

Is There "Feedback" During Visual Imagery? Evidence From a Specificity of Practice Paradigm

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Abstract The specificity of practice hypothesis predicts the development of a sensorimotor representation specific to the afferent feedback available during skill acquisition (Proteau, 1992; Proteau, Marteniuk, Girouard, & Dugas, 1987). In the present investigation, we used the specificity of practice hypothesis to test whether skill acquisition through visual imagery would lead to the development of a sensory-specific movement representation similar to one resulting from actual practice. To accomplish this objective, participants practiced walking a 12-m linear path in one of three practice conditions, full-vision (FV), no-vision (NV), or visual imagery (VI), for either 10 or 100 trials. Knowledge of spatial and/or temporal results (KR) was provided to participants following each trial during this phase. Following acquisition, participants completed 10 NV trials without KR. An analysis of root-mean-squared-error (RMSE) indicated NV participants were more accurate than both FV and VI participants in the transfer condition. We believe the equivalence in transfer RMSE between FV and VI suggests that there are similarities between the movement representations attained by FV and VI practice.

Skilled motor performance is controlled by a combination of central planning and online control mechanisms (Abbs, Gracco, & Cole, 1984; Meyer, Abrams, Kornblum, Wright, & Smith, 1988; Schmidt, 1975; van der Meulen, Gooskens, Denier van der Gon, Gielen, & Wilhem, 1990; Woodworth, 1899). There is, however, continued debate as to the degree to which feedback is used by each of these mechanisms during skill acquisition. One view emphasizes the use of afferent feedback during the early stages of motor skill learning and proposes that with practice there is a gradual diminution of online, feedback-based control (Pew, 1966; Schmidt, 1975). In contrast to this view, Proteau and co-workers (e.g., Proteau, 1992; Proteau, Marteniuk, Girouard, & Dugas, 1987) proposed the specificity of practice hypothesis, which states that: 1) learning is specific to the sources of afferent information available during practice and 2) reliance on the afferent resources available during practice increases as a function of practice

time. Although Proteau and colleagues acknowledge that central planning changes occur with practice, they argue that the majority of skill refinement reflects enhancement of feedback-based error detection and correction mechanisms.

The specificity of practice hypothesis was developed from Proteau et al.'s (1987) original work examining the accuracy of aiming movements performed for brief (200 trials) or extended (2,000 trials) practice in full-vision (FV) or target only (TO) visual conditions. Following acquisition, all four groups were transferred to the TO condition. The results of the study demonstrated that FV practice led to decreased target accuracy in the transfer condition relative to the group that practiced in the TO condition. Further, the performance decrement was found to be more profound for the prolonged FV as opposed to the brief FV practice group. These results reflected the development of a sensory-specific movement representation with practice in addition to demonstrating that the withdrawal of sensory information previously available during acquisition disrupted the performers' ability to accurately point to the target object. This finding is a typical prediction of the specificity hypothesis; due to the development of a sensory-specific movement representation during skill acquisition, a participant's skill in a transfer condition will be determined by the similarity of the feedback between the acquisition and transfer conditions. In other words, when sensory conditions available during practice do not match the sensory conditions available during a (similar) transfer task, there will be a significant reduction in performance. Moreover, the specificity hypothesis predicts an increased reliance upon a specific form of afferent feedback as a function of the time spent in acquisition.

Subsequent work has examined the applicability of the specificity hypothesis to gross motor tasks (i.e., walking, weightlifting, balance beam, catching). In a study particularly relevant to the current research, Proteau, Tremblay, and DeJaeger (1998) tested the specificity of practice hypothesis in the context of a precision walking task. Participants were divided into either FV or no-vision (NV) practice groups and walked

a 20-m straight line path in either a brief (20 trials) or extended practice condition (100 trials). Following acquisition, all participants were transferred to a 20-trial NV condition without knowledge of results (KR). Analysis of root mean squared error (RMSE) in the transfer condition revealed that the extended practice FV group had a larger RMSE than any of the other practice groups. These data support the specificity position as the pattern of results was similar to previous manual aiming studies (e.g., Elliott, Lyons, & Dyson, 1997; Proteau, 1992; Proteau et al., 1987). Consistent with the prediction that reliance upon a particular source of afferent feedback would increase as a function of practice, Proteau and colleagues found the extended FV group was less accurate in the transfer phase relative to the brief FV group. However, contrary to the specificity hypothesis, no significant difference was found in transfer performance between the brief and extended practice NV groups. This lack of difference in transfer performance due to practice length has also been noted in other studies examining the specificity hypothesis in gross motor tasks (Robertson, Collins, Elliott, & Starkes, 1994; Tremblay & Proteau, 1998).

