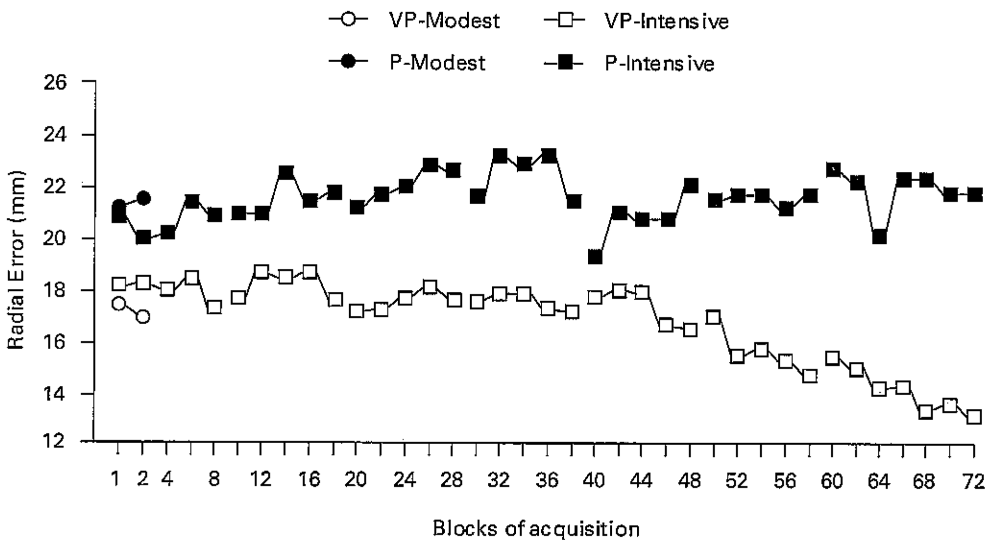

Figure 1. Radial error (in mm) as a function of level of practice (modest vs. intensive), feedback conditions (VP vs. P) and blocks of trials. Data points that are not connected by a solid line indicate breaks (10 min) in the experimental session.

tions used in the posttests provided relevant information as a function of the sensory conditions of practice. First, when the acquisition phase occurred in the VP condition, the posttest P assessed the effect of withdrawing visual information. Second, when practice occurred in the P condition, the posttest VP assessed the effect of adding visual information. For the VP and P conditions in acquisition, the VP and P posttests, respectively, revealed the effect of withdrawing KR only (control conditions). The results section, therefore, is divided into two parts according to the sensory conditions available during acquisition (VP or P condition). The dependent variables were submitted to a 2 Level of Practice (modest vs. intensive) x 3 Experimental Phase (late acquisition, posttest VP, posttest P) ANOVA with repeated measures on the last factor.

Withdrawal of Visual Information in Posttest

The ANOVA on MT revealed a significant main effect of experimental phase, $F(2, 32) = 3.98$, $p < .05$. MT was shorter in acquisition (1,137 ms) than in the posttest VP (1,158 ms), while there was no significant difference in the posttest P (1,143 ms). The within-participant MT variability was higher in acquisition (58 ms) than in the posttest VP (45 ms) and P (49 ms), $F(2, 32) = 11.24$, $p < .001$.

The ANOVA computed on the radial error revealed significant main effects for the level of practice, $F(1, 16) = 6.41$, $p < .05$, and experimental phase, $F(2, 32) = 10.25$, $p < .001$, as well as a significant Level of Practice x Experimental Phase interaction, $F(2, 32) = 6.43$, $p < .01$. Figure 2 (left graph) illustrates the breakdown of the interaction. The radial error remained stable across the experimental phases for intensive practice. Conversely, the radial error significantly increased in the posttest P after a modest practice, while performance did not vary in the posttest VP.

Addition of Visual Information in Posttest

The ANOVA revealed that MT was shorter in the modest acquisition condition (1,136 ms) than the intensive one (1,154 ms), $F(1, 16) = 5.32$, $p < .05$. There were no significant main effects or interactions for the within-participant MT variability, $p > .29$. The ANOVA on the radial error revealed no main effect or interaction, $p > .12$. Spatial accuracy remained stable across the experimental phase, regardless of practice level (19.36 mm average; see Figure 2, right graph).

