

Concurrent Visual Feedback, Practice Organization, and Spatial Aiming Accuracy in Rapid Movement Sequences

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ABSTRACT

Int J Exerc Sci 3(2) : 78-91, 2010. While the availability of visual feedback is a well-known factor influencing the accuracy of rapid aiming movements, little is known about how vision might interact with a contextual variable like practice organization. In the current study, the interaction of concurrent visual feedback (CVF) and practice organization on aiming movement accuracy was investigated in the dominant limb of 40 college-aged participants. Participants performed “triplets” of rapid aiming movements with a lightweight lever in the sagittal plane involving short (20°), medium (40°), long (60°) distances and were randomly assigned to one of four groups (n=10) in a 2 (Group: Blocked Practice, Random Practice) × 2 (Vision: CVF, no CVF) factorial design. Participants performed 24 triplets in acquisition and 10 triplets of a novel pattern (15°-45°-15°) on transfer. Movement time was controlled by a metronome set at 1.43 cycles per second resulting in a cycle time of approximately 700 ms per movement. The constant error and overall error in distance were calculated for each distance and analyzed with separate 2 (Group) × 2 (Vision) × 3 (Movement) ANOVAs with repeated measures on the last factor. When CVF was available, contextual interference effects were shown by better accuracy for the blocked practice groups during acquisition compared to the random practice group. Without CVF, participants tended to overshoot the targets and contextual interference effects were minimized during acquisition and on the first transfer trial. Random practice resulted in better transfer performance compared to blocked practice for both vision conditions when all transfer trials were included in the analysis. The findings contributed to the current literature by demonstrating the importance of practice context and visual feedback to aiming accuracy.

KEY WORDS: Contextual interference, task switching, motor transfer

INTRODUCTION

Beginning with the seminal work of Woodworth (35) over 100 years ago researchers in human motor control have been interested in the factors that affect the spatial accuracy of rapid aiming movements. Even if a simple movement like reaching for a glass is made too quickly, spatial errors may result in spilled liquid. This well-known trade-off between

speed and accuracy has been demonstrated many times in the laboratory (6, 22, 35). However, providing visual feedback allows us to correct for our errors as long as there is enough time available to make corrections based on the feedback (3, 5, 11, 31, 35, 37).

Certainly speed and the opportunity to use vision have dramatic effects on the accuracy of our movements. But more recent

research has focused on the *context* in which a movement is performed. For example, suppose one shoots a basketball from 5 feet from the basket and then from 10 feet from the basket. The accuracy of the 10-foot shot could be biased by the previous 5-foot shot. In the laboratory, asking learners to alternate between shorter- and longer-distance aiming movements might simulate this practice sequence. In this situation, the shorter movements are longer and the longer movements are shorter than control conditions where each movement is practiced separately. These effects are called *assimilation effects* because the resulting amplitudes approximate the amplitude of the other movement in the sequence (26, 27).

These assimilation effects in aiming movements have been attributed to interference in the movement planning process. According to generalized motor program (GMP) theory, different distance aiming movements are accomplished by changing an amplitude scaling parameter value while maintaining invariant features like relative timing and sequencing (9, 20, 21, 22). According to this view, the GMP is retrieved from long-term memory while the appropriate amplitude parameter value is selected from a recall schema or a similar memory structure (20, 28). The program is integrated with the parameter in working memory and the program is constructed and initiated during response production (21). According to Rosenbaum et al., errors are small in constant practice conditions because the same value of the program parameter value is maintained throughout a practice condition (19). However, in variable practice when the values of the program parameter are changed from movement to movement, interference

between parameter values causes increases in errors compared to constant practice. In a variety of sequential keyboarding tasks, Rosenbaum and colleagues showed speed and accuracy of sequential movements were enhanced in constant practice, presumably due to the preservation of the value of a given parameter from movement to movement. Interference occurred when a parameter value was changed between movements resulting in slower and more inaccurate responses (19).

In addition to the variation between constant and variable practice, random practice can also create contextual interference. In random practice, a different GMP is used on each trial. So hitting a forehand, backhand and then a volley in tennis on three consecutive movements constitutes random practice. In blocked practice, the same GMP is used on a series of trials before practicing with other GMPs. Hitting all forehands on a series of trials before switching to the backhand in tennis is a common example of blocked practice. Theoretically, the advantages of random practice over blocked practice in learning new skills are thought to be due to the greater opportunity to compare and contrast task variations in working memory (1, 2). The assumption of this elaboration hypothesis is that all of the motor programs to be used during random practice are held in working memory concurrently allowing for an efficient comparison between them (23, 24). Blocked practice, where only one program is held in working memory at one time does not afford the same opportunity for comparison. On a transfer test, random practice results in better generalization to the new skill compared to blocked practice due to the enhanced information processing

required by random practice during acquisition.