Visual Imagery and Skill Acquisition

Practice through visual imagery has been shown to be beneficial to the acquisition and performance of motor skills (Lejeune, Decker, & Sanchez, 1994; Meacci & Pastore, 1995; Mendoza & Wichman, 1978; Noel, 1980; Pascual-Leone et al., 1995; Wiegardt, 1998; Yue & Cole, 1992). How visual imagery facilitates skill performance, however, is still a matter of some debate (Jeannerod, 1994). One hypothesis is that visual imagery and actual skill performance activate similar cortical regions, an idea supported by both positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) research. For example, Roland, Larsen, Lassen, and Skinhoj (1980) found that overt physical performance of a motor sequencing task as well as mental rehearsal of that same task resulted in similar activation of supplementary motor area (SMA): a cortical region thought to play an important role in sequential motor actions (e.g., van Mier, Perlmutter, & Petersen, 2004). More recently, Miyai and colleagues (2001) used a combination of near-infrared spectroscopic topography and fMRI to examine cortical activation during human gait. Their findings also showed activation of SMA during the actual and imagined practice conditions.

Further similarities exist between actual practice and imagery when one examines vision in these conditions. Research by Laeng and Teodorescu (2002) demonstrated similarities between ocular scanning during actual vision and imagined vision of a presented image. In

this study, participants first visually scanned an image and then were subsequently asked to imagine viewing the same image. The data from this study indicated that visual scanning during actual vision of the visual scene was significantly correlated with visual scanning of the imagined scene. These results demonstrated that gaze paths during visual imagery mirrored those during actual perception of a visual scene, suggesting that during visual imagery the participant is actively "looking" at the "imagined" visual environment. This finding is supported by Ganis, Thompson, and Kosslyn (2004) who used fMRI to demonstrate similar frontal and parietal cortical activation between actual and imagined vision of a visual scene.

The emulation theory of representation (Grush, 2004) provides a model that accounts for the similarities between actual and imagined practice. Essentially, emulation theory proposes that in addition to generating motor output during movement, the brain activates neural circuits that act as representations of the movement process and environment. An efference copy of the movement allows the representation to work in parallel with online systems. The emulative neural representations can be utilized in a forward manner, allowing anticipation of future feedback and its consequences. Alternatively, the emulative representation can be used to evaluate and enhance existing feedback. In terms of motor imagery, Grush proposes that the neural circuitry of an emulative neural representation for a movement can be executed without motor output to produce imagery. Conversely, practice with imagery can generate or enhance an existing emulative neural representation. This idea can also be extended to visual imagery, where the emulative representations are activated by imagined visual processing. As such, similarities between actual and imagined practice can be explained in terms of the emulative model as these practice conditions share common emulative representations.

In the present experiment, we utilized the specificity of practice hypothesis to test whether practice with visual imagery would lead to the development of a similar movement representation as that acquired during actual practice. To accomplish this, participants practiced walking a 12-m linear path in either full-vision (FV), no-vision (NV), or visual imagery (VI) conditions for either 10 (brief) or 100 (extended) trials. Following acquisition, all participants performed 10 transfer trials in the NV condition without KR. In line with the specificity of practice hypothesis and our prediction that FV and VI participants would employ similar movement representations, we predicted that NV participants would be more accurate than FV and VI participants in the transfer condition. Although there is

some contradictory evidence as to whether reliance upon a specific source of afferent feedback increases as a function of practice (i.e., Proteau et al., 1998), we predicted that the extended practice NV group would be more accurate than the brief practice NV group and that the extended practice FV and VI groups would be less accurate than their brief practice counterparts in the transfer condition.