Pretest Versus Posttest Analyses

Data obtained in the pre- and posttests were compared to examine whether different practice levels under the VP and P conditions had specific effects on the accuracy of the visuoproprioceptive (VP) and proprioceptive (P) reference systems. The results are divided into two parts, according to the sensory conditions used in the acquisition phase (VP condition or P condition). The dependent variables were analyzed by a 2 Level of Practice (modest vs. intensive) x 2 Experimental Phase (pretest vs. posttest) x 2 Feedback Condition (VP vs. P) ANOVA with repeated measures on the last two factors.

Effect of VP Learning on the Visuoproprioceptive and Proprioceptive Reference Systems

The statistical analyses on MT revealed no significant main effects or interactions, $p > .05$. For within-participant MT variability, significant main effects of practice level, $F(1, 16) = 7.75$, $p < .05$, and experimental phase, $F(1, 16) = 4.98$, $p < .05$, were observed. The within-participant MT variability was higher in the modest practice condition (53 ms) than in the intensive condition

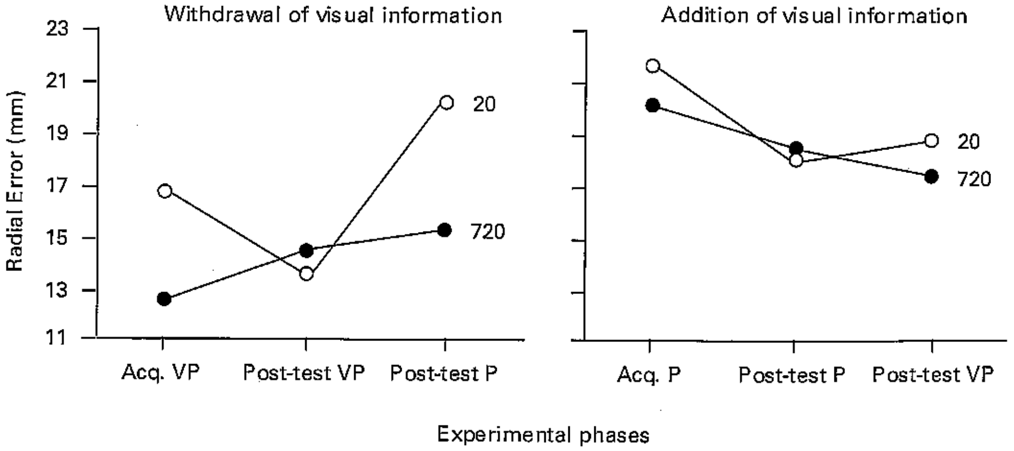

Figure 2. Radial error (mm) as a function of practice level (modest vs. intensive) and experimental phases (end of acquisition, posttest VP, posttest P). The left graph illustrates performance obtained when participants practiced in the VP condition. The right graph illustrates performance obtained when participants practiced in the P condition.

(47 ms) and higher in pretests (52 ms) compared to posttests (47 ms).

The ANOVA computed on the radial error revealed significant main effects of experimental phase, *F*(1, 16) = 18.01, $p < .001$, and feedback condition, *F*(1, 16) = 31.74, $p < .001$. Significant interactions were also found: Level of Practice x Feedback Condition, *F*(1, 16) = 4.72, $p < .05$, and Level of Practice x Experimental Phase x Feedback Condition, *F*(1, 16) = 9.60, $p < .01$. As illustrated in Figure 3 (upper graph), the breakdown of the latter interaction indicated the radial error was higher for the pretest in the P condition than the VP condition ($p < .01$). However, after 720 trials, participants were as efficient in the P condition as they were in the VP condition.

Effect of P Learning on the Visuoproprioceptive and Proprioceptive Reference Systems

The ANOVA on MT revealed significant main effects of level of practice, *F*(1, 16) = 5.74, $p < .05$, and feedback condition, *F*(1, 16) = 6.40, $p < .05$. MT was shorter in the modest practice condition (1,137 ms) than the intensive one (1,152 ms) and shorter in the P condition (1,137 ms) compared to the VP condition (1,153 ms). Within-participant MT variability was higher in the modest practice (56 ms) than the intensive practice (51 ms), *F*(1, 16) = 7.90, $p < .05$. The ANOVA computed on the radial error revealed no significant main effects or interactions, $p > .21$. Spatial accuracy remained stable across the experimental phase regardless of practice level, (18.84 mm average; see Figure 3, lower graph).