Clearly, practice organization has a strong effect on motor performance and the ability to perform similar tasks on transfer tests. The main question addressed in the present study was whether concurrent visual feedback (CVF) modulates the effect of practice organization. In the case of aiming movements, random practice may allow for better spatial parameter selection on transfer compared to blocked practice. By providing precise CVF the elaboration process might be enhanced by helping the performer to understand the similarities and differences between the motor programs involved in the task more effectively than a reliance on proprioception, or delayed visual feedback. According to this line of reasoning, differences between blocked and random practice groups should be highly evident when visual feedback is available. When visual feedback is not available, participants might have more difficulty discriminating between motor programs, reducing the differences between blocked and random practice groups and lessening the potential advantage of random practice on transfer tests.

Therefore, the aim of the present experiment was to investigate whether CVF interacts with practice organization in the production of sequences of aiming movements.

METHODS

Participants

The participants were 40 undergraduate students (aged 18-22, male N=18, female N=22) at the University of Colorado.

Inclusion criteria included right-handedness based on the Edinburgh Handedness Inventory (17) and not having previous experience with the task. Right-handed participants were desired so that comparisons could be made with our previous work in this area (26, 27). All participants received course credit equal to 1% of their final course grade for their participation. The Human Research Committee at the University of Colorado approved the work and the participants signed an informed consent form before participating.

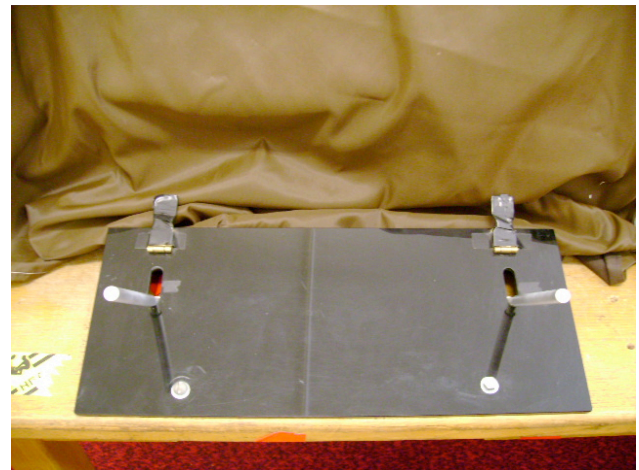


Figure 1. The lever apparatus used in the experiment.

Protocol

The apparatus (shown in figure 1) was a Plexiglas platform on a standard table top, which was slotted to allow two aluminum hand levers (16 cm in length and 36.5 cm apart) to rotate 75° in the sagittal plane, with the most proximal position called 0°. Precision potentiometers (Beckman Industrial, #3381, 10K) were affixed to the base of each lever so displacement could be recorded. The measurement error of the potentiometers was .1°. Due to the arrangement of the hand levers and the potentiometers, the hand and levers moved

in a slightly curvilinear path such that the maximum vertical change in displacement of the tip of the lever was 3 cm. The maximum curvilinear distance the levers could travel in the sagittal plane was approximately 22.5 cm. The output of the potentiometers were digitized on-line at 1000 Hz and stored on a PC. An interval timer (Lafayette Instruments, Model 52011) was used to control movement time. A 16" monitor (HP Pavilion) was placed 45 cm from the participant at eye level and was used to provide visual feedback. The grid on the monitor clearly showed the goal distances. The ratio of lever movement to cursor movement was 1.6/1.

A cardboard shield was attached to the monitor and was used to cover the monitor screen in conditions where visual feedback was to be prevented. All testing was done while the participants were seated in front of the apparatus. We prevented participants from viewing their hands by placing a frame-supported opaque sheet over the apparatus (see figure 2).



Figure 2. Photograph of a participant seated in the testing position and receiving visual feedback of the performance. The apparatus shown in Figure 1 is covered by a frame and sheet.

During acquisition, participants practiced three movement distances, short (20°),

medium (40°) and long (60°) 24 times each, but organized in "triplets". Each triplet involved a sequence of 3 rapid reversal movements with the goal distance for each movement of the triplet varied depending on group assignment. All participants used the lever on the right side of the apparatus. The participants were instructed to make smooth movements out to the reversal point and back to the 0° starting position, without waiting or hesitating at the reversal point. When the movements were performed correctly, the output of the potentiometers were bell-shaped, but with a distinct peak at the reversal point (see figure 3). The movement to the reversal point required extension at the elbow joint and flexion at the shoulder joint. Returning the lever to the start position involved flexion at the elbow joint and extension of the shoulder joint. It should be emphasized that there were no target zones; instead, the participant attempted to reverse the lever at the 20°, 40°, or the 60° point along the path of the lever.

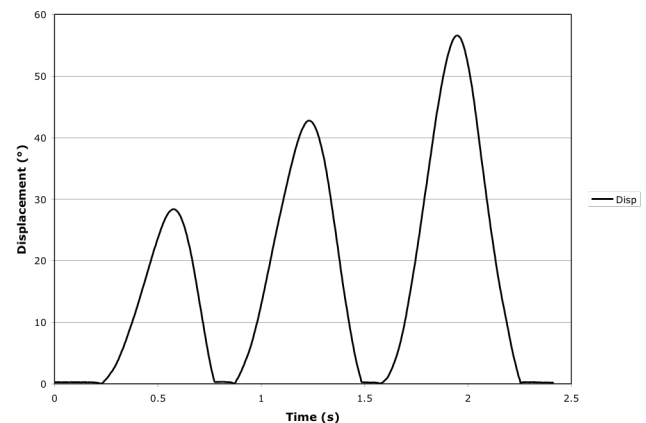


Figure 3. A sample displacement-time record from one participant in the 20°-40°-60° condition in the random practice group.