Methods

Participants

Forty-two individuals ranging in age from 18 to 32 years participated in this experiment. All had normal or corrected-to-normal vision, normal locomotor skills, and none had previous visual imagery training. All participants provided informed consent in accordance with human subjects guidelines established by the University of Victoria.

Task and Apparatus

This experiment was undertaken in a 45 m by 20 m by 6 m testing room. Participants, who all wore shoes during the experiment, walked along a 12-m linear path (2.5 cm wide) affixed to the floor with spiking tape. Movement time (MT) was measured by the experimenter or participant (see Procedure) with a hand-held chronometer and the number of steps to complete the walking task was also recorded by the experimenter. The final position of the participants relative to the end of the spiking tape was recorded to compute root-mean-squared-error¹ in the primary (amplitude error: over or undershooting of the endpoint) and secondary (directional error: deviations to the left or right of the endpoint) movement directions. During no-vision (NV) trials, participants wore a pair of blacked-out goggles to occlude vision. For all trials, participants listened to a selection of classical music (Ennio Morricone, "The Mission") to lessen auditory feedback and disrupt possible step-counting strategies.

Procedure

Participants completed 10 (Brief: B) or 100 (Extended: E) acquisition trials in full-vision (FV), no-vision (NV), or visual imagery (VI) conditions yielding six experimental groups: BFV, BNV, BVI, EFV, ENV, and

EVI. Participants assigned to the FV groups practiced the walking task under normal visual conditions. Participants in NV groups practiced the task while wearing the blacked-out goggles; however, they were instructed to lift the goggles before and after each trial in order to plan their movement and then to evaluate their performance (i.e., knowledge of results based on their end position in relation to the target line). Participants in the VI groups used a combination of FV and VI (1:9 ratio, 1 FV trial for every 9 VI trials) during acquisition. For instance, participants in the BVI group walked the path with FV for their first acquisition trial. Following this FV trial, nine trials were performed where the participant did not walk the path, but instead imagined walking the path while standing at the starting point. Similarly, the EVI group performed 100 acquisition trials in a similar manner (10 blocks of 10 trials conducted in the same fashion as the BVI group). The ratio of visual imagery to physical practice was based on previous work showing that minimal physical exposure to a task is required in order to adopt a "mental map" of the action. Participants in VI conditions were instructed to see themselves walking the path through their own eyes, using their previous FV trial as a basis for the imagery. Such internal imagery was used to simulate the sensory consequences experienced by the FV practice group. Participants timed themselves during VI trials using a hand-held chronometer (i.e., starting and stopping the chronometer when they initiated and completed an imagined trial) and were given feedback by the experimenter relating the duration of the VI trial to the duration of their most recent FV trial (i.e., "You imagined walking too fast/slow" or "That was good"). A VI trial time was considered acceptable when it was within plus or minus two seconds of the most recent FV trial. Following the last acquisition trial, participants in all groups performed a transfer test that consisted of 10 trials performed in the NV condition. Unlike the NV trials in acquisition, participants did not receive any visual or spatial KR as participants were guided back to the start position along a random path by an experimenter. Dependent variables used in this study included MT, the number of steps taken (ST), and root-mean-squared-error (RMSE: the square root of the sum of constant error squared and variable error squared) in the primary (amplitude error) and secondary (directional error) movement directions.

Results

Data from two subjects differed from their respective group means by more than two standard deviations and therefore were removed from further analysis as outliers.

¹ A preliminary analysis of the data in terms of constant (CE) and variable error (VE) revealed similar results between these two measures. As such (and in line with previous research examining the specificity of practice hypothesis, i.e., Proteau et al., 1998), these two dependent measures were combined and analyzed as root-mean-squared-error (RMSE), $RMSE = \sqrt{CE^2 + VE^2}$.