Discussion

There is an abundant literature on the specificity effect of learning when aiming toward visual targets (Coull et al., 2001; Elliott & Jaeger, 1988; Ivens & Marteniuk, 1997; Proteau, 1992). By contrast, the characteristics of the sensorimotor integration in aiming toward visually and proprioceptively encoded targets have not been investigated. The main objective of the present experiment was to determine if the specificity of learning hypothesis held when aiming movements were based on internal cues, as in the present experiment, with the participant-directing

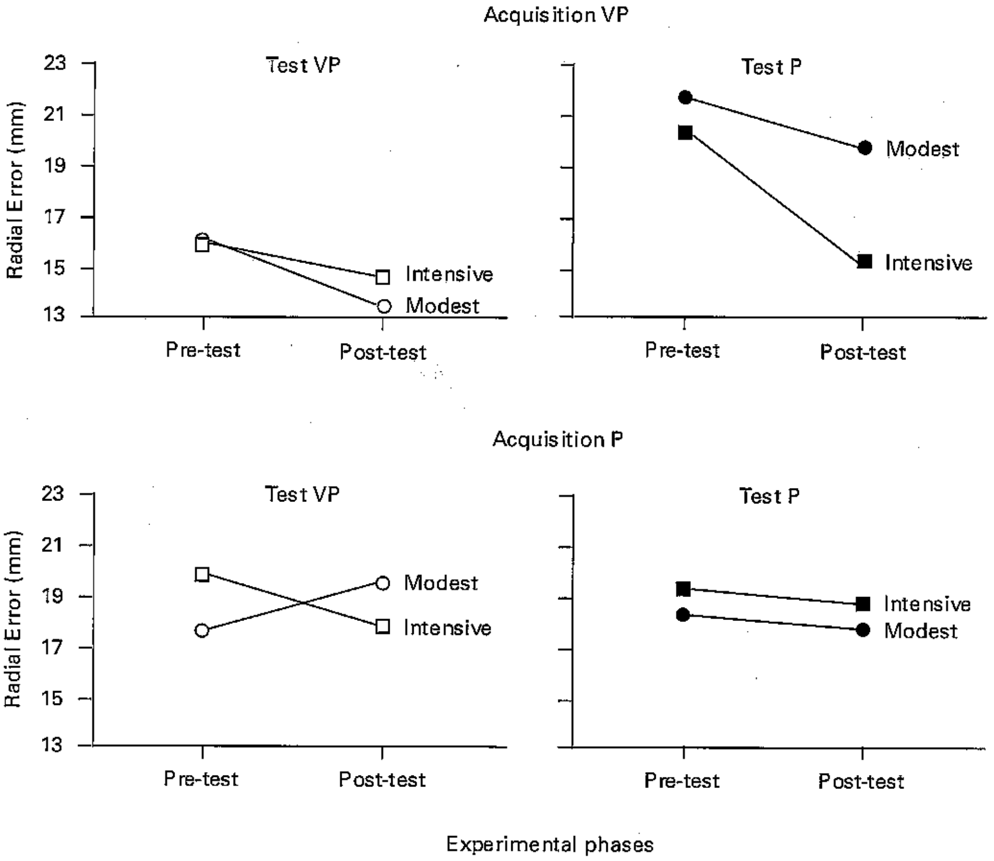

Figure 3. Radial error (mm) as a function of level of practice (modest vs. intensive), test conditions (VP vs. P) and experimental phases (pre- vs. posttest). The upper graph illustrates performance obtained when participants practiced in the VP condition; the lower graph illustrates performance obtained when participants practiced in the P condition.

the hand to a "self-defined" target. In accordance with the specificity hypothesis, we predicted that the dominance of visual information, once established, should be evident through (a) the performance decrement appearing in a posttest (P condition), and (b) the improvement of spatial accuracy from pretest to posttest, appearing essentially when aiming was performed in a feedback condition that matched the training condition, provided visual cues were available (VP condition). We also predicted that the dominance of vision in motor control should manifest the performance decrement when visual cues were added in posttest (VP condition), which were not available during acquisition (P condition).