We randomly assigned the participants to one of four groups ($n = 10$) based on a 2 (Vision) \times 2 (Group) factorial design (see table 1). Participants were randomly

assigned to either a blocked or random practice group, and to a CVF or non-CVF group. In order to help minimize practice order effects, half of the blocked practice group used an ascending order of the three distances and the other half used a descending practice order. The ascending subgroup performed 8 consecutive triplets for each distance beginning with the short distance (as noted by 20°-20°-20°), followed by the medium distance (40°-40°-40°), and ending with the long distance (60°-60°-60°). The descending subgroup performed 8 consecutive triplets for each distance with the opposite order of the ascending group. The random group performed 4 triplets of each of the six combinations of the three distances (20°-40°-60°, 20°-60°-40°, 40°-20°-60°, 40°-60°-20°, 60°-40°-20°, 60°-20°-40°) in a random order. Participants assigned to the CVF group had full vision of the monitor screen throughout the testing. Participants assigned to the non-CVF group performed all movements with the shield covering the monitor screen. Immediately following acquisition, participants performed 10 trials of a novel triplet (15°-45°-15°) maintaining the visual feedback condition as in acquisition.

Statistical Analysis

Because there was a high likelihood of biasing effects (i.e., greater overshooting in the shorter movements when following a longer movement) in the random practice groups we determined spatial accuracy from the potentiometer output by computing the mean constant error (CE) in the reversal point for each movement in the triplet. Positive CEs indicated overshoots and negative CEs indicated undershoots. We also calculated the mean overall error (E) in the reversal point, where E is defined as the within-subject standard deviation

about the target. In order to determine if the participants maintained the required tempo, we computed the mean movement time (MT) for each movement of the triplet by measuring the time between movement onset (i.e., when the potentiometer signal reached 1° above the baseline) to offset (when the signal returned to 1° above baseline following a reversal). However, based on the design of the experiment, the means for acquisition were based on differing numbers of trials. For the blocked practice groups the means were based on 8 triplets and the random practice groups 4 triplets. For the transfer test the CE on the first transfer trial was calculated for each movement in the triplet. We also calculated the mean CE, E, and MT for each movement of the triplet based on all 10 transfer trials.

Table 1. The Experimental Design.

N	Practice Type	Subgroup	Vision Condition
10	Blocked	Ascending (N=5)	CVF Available
		Descending (N=5)	CVF Available
10	Blocked	Ascending (N=5)	No CVF
		Descending (N=5)	No CVF
10	Random		CVF Available
10	Random		No CVF

Before directly comparing the random and blocked groups on the acquisition data, preliminary analyses were carried out separately on the data from the blocked and random practice groups. To determine any differences between the first, second, and third movements of the triplets and the affect of practice order for the blocked practice groups the CE, E, and MT were analyzed with 3 (Movement) x 2 (Order)

ANOVAs with repeated measures on movement. Separate ANOVAs were run for each dependent variable and goal distance (i.e., 20°, 40°, 60°). Alpha levels were set at .05. There was no effect of order or movement for any analysis, so the data were averaged across movement and both blocked subgroups for comparison with the random practice groups. To determine any differences between the different practice orders for the random practice group, the common conditions were first averaged based on serial position. For example, the CE, E, and MTs for the 20° movement in the first position were averaged over the 20°-40°-60° and the 20°-60°-40° practice orders. For the second serial position, the 20° movements from the 40°-20°-60° and 60°-20°-40° conditions were averaged, and so on for each distance and serial position. The resulting means were analyzed with a 3 (Serial Position) × 3 (Distance) ANOVA with repeated measures on both factors. There was no effect of serial position or any interaction with serial position, so the data were averaged over the remaining conditions for comparison with the blocked practice group.

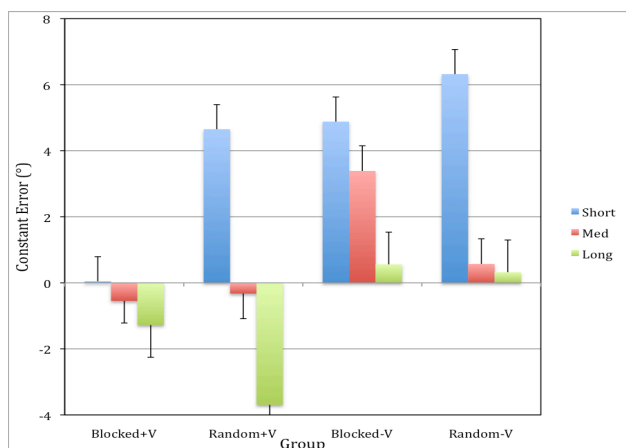


Figure 4. The mean constant error (CE) in acquisition for the short (20°), medium (40°), and long (60°) movements for the blocked and random practice groups in both the CVF (+V) and non-CVF (-V) conditions. Standard errors are also shown.