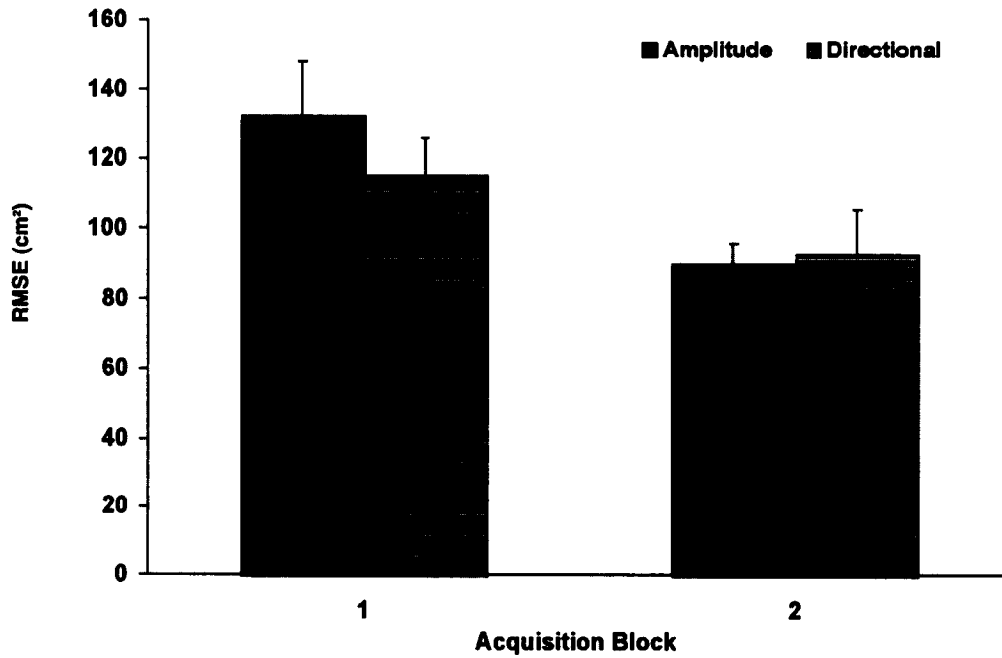


Figure 1a. Acquisition and directional RMSE for brief practice no-vision participants as a function of acquisition block. Error bars represent the Standard Error of the Mean.

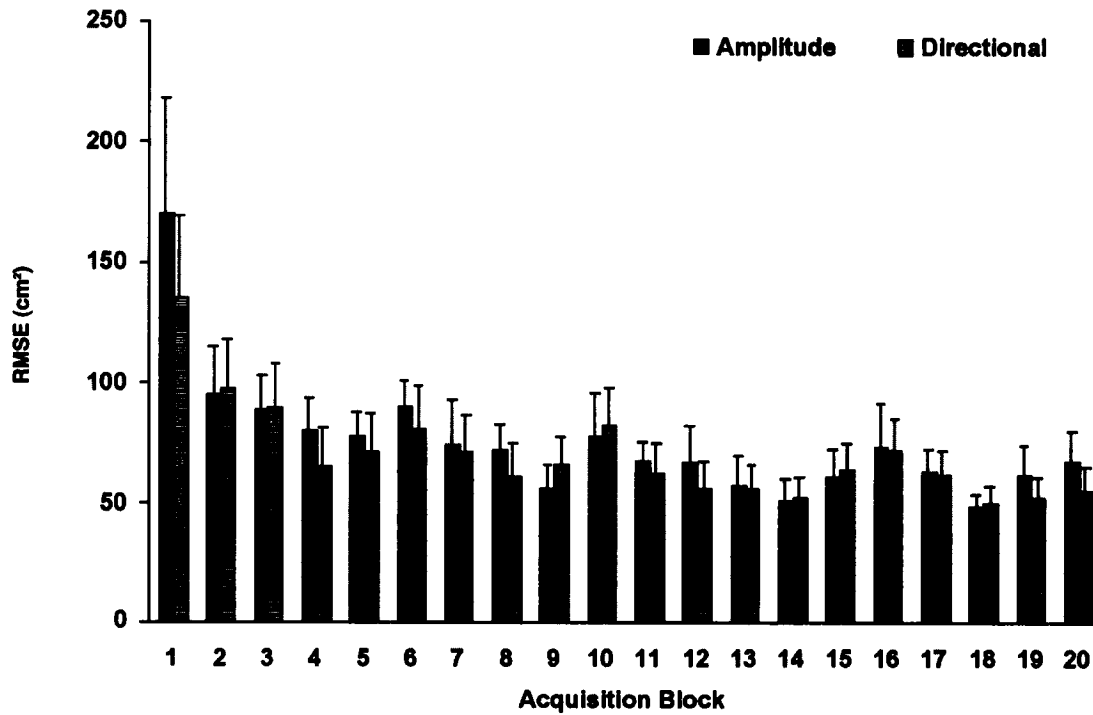


Figure 1b. Acquisition and directional RMSE for extended practice no-vision participants as a function of acquisition block. Error bars represent the Standard Error of the Mean.