The main results showed that initial performance, as indicated by the pretest performance, was more accurate in the VP condition than in the P condition. Moreover, the acquisition session analysis revealed that more practice under the VP condition led to a higher performance level. These results supported the idea that having dynamic visual feedback during movement production was beneficial. Contrary to our expectations, the comparison between the posttest data and those obtained at the end of the acquisition phases (i.e., after 20 and 720 trials) showed that: (a) removing the visual information had a deteriorating effect early in practice, but did not modify participants' performance accuracy after intensive practice; (b) adding the visual information after modest or intensive practice in a P condition did not induce performance decrement. Unlike the results reported for aiming toward visually defined targets (Coull et al., 2001; Elliott & Jaeger, 1988; Proteau, 1992; Proteau & Carnahan, 2001; Soucy & Proteau, 2001; Tremblay & Proteau, 1998), our data indicated that motor learning for "self-defined" targets did not result in more efficient use of visual feedback for movement accuracy. Moreover, whatever the level of practice, adding visual information in the posttest did not necessitate a new sensorimotor representation integrating visual and proprioceptive afferent information. These results contradict the initial intersensory integration explanation of the specificity of practice (Proteau, 1992; Proteau, Marteniuk, & Lévesque, 1992). Thus, it appears that not all sensory feedback received while performing aiming movements toward "self-defined" targets found their way into the sensorimotor representation.

In the present experiment, higher performance accuracy was observed in the VP condition than the P condition at the end of the intensive acquisition phase. However, vision cannot be considered the dominant source of information when practice increases; the comparison between posttest data and those obtained at the end of the intensive acquisition phase did not show a performance accuracy decrement when vision was removed. The dominance of vision, when observed, only appeared in the early stages of practice. This result raises important questions regarding the role of vision or, more generally, of afferent information during practice aiming toward "self-defined" target locations. Motor learning could evolve either from visual to proprioceptive control, as previously reported (Fischman & Schneider, 1985; Fleishman & Rich, 1963), or from a closed- to open-loop control (Schmidt, 1975). The results of the present study do not allow one to conclude the dominance of proprioception as practice increases. No learning effects appeared when practice occurred in the P condition, and more practice in the VP condition led to a higher performance level than in the P condition. When the participant aimed toward "self-defined" targets, kinesthetic information from the arm and motor commands used in the encoding phase were available. Consequently, it may be possible that, in the present task, motor learning resulted from better practice specification for motor commands or both motor commands and on-line proprioceptive control, although participants had enough time to make ongoing corrections. Additional studies are, therefore, necessary to distinguish the contribution of kinesthetic information and central efferent mechanisms in the learning and controlling aiming toward remembered target locations.

Comparisons between pre- and posttest trials provided information on the effect of the practice condition (VP or P) on motor performance. The main results showed the proprioceptive system of reference significantly improved after intensive practice under the VP condition, although the sensory context of the test differed from that available during practice. After 720 practice trials, the participants were as efficient in the P test as in the VP test. On the other hand, performance did not change in the VP and the P posttests, when practice occurred in the P condition. The increase of accuracy of the proprioceptive system of reference, observed only after practice in the VP condition, suggests vision played a potent role in motor control. Having visual information when aiming toward "self-defined" targets could benefit developing accurate efferent mechanisms and online proprioceptive control, which would probably necessitate a constant updating of the proprioceptive system. The absence of learning effect reported for the visuoproprioceptive system of reference (VP test) after practice in the VP condition could be due to a floor effect, with the radial error being relatively small in the pretest.

In the present experiment, the quality of the stored representation for target location could explain that vision did not appear to be the dominant source of afferent information with practice to ensure optimal aiming accuracy. Some studies have shown that the memory for target location differs, depending on the modality in which the information is encoded and stored. In general, the results have shown that memory for target location based on kinesthetic information does not decay over a 10-s delay (Chapman, Heath, Westwood, & Roy,

2001) but does decay over brief delays (< 500 ms), when target location is based on visual information (Elliott & Madalena, 1987; Westwood, Heath, & Roy, 2001). In this experiment, it is possible that the stability of the memory representation for target location kinesthetically leads participants to progressively extract proprioceptive cues or efferent mechanisms as a more efficient source of information for accurate aiming than vision.

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Notes

1. A 24-hr delay has been used to ensure that what is learned during the acquisition phase influences motor performance in a relatively permanent way.
2. Statistical analyses computed on both extent and directional root mean squared error were similar to those reported for the radial error.

Authors' Notes

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