The blocked and random practice groups were then compared on the CE, E, and MT data from acquisition with separate 2 (Group) × 2 (Vision) × 3 (Movement) ANOVAs with repeated measures on the last factor. The analysis was repeated for the CE on the first transfer trial, and the mean CE, E, and MT over all transfer trials. Significant main effects or interactions were followed up with Least Significant Difference (LSD) post hoc tests.

RESULTS

Acquisition

The mean acquisition CE for the short, medium, and long movements for all groups is shown in figure 4. When CVF was provided, the short movement was overshoot and the long movement undershot, particularly, for the random practice group. When CVF was not provided, all movements were overshoot, particularly for the short movement. This pattern of results indicated a significant three-way interaction between group, vision, and movement, $F(2, 72) = 5.0$, $p < .05$, $\eta^2 = .12$. LSD post-hoc tests showed that when CVF was provided, the errors for the short and long movements of the random practice group were significantly greater from those of the blocked practice group. For the groups without CVF, the medium distances of the blocked and random groups differed. The main effects of movement, $F(2, 72) = 54.7$, $p < .001$, $\eta^2 = .60$, and vision, $F(1, 36) = 21.3$, $p < .001$, $\eta^2 = .37$, were also significant. Post hoc tests showed significantly greater overshooting of the short movement compared to the medium or long movements. CEs were also higher in the non-CVF groups compared to the CVF groups.

Overall errors for acquisition are shown in figures 5 and 6 and both show significant two-way interactions. Figure 5 shows the significant Movement \times Group interaction demonstrating greater errors in the random groups, particularly for the shorter and longer movements, $F(2, 72) = 4.4, p < .05, \eta^2=.11$. Figure 6 shows that overall errors were greater for the random practice groups, but only for the CVF condition. The Group \times Vision interaction was significant, $F(1, 36) = 7.0, p < .05, \eta^2=.16$. Post-hoc tests confirmed the finding noted here.

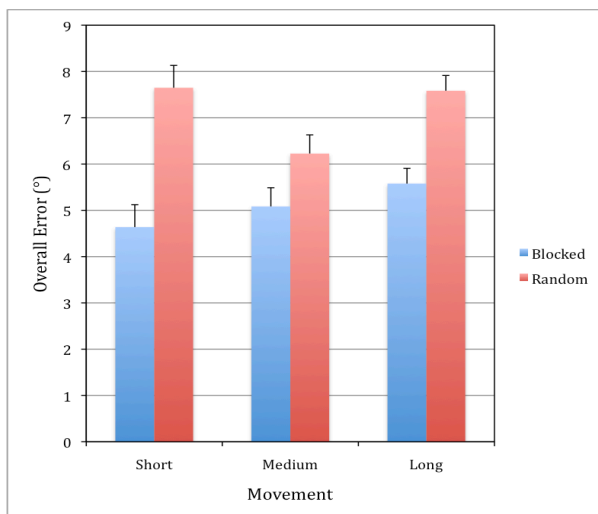


Figure 5. The mean overall error (E) in acquisition for the short (20°), medium (40°), and long (60°) movements for the blocked and random practice groups. Standard errors are also shown.

The main effects for movement, $F(2, 72) = 4.3, p < .05, \eta^2=.11$, group, $F(1, 36) = 20.4, p < .001, \eta^2=.36$, and vision, $F(1, 36) = 28.5, p < .001, \eta^2=.44$, were significant as well.

For MT, the main effect of movement was significant, $F(2, 72) = 50.9, p < .001, \eta^2=.61$. Post hoc tests showed the MTs for the short (591 ms), medium (680 ms), and long (714 ms) movements were all significantly different from each other.

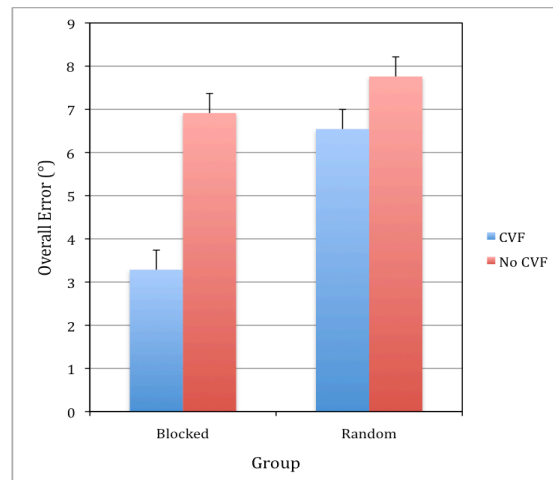


Figure 6. The mean overall error (E) in acquisition for the CVF and non-CVF conditions for the blocked and random practice groups. Standard errors are also shown.