TABLE 1
Mean Number of Steps Taken for the Brief and Extended Practice Groups in Both the Acquisition and Transfer Conditions

Practice Length	Practice Condition		
	Full-Vision	No-Vision	Visual Imagery
	Acquisition		
Brief	20.8 (1.3)	21.2 (1.2)	NA
Extended	20.6 (0.4)	20.0 (0.6)	NA
	Transfer		
Brief	21.5 (1.7)	21.0 (1.3)	22.0 (0.7)
Extended	20.2 (0.4)	20.7 (0.6)	20.2 (1.1)

Note. The standard error of the mean is reported in parentheses.

TABLE 2
Mean Movement Time(s) for the Brief and Extended Practice Groups in Both the Acquisition and Transfer Conditions

Practice Length	Practice Condition		
	Full-Vision	No-Vision	Visual Imagery
	Acquisition		
Brief	11.7 (0.5)	12.1 (0.9)	12.4 (0.5)
Extended	10.7 (0.4)	11.5 (0.6)	11.5 (1.4)
	Transfer		
Brief	12.8 (0.9)	12.3 (0.9)	13.3 (1.7)
Extended	11.5 (0.3)	11.7 (0.4)	11.5 (1.3)

Note. The standard error of the mean is reported in parentheses.

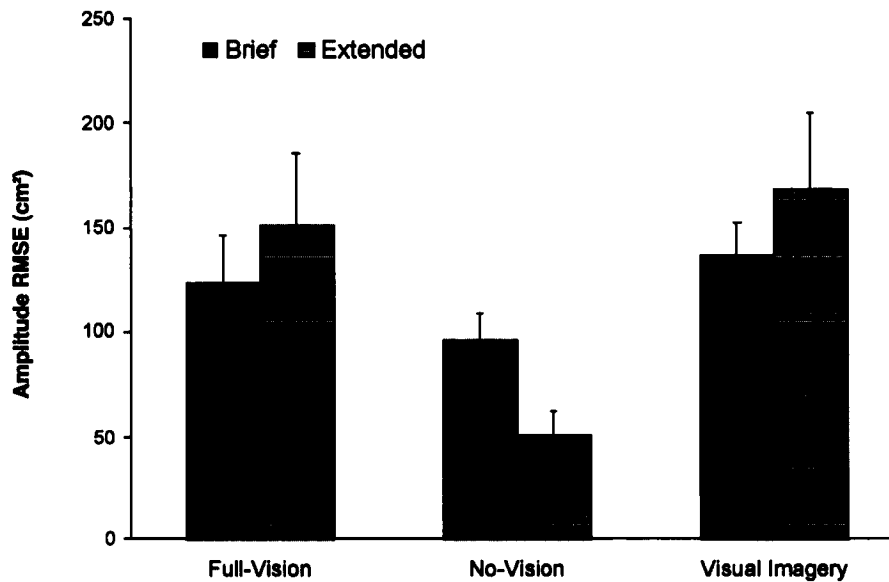


Figure 2a. Amplitude RMSE as a function of practice condition and practice length in the transfer condition. Error bars represent the Standard Error of the Mean.

Acquisition

Spatial accuracy. For RMSE, only data for the NV practice groups were examined as the practice conditions associated with FV and VI conditions contained no observable errors. To examine the acquisition phase of the experiment, the brief practice trials were collapsed into two practice blocks of five trials, and the extended practice trials were collapsed into 20 practice blocks of five trials. A paired samples t-test was applied to the RMSE for the NV brief practice group and a 20 (practice block) fully repeated measures analysis of variance (ANOVA) was applied to the data of the extended practice group. Post-hoc comparisons were made for signif-

icant main effects and interactions using Tukey's HSD method with alpha set at 0.05.