Transfer Performance

Figure 7 shows the CE for the first transfer trial. When CVF was provided, the random group showed smaller errors than the blocked group, but when CVF was not available, there was little difference between the blocked and random practice groups. The interaction between group, movement, and vision was significant, $F(2, 72) = 4.8, p < .05, \eta^2=.12$. Post hoc tests showed that the shorter and medium movements of the random practice group were less than those of the blocked practice group when CVF was provided. No group differences were shown when CVF was not provided. Main effects for movement, $F(2, 72) = 29.7, p < .001, \eta^2=.45$, and vision, $F(1, 36) = 25.8, p < .001, \eta^2=.42$, were significant.

When all transfer trials are included in the analysis (figure 8), the interaction between group, movement and vision was nearly significant, $F(2, 72) = 2.9, p < .06, \eta^2=.07$. Trends do show smaller errors in the random groups relative to the blocked groups, particularly for the second short

movement in the non-CVF condition. Errors were smaller in the random practice group ($M=2.0$) compared to the blocked practice group ($M=3.1$), $F(1, 36) = 6.1$, $p < .05$, $\eta^2=.14$. Errors were also higher in the non-CVF groups ($M=4.1$) compared to the CVF groups ($M=0.9$), $F(1, 36) = 52.2$, $p < .001$, $\eta^2=.59$. The main effect of movement was also significant, $F(2, 72) = 90.5$, $p < .001$, $\eta^2=.71$.

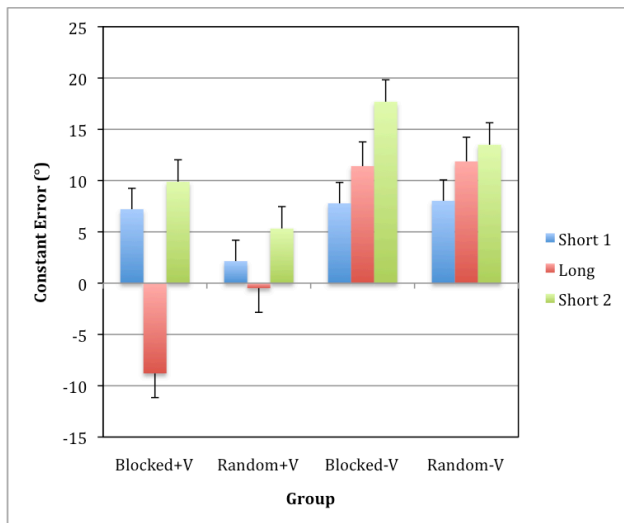


Figure 7. The constant error (CE) for each movement on the first transfer trial of the novel triplet [15° (Short 1) - 45° (Long) - 15° (Short 2)] for the blocked and random practice groups in both the CVF (+V) and non-CVF (-V) conditions. Standard errors are also shown.

The mean overall error for transfer is shown in figure 9. Smaller errors were shown for the random practice groups compared to the blocked practice groups, although the errors were higher in the non-CVF groups. The main effects for movement, $F(2, 72) = 22.9$, $p < .001$, $\eta^2=.39$, group, $F(1, 36) = 15.0$, $p < .001$, $\eta^2=.29$, and vision, $F(1, 36) = 45.8$, $p < .001$, $\eta^2=.57$ were significant.

For MT, the main effect of movement was significant, $F(2, 72) = 284.0$, $p < .001$,

$\eta^2=.84$. Post hoc tests showed the MT for the second movement (742 ms), was longer than the first (552 ms) and third (568 ms) movements.

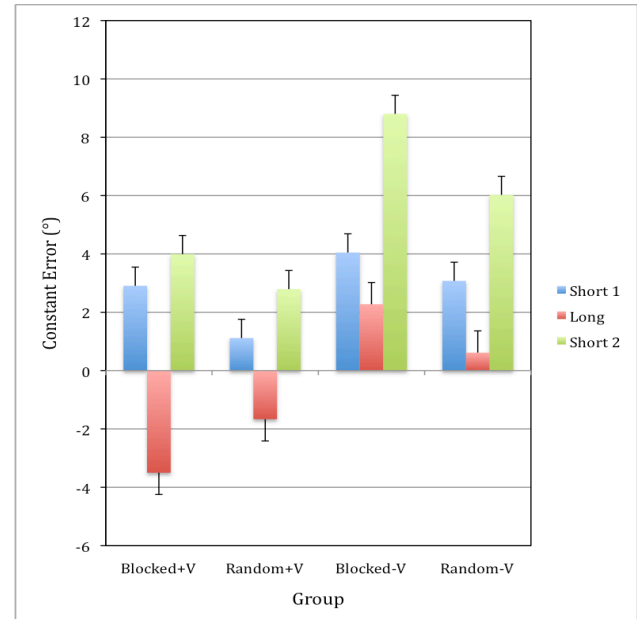


Figure 8. The mean constant error (CE) for each movement averaged over all transfer trials of the novel triplet [15° (Short 1) - 45° (Long) - 15° (Short 2)] for the blocked and random practice groups in both the CVF (+V) and non-CVF (-V) conditions. Standard errors are also shown.

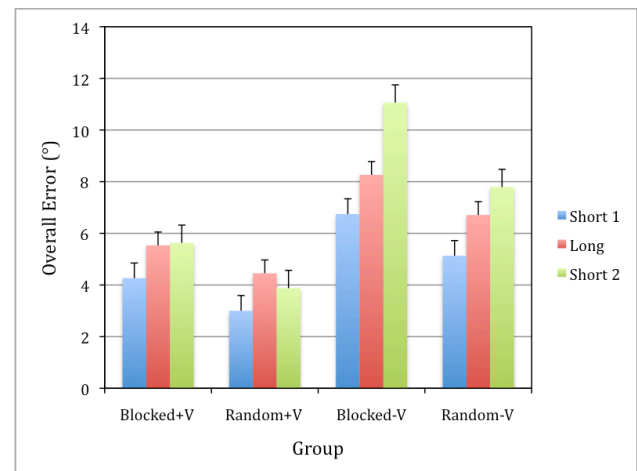


Figure 9. The mean overall error (E) for each movement averaged over all transfer trials of the novel triplet [15° (Short 1) - 45° (Long) - 15° (Short 2)] for the blocked and random practice groups in both the CVF (+V) and non-CVF (-V) conditions. Standard errors are also shown.

DISCUSSION

Our main goal in this experiment was to determine if practice organization interacts with CVF relative to spatial errors in short sequences of aiming movements. According to one hypothesis, if CVF allows for more effective elaboration processes compared to non-CVF conditions, then random practice should result in better transfer performance than blocked practice when CVF is provided compared to non-CVF conditions. One alternative hypothesis could be that CVF would reduce elaboration and reconstruction processes thereby minimizing the differences between blocked and random practice groups on transfer. Blocked practice groups should perform better than random practice groups on acquisition because there is no need to change the motor program or the program parameter value on each trial (19).

Acquisition

In general, the random practice groups showed greater error than the blocked practice groups during acquisition, particularly when CVF was provided. This finding confirms a large body of work showing the disadvantages of random practice relative to blocked practice for motor performance (4,16, 25). The main causes of spatial error in this case were probably parameter value switching as described by Rosenbaum and associates and greater contextual interference in the random practice groups (19). In most cases, when participants were required to switch amplitude parameter values during the triplet in the random practice groups, the short distance was overshoot and the long movement undershot relative to the blocked practice group (see figure 4). The pattern of results supports Rosenbaum and

colleague's data structure approach to motor programming described earlier (19). When the motor program parameter value is preserved for use on consecutive movements, performance is enhanced because program editing is not required. When a change in the parameter value is called for during random practice, interference occurs in the response production process resulting in poorer performance compared to blocked practice. According to theories of motor control, random practice caused errors in selecting the proper program parameter value resulting in greater movement errors compared to blocked practice (20, 21, 22).

However, the blocked-random practice differences in acquisition were minimized when CVF was not provided. It could be that the lack of CVF increased task difficulty for both the blocked and random practice groups, as suggested by the greater overall errors in the non-CVF conditions compared to the conditions with CVF. Perhaps a reliance on less precise proprioception or on weak motor programs increased the task difficulty when CVF was not provided. In any case, any blocked-random practice differences due to program parameter value switching or contextual interference was overshadowed by the lack of CVF. Another factor that could be involved is the tendency for the motor performance to "drift" under certain no-feedback conditions. A number of studies with normal and patient populations have shown increased overshooting of targets when visual feedback was withdrawn (7, 18). It could be that the proprioceptors of the body are subject to drift and need to be continuously calibrated with vision (10, 32). In the current study, the effect of drift under non-

CVF conditions clearly had a significant effect on performance and outweighed the effects of contextual interference and program parameter value switching, at least for acquisition.

The significant difference between the blocked and random practice groups in acquisition suggests that providing CVF did little to reduce the interference due to program parameter value switching. This finding, however, is restricted to tasks where participants did not have the opportunity to correct errors during the movement sequence. We required participants to make 3 aiming movements in 2100 ms. With average MTs in the range of 500-700 ms there may have been time to make movement adjustments during a movement, but they had to return to the start position between each movement and make the next movement to keep up with the required rhythm. Had we provided more time for movement error correction, the differences between the groups would have been reduced markedly.

First Transfer Trial Performance

We expected that random practice would result in better transfer performance than blocked practice when CVF is provided compared to non-CVF conditions. This expectation was supported by the CE results on the first transfer trial where the random practice group showed smaller errors than the blocked practice group when CVF was provided, but with no group differences when CVF was not available. As with acquisition without CVF, overshooting was also shown in all movements on the first transfer trial when CVF was not provided. The finding again suggests that performance drift without

visual feedback has a strong effect on motor performance.

The better performance on the first transfer trial by the random practice group compared to the blocked practice group when CVF was provided supports our hypothesis about the interaction between CVF and practice organization. By providing precise CVF the elaboration process was likely enhanced by helping the random practice group to understand the similarities and differences between the motor programs and parameter values involved in the task more effectively than the non-CVF groups. The enhanced elaboration processing engaged during acquisition allowed the random practice groups to perform the novel transfer task more effectively than the non-CVF groups whom may have had to rely on less precise proprioceptive feedback, or delayed visual feedback and suffered from performance drift. Apparently, the random practice group without CVF had more difficulty discriminating motor programs and parameter values, resulting in performance equal to the blocked practice group on the first transfer trial.