Analysis of acquisition RMSE for the BNV group indicated no significant effect for practice block in either movement axis ($p > 0.05$, see Figure 1a).² RMSE for the extended practice group decreased as a function of practice for both movement amplitude, $F(19,114) =$

² Visual inspection of Figure 1a may suggest an effect for practice block in terms of amplitude RMSE for the BNV group. Indeed, the t-test comparing the two blocks did approach the conventional level of significance ($p = 0.06$).

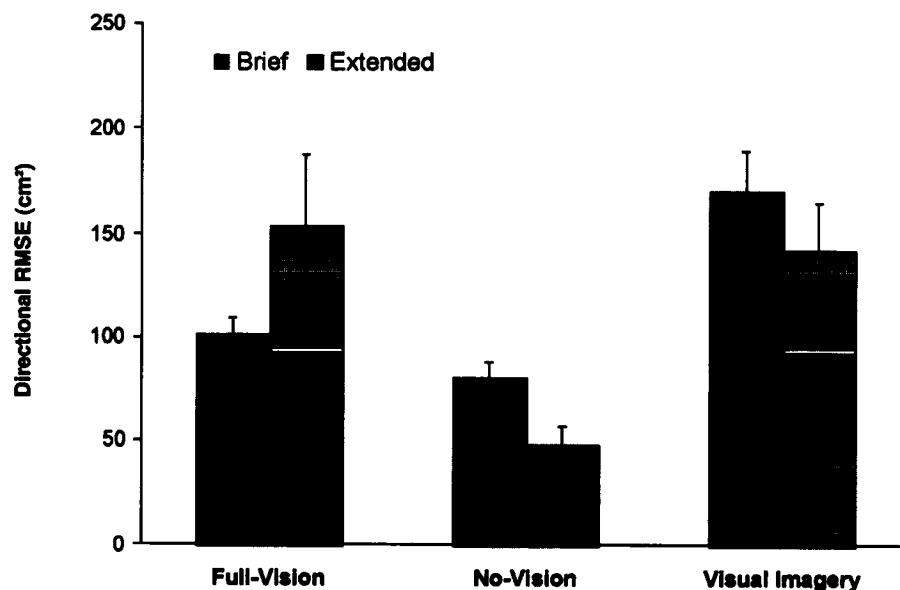


Figure 2b. Directional RMSE as a function of practice condition and practice length in the transfer condition. Error bars represent the Standard Error of the Mean.

2.62, $p < 0.01$, and movement direction, $F(19,114) = 3.24$, $p < 0.001$ (see Figure 1b).

Steps taken (ST) and movement time (MT). As VI participants only physically walked the path once every 10 trials during acquisition, we did not have sufficient data to analyze ST for these groups. However, analyses for ST were performed for the FV and NV groups. Data for ST were subjected to 2 (practice condition: FV, NV) by 2 (practice block: brief practice) or 20 (practice block: extended practice) ANOVA with repeated measures on the last factor. Movement time data were subjected to 3 (practice condition: FV, NV, VI) by 2 (practice block: brief practice) or 20 (practice block: extended practice) ANOVA with repeated measures on the last factor. The analysis of MT and ST data did not indicate any significant effects or interactions ($p > 0.05$).

Transfer

Data collected in the transfer test for each dependent variable were subjected to a 3 (practice condition: FV, NV, VI) by 2 (practice length: 10, 100) between-subjects ANOVA. Post-hoc comparisons were made for significant main effects and interactions using Tukey's HSD method.

Spatial accuracy. Examination of amplitude RMSE indicated a main effect for practice condition, $F(2,34) = 5.96$, $p < 0.01$. Post hoc analysis of this effect indicated that NV participants were significantly more accurate

than FV and VI participants, who did not differ from one another (see Figure 2a). Analysis of directional RMSE revealed a main effect for practice condition, $F(2,34) = 13.23$, $p < 0.001$, and a practice condition by practice length interaction, $F(2,34) = 3.31$, $p < 0.05$. Post-hoc analysis of this interaction indicated that BFV and BNV participants were more accurate than BVI participants ($p < 0.05$). However, in the extended practice condition, ENV participants were more accurate than EFV and EVI participants who did not differ ($p < 0.05$) (Figure 2b).

To test the prediction that practice length impacted movement accuracy, we also made comparisons within visual conditions. These analyses indicated that for amplitude RMSE, ENV participants were more accurate than BNV participants ($p < 0.05$). However, no differences were found between BFV and EFV nor BVI and EVI participants ($p > 0.05$). In terms of directional RMSE, ENV participants were more accurate than BNV participants and EFV participants were less accurate than BFV participants ($p < 0.05$), but EVI and BVI participants did not differ ($p > 0.05$).

Steps taken and movement time. Neither the analysis of MT or ST resulted in any significant effects or interactions ($p > 0.05$).

Discussion

The primary purpose of this investigation was to use the specificity of practice hypothesis to examine

whether practice through visual imagery led to the development of a sensory-specific movement representation similar to that developed under full-vision physical practice conditions. In the present study, analyses of amplitude and directional RMSE in the transfer condition indicated that NV participants were more accurate than FV and VI participants. In other words, participants who practiced with feedback similar to that used in the transfer condition (i.e., NV) were more accurate than participants who had their actual or imagined sensory feedback withdrawn (i.e., FV, VI). Thus, our results support the first tenet of the specificity hypothesis, that is, the development of a sensory-specific movement representation with practice.

The second tenet of the specificity hypothesis predicting an increase in reliance upon a particular source of afferent feedback with practice is only partially supported by the results of the present study. Although the predicted interaction between practice condition and practice length was not significant in terms of amplitude RMSE, planned comparisons within each visual condition revealed ENV participants were more accurate than BNV participants. No differences in amplitude RMSE were found between brief and extended FV or VI participants. Our analysis of directional RMSE indicated an interaction between practice condition and practice length, a finding more in line with the second prediction of the specificity hypothesis. Specifically, we found ENV participants were more accurate than their BNV counterparts, and that EFV participants were less accurate than BFV participants. The results did not indicate a difference in directional RMSE between BVI and EVI participants. Interestingly, our results also indicated that EFV and EVI participants did not differ in terms of amplitude or directional RMSE. As the movement time and number of steps data did not indicate any group differences, it appears that the accuracy results do not result from speed-accuracy trade-offs (c.f. Fitts, 1954). Overall, our results are consistent with the specificity of practice hypothesis and are similar to previous research examining the specificity hypothesis in a similar task (c.f. Proteau et al., 1998). Furthermore, the equivalency in transfer RMSE between the FV and VI groups in the present study suggests similarities in the movement representations employed by these participants.

Visual Imagery and the Specificity of Practice Hypothesis

Our results suggest that practice with VI results in the development of a movement representation reliant upon imagined visual feedback, a process similar to that experienced by FV participants who developed a movement representation reliant upon visual feedback. This interpretation is consistent with the work of Laeng

and Teodorescu (2002) who showed that participants using VI scanned regions of visual space similar to those scanned during actual practice, possibly suggesting that during VI the participant is actively "looking" at the "imagined" visual environment. Also, work by Ganis et al. (2004) demonstrated similar frontal and parietal cortical activation between actual and imagined visual scanning. It would therefore appear that during VI practice participants are experiencing imagined visual feedback similar to the visual feedback available during physical practice. If so, then one would expect participants practicing with VI to develop a sensory-specific movement representation reliant upon imagined visual feedback. As such, when transferred to a task condition with different feedback demands (i.e., the NV condition in the present experiment), we would expect VI participants to undergo performance decrements similar to those experienced by FV participants. In the present experiment, we found equivalent RMSE in both movement axes between EFV and EVI participants, a result supporting our hypothesis. Interestingly, this finding highlights the fact that one can become dependent upon an imagined source of visual feedback in the same manner as one can become dependent upon actual feedback.

Another possible explanation for the equivalency in movement error between FV and VI participants relates to the emulative theory of representation proposed by Grush (2004). The emulative theory states that participants develop and utilize emulative neural representations in order to better predict movement outcomes and evaluate sensory information. Importantly, the emulative theory links actual and imagined practice by suggesting imagery performance is the execution of an emulative representation without motor output. Alternatively, practice with imagery may lead to the development of an emulative representation that enhances subsequent motor performance. In terms of Grush's theory, in the present experiment FV and VI participants would have developed emulative representations during acquisition specific to the task demands they experienced. However, in the no-vision transfer condition, the effectiveness of the emulative representations employed by FV and VI participants would have been reduced due to the removal of visual feedback. As a result, the use of inadequate but similar emulative representations resulted in greater movement error for FV and VI participants.