Mean Transfer Performance

However, when the mean errors were calculated for all of the transfer trials, the pattern of results differed somewhat from the first transfer trial. Statistically, the interaction between group, vision, and movement was not significant (i.e., $p < .06$), unlike the first transfer trial, but the trends indicated that random practice groups were more accurate than the blocked practice groups with and without CVF (see figures 8 and 9). The random practice groups showed less overshooting of the shorter movements on the transfer task than the

blocked practice groups and lower overall errors as well. It could be that practice with the delayed visual feedback provided to the non-CVF groups during the transfer task reduced the effects of performance drift noted on the first transfer trial, allowing the positive effect of practice organization to emerge on the remaining transfer trials.

Moreover, our results suggest that the transfer benefits of random practice compared to blocked practice can occur regardless of whether or not CVF is available during acquisition. The participants were able to use concurrent or delayed visual feedback, or proprioceptive feedback to learn to discriminate between the programs and parameters under random practice conditions compared to blocked practice. The fact that the random practice groups performed better than the blocked practice groups based on mean transfer scores supports the elaboration hypothesis that random practice allows participants an opportunity to compare and contrast multiple programs in working memory more effectively than blocked practice (23, 24). Our finding also supports previous work showing random practice is more effective than blocked practice for program parameter learning (8, 15, 36). Our data also shows the advantages of random practice over blocked practice on transfer when the sequence of the GMP is changed. Apparently altering the order of the practiced amplitudes generates a high enough level of contextual interference to improve transfer performance relative to blocked practice. A lack of contextual interference effects would have supported the alternative hypothesis that CVF would eliminate or minimize differences between the random and blocked practice groups on transfer. This was not the case. Providing

CVF evidently did not disrupt or prevent program reconstruction in the random practice group.

It should be noted that our use of CVF in the current study was different from how visual information had been used in earlier contextual interference studies. For example, Lee et al. provided a visual map of the upcoming movement to be learned under random practice conditions along with an auditory template of the required timing prior to each practice trial (14). Their use of visual and auditory information eliminated the random practice benefit on transfer presumably due to the reduction in the information processing activities normally associated with random practice. Clearly one should not provide the learner with the “solution” to the motor task during random practice (29, 30). The use of CVF in the current study allowed the participant to effectively compare and contrast task variations without preventing motor program reconstruction, leading to successful transfer performance.

Aiming Accuracy and Context

Our current work supports the long-held belief that visual feedback reduces errors in aiming movements (18, 35, 37). When CVF was available, spatial errors were less than when CVF was not available. Apparently, providing CVF allowed the selection of amplitude parameters to be more effective compared to non-CVF conditions. Although no obvious movement corrections were apparent in the displacement records, visual feedback could have allowed the participants to use visual information to guide movements to the target (18), or to plan the later movements of the triplet more effectively compared to when CVF was not provided.

Our experiment also suggested that the principles of aiming accuracy for movements embedded in a sequence are different from single aiming movements. In single aiming movements spatial errors are directly proportional to distance and average velocity (22). However, for sequences of aiming movements, spatial error also depends on the context (33, 34). For example, during random practice in acquisition, the shorter movements were overshoot and the longest movements were undershot when CVF was provided showing biasing effects from the other movements in the sequence. On the transfer task errors were generally greater on the last movement in the sequence even though the goal amplitude was the same as the first movement in the sequence. As stated earlier, a current movement can be biased by the amplitude parameter of a previous movement resulting in spatial errors due to a change in the value of the program parameter (25, 26).

In summary, it is clear that producing accurate aiming movements involves more than simply selecting appropriate amplitude parameters from working memory and constructing the GMP accordingly. Engaging in random practice or practice without CVF, increases aiming errors relative to blocked practice or practice with CVF early in training. On the other hand, random practice reduces errors relative to blocked practice when a novel aiming task is performed. Spatial errors are also affected by performance drift when CVF is not provided, but providing appropriate feedback may reduce these errors. Selecting and producing the proper amplitude parameters for accurate aiming is a complex process that is affected by a

number of kinematic and contextual variables.

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REFERENCES

1. Battig WF. Facilitation and interference. In Bilodeau EA (ed) Acquisition of skill. New York: Academic Press: 215-244, 1966.
2. Battig WF. The flexibility of human memory. In Lermak LS, Craik FIM (eds). Levels of processing in human memory. Hillsdale, NJ, Erlbaum: 23-44, 1979.
3. Beggs WDA, Howarth CI. Movement control in man in a repetitive motor task. *Nature* 221: 752-753, 1970.
4. Brady F. A theoretical and empirical review of the contextual interference effect and the learning of motor skills. *Quest* 50: 266-293, 1998.
5. Carlton LG. Visual processing time and the control of movement. In Proteau L, Elliott D (eds) Vision and motor control. Amsterdam: North-Holland: 3-31, 1992.
6. Fitts PM. The information capacity of the human motor system in controlling the amplitude of movement. *J Exp Psychol* 47: 381-391, 1954.
7. Ghez C, Gordon J, Ghilardi MF. Impairments of reaching movements in patients without proprioception. II. Effects of visual information on accuracy. *J Neurophysiol* 73: 361-372, 1995.
8. Hall KG, Magill RA. Variability of practice and contextual interference in motor skill learning. *J Mot Behav* 27: 299-309, 1995.
9. Heuer H, Schmidt RA, Ghodsian D. Generalized motor programs for rapid bimanual tasks: A two-level multiplicative-rate model. *Biol Cybern* 73: 343-356, 1995.