Finally, one must consider the possibility that VI participants did not develop a movement representation for the walking task. Given the similarities in RMSE between the brief and extended VI groups in the transfer condition, this explanation may at first seem plausible. However, if this explanation is true, and VI partici-

pants did not develop a movement representation for the walking task, we must consider what this implies about the results of the FV participants. In our experiment, FV participants demonstrated similar RMSE to VI participants in the transfer condition, even after 100 trials of practice. If one concludes that VI participants did not develop a movement representation for this task, then logically one must also conclude that the movement representation employed by FV participants in the transfer condition was as ineffective as having no movement representation at all. Does this mean if a transfer condition is markedly different from one experienced during acquisition there is no benefit to practice? In light of previous research, which has demonstrated that participants develop a movement representation for a walking task when practising with vision (c.f. Proteau et al., 1998), we presume that both FV and VI practice led to the development of similar but separate sensory-specific movement representations.

Differential Coding of Movement Amplitude and Direction

Our results also imply that the acquisition of the amplitude and directional components of a task may be differentially impacted by practice condition and length. Loarer and Savoyant (1991) have suggested that tasks with only a movement amplitude component are less complex than those with both amplitude and directional components. Consistent with this notion, we suggest that our results indicating differing degrees of error in movement amplitude and direction may be attributed to task complexity, (i.e., the amplitude component of the walking task was easily mastered and therefore no significant interaction between practice condition and practice length was found). An alternative explanation may be that the amplitude component of the walking task was difficult to master and 100 trials of practice were insufficient for observable differences to occur between the brief and extended practice lengths (c.f. Proteau et al., 1987, 1998). With regard to directional error, however, participants were able to improve at the directional component of the task between 10 and 100 trials of practice, a result replicating Proteau et al.'s (1998) previous findings.

In conclusion, our results are in line with the specificity of practice hypothesis as we demonstrated that participants who had a dependent source of feedback removed in a transfer condition demonstrated greater movement error than those who did not. Interestingly, the results also demonstrated a similarity in movement error between FV and VI participants in a NV transfer condition, a finding that may suggest participants utilizing VI experience imagined visual feedback similar to that experienced in physical practice conditions.

Additionally, our results imply that the development of a movement representation may be influenced by task complexity. Further examination of the impact of task complexity on the development of movement representations is necessary as this may explain discrepancies in previous studies investigating the specificity of practice hypothesis.

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Sommaire

L'hypothèse de la spécificité de la pratique permet de prédire le développement d'une représentation sensorimotrice propre à la rétroaction afférente disponible pendant l'acquisition d'automatismes (Proteau, 1992; Proteau, Marteniuk, Girouard & Dugas, 1987). Dans la présente étude, nous avons eu recours à l'hypothèse de la spécificité de la pratique pour vérifier si l'acquisition d'automatismes au moyen de l'imagerie visuelle pouvait conduire au développement d'une représentation sensorielle propre au mouvement semblable à celle qu'engendre la pratique réelle. Pour ce faire, les participants ont effectué une tâche consistant à marcher sur un chemin linéaire de 12 mètres tout en se soumettant à l'une des trois conditions suivantes : condition de vision normale (FV), condition de vision nulle (NV) ou

imagerie visuelle (VI). Les participants effectuaient 10 ou 100 essais. Après chaque essai de cette phase, les participants étaient informés des résultats concernant leur performance spatiale et/ou temporelle (KR). Une fois l'acquisition des automatismes terminée, les participants effectuaient 10 essais en condition NV sans KR. Une analyse de l'erreur-type indique que les participants étaient plus précis que les participants des conditions FV et VI lors de la condition de transfert. Nous croyons que l'équivalence de l'erreur-type dans la condition de transfert entre la condition FV et la condition VI suggère qu'il y aurait des similarités entre les représentations du mouvement développées par la pratique lors de la condition FV et VI.