10. Jennerod M. The neural and behavioural organisation of goal directed movements. Claredon Press, Oxford, 1989.
11. Keele SW, Posner MI. Processing of visual feedback in rapid movements. *J Exp Psychol* 77: 155-158, 1968.
12. Lee TD, Magill RA. The locus of contextual interference in motor-skill acquisition. *J Exp Psychol Learn Mem Cogn* 9: 730-746, 1983.
13. Lee TD, Magill RA. Can forgetting facilitate skill acquisition? In Goodman D, Wilberg, RB, Franks IM (eds) *Differing perspectives in motor learning, memory, and control*. Amsterdam, Elsevier: 3-22, 1985.
14. Lee TD, Wishart LR, Cunningham S, Carnahan H. Modeled timing information during random practice eliminates the contextual interference effect. *Res Q Exerc Sport* 68: 100-105, 1997.
15. Lee TD, Wulf G, Schmidt RA. Contextual interference in motor learning: Dissociated effects due to nature of task variations. *Q J Exp Psychol* 44A: 627-644, 1992.
16. Magill RA, Hall KG. A review of the contextual interference effect in motor skill acquisition. *Hum Move Sci* 9: 241-289, 1990.
17. Oldfield RC. The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia* 9: 97-113, 1971.
18. Prablanc C, Pélisson D, Goodale MA. Visual control of reaching movements without vision of the limb. *Exp Brain Res* 62: 293-302, 1986.
19. Rosenbaum DA, Weber RJ, Hazelett WM, Hindorff V. The parameter remapping effect in human performance: Evidence from tongue twisters and finger fumlbers. *J Mem Lang* 25: 710-725, 1986.
20. Schmidt RA. A schema theory of discrete motor skill learning. *Psychol Rev* 82: 225-260, 1975.
21. Schmidt RA, Lee TD. *Motor Control and Learning*. Human Kinetics, Champaign, IL, 2005.
22. Schmidt RA, Zelaznik HN, Hawkins B, Frank JS, Quinn JT. Motor-output variability: A theory for the accuracy of rapid motor acts. *Psychol Rev* 86: 415-451, 1979.
23. Shea JB, Zimny ST. Context effects in memory and learning movement information. In Magill RA (ed) *Memory and control of action*. Amsterdam, Elsevier: 345-366, 1983.
24. Shea JB, Zimny ST. Knowledge incorporation in motor representation. In Meijer OG, Roth K (eds), *Complex movement behaviour: "The" motor-action controversy*. Amsterdam, Elsevier: 289-314, 1988.
25. Sherwood DE. The benefits of random variable practice for spatial accuracy and error detection in a rapid aiming task. *Res Q Exerc Sport* 67, 35-43, 1996.
26. Sherwood DE. Separate movement planning and spatial assimilation effects in sequential bimanual aiming movements. *Percept Mot Skills* 105: 501-513, 2007.
27. Sherwood DE. Spatial assimilation effects in sequential movements: Effects of parameter value switching and practice organization. *J Mot Behav* 40: 232-245, 2008.
28. Sherwood DE, Lee TD. Schema theory: Critical review and implications for the role of cognition in a new theory of motor learning. *Res Q Exerc Sport* 74: 376-382, 2003.
29. Simon DA, Bjork RA. Metacognition in motor learning. *J Exp Psychol Learn Mem Cogn* 27: 907-912, 2001.
30. Simon DA, Bjork RA. (2002). Models of performance in learning multisegmental movement tasks: Consequences for acquisition, retention, and judgments of learning. *J Exp Psychol Learn Appl* 8:222-232, 2002.
31. Vince MA. Corrective movements in a pursuit task. *Q J Exp Psychol* 1: 85-103, 1948.
32. Wann JP, Ibrahim SF. Does limb proprioception drift? *Exp Brain Res* 91: 162-166, 1992.
33. Wilson EJ, Sherwood DE. Do the principles of motor program editing apply to longer sequences of rapid aiming movements? I. *Int J Exerc Sci* 1(1), 2008.
34. Wilson EJ, Sherwood DE. Do the principles of motor program editing apply to longer sequences of

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rapid aiming movements? II. Int J Exerc Sci 1(2), 2008.

35. Woodworth RS. The accuracy of voluntary movement. Psychol Rev Mono Suppl 3: 1-119, 1899.

36. Wulf G, Lee TD. Contextual interference in movements of the same class: Differential effects on program and parameter learning. J Mot Behav 25: 254-263, 1993.

37. Zelaznik HN, Hawkins B, Kisselburgh L. Rapid visual feedback processing in single-aiming movements. J Mot Behav 15: 217-236, 1983.