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NEGATIVE RESULT

Augmented Reality-Based Trajectory Feedback Does Not Improve Aiming in Dart-Throwing

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Ethics Review Board of the National Defense Academy of Japan.

ABSTRACT In this study, augmented reality (AR)-based training did not improve aiming during dart-throwing. Several studies have suggested that motor skill learning is influenced by the learner's attentional focus. An external focus of attention (e.g., dart motion) is more important for dart-throwing training than an internal focus of attention (e.g., physical motion). In computational neuroscience, motor learning theory posits that explicit error feedback is essential for acquiring novel motor skills. Thus, we hypothesized that dart-throwing performance can be improved by feedback based on the dart trajectory in a previous trial using an AR head-mounted display (HMD). To test our hypothesis, we tested an AR training system in 20 participants who threw darts under several conditions, with or without being presented with the trajectory and with or without wearing the AR HMD. However, we did not observe any significant effects of the AR-based trajectory feedback on aiming accuracy during dart throwing. Thus, trajectory feedback does not improve the dart-throwing performance. Our results will provide a basis for further research on AR applications.

INDEX TERMS Human information processing, human performance, virtual and augmented reality, human-computer interaction, enhancement, sports.

I. INTRODUCTION

The acquisition of motor skills is influenced by attentional focus [1]. For example, when throwing a dart, an external focus (EF; e.g., dart trajectory) is more effective in improving skill than an internal focus (IF; e.g., physical motion) [2]. Additionally, the motor learning theory in computational neuroscience posits that explicit error feedback is essential for learning new motor skills [3], [4]. Thus, we hypothesized that a visible dart trajectory can improve performance.

Augmented reality (AR) technology enables virtual objects to be superimposed on real-world objects, thus allowing users to interact with the objects using their hands and feet. This technology is widely used to combine virtual experiences with real-world perceptual-cognitive and motor skills through wearable devices, such as head-mounted displays (HMDs). AR technology has been used for training and learning in the psychology, medicine, and military domains to enhance perceptual-cognitive and motor skills [5]. AR is expected to have a major impact on multiple industries [6], [7], despite several remaining problems [8].

To evaluate our hypothesis, we assessed the effectiveness of an AR-based training system for dart throwing. The system allows players to correct trajectory error while throwing a dart by displaying the trajectory of a previously thrown dart on an AR HMD (HoloLens 2; Microsoft Corp., Redmond, WA, USA) (Fig. 1a). When a newly thrown dart was stuck on the dartboard, the presented trajectory was overlaid by the new one (Fig. 1b). We compared aiming accuracy among conditions with and without presentation of the trajectory, and with and without wearing the AR HMD. Although the AR trajectory did not improve the aiming performance, our

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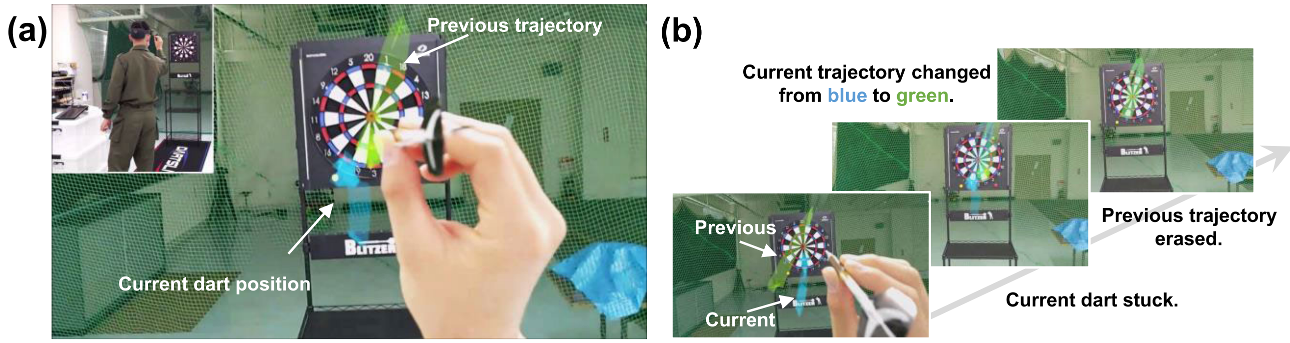

FIGURE 1. Throwing a dart with an augmented reality (AR)-based trajectory on a head-mounted display (HMD). (a) AR view. Upper left panel depicts the AR view. (b) Update process to overlay the new trajectory on the AR HMD. The dart trajectory of the previous trial is indicated by the green line, and the current dart position and trajectory are indicated by the blue line. When the current dart strikes the dartboard, the previous trajectory is erased and the color of the current trajectory changes from blue to green (see Supplementary Material S1.mp4).

results provide a basis for further research of AR applications for improvement of motor performance.

II. RELATED WORK

Multiple studies have evaluated the factors that affect aiming motor tasks, such as dart-throwing. In particular, the learner's focus of attention (FOA) plays an important role in the acquisition of these motor skills. This chapter reviews the literature on throwing tasks and FOA.

A. THROWING TASKS

Precision throwing is a human-specific ability [9] that relies on cognitive skills [10], [11], attentional focus [2], [12], arm kinematics [13], [14], release timing [15], and motivation [16]. The optimal throwing strategy should optimize both motor and cognitive skills [17]. However, in biological systems, motor noise introduces uncertainty in movements [18], [19], and noise robustness is important for the brain to fine-tune motor activity [20], [21]. When aiming to hit the bull's-eye (center of the dartboard) during dart throwing task, motor noise can cause variability in the landing positions of darts. Neural control signals can be corrupted by motor noise, which increases with the size of the control signal. Motor planning minimizes the deleterious effects of noise [22]. Optimal dart-throwing motion can maximize the probability of hitting the bull's-eye during dart-throwing simulations [23]. Therefore, motor noise plays a critical role in motor control, including dart-throwing. Motor learning depends on the properties of motor noise, such as the fraction of planning and execution noise in the motor noise [24].

Virtual reality has gained attention as a tool for sports training, particularly for throwing tasks. Studies have shown that simulated ball-throwing [25] using virtual reality provides more effective feedback than the feedback provided by real trainers when real balls were thrown [26]. Furthermore, HMDs provide a third-person perspective (3PP), which can also be applied to aiming tasks, including throwing. Previous studies have examined the effects of sports training using 3PP on ball-catching [27] and basketball free-throw [28] performance, and found that the 3PP view was more similar to the real-world view than the first-person perspective (1PP) in virtual environments, although performance did not differ between the 1PP and 3PP conditions. However, a recent study suggested that the effect of 3PP training on dart-throwing tasks may be limited by the lack of a sense of agency and body ownership [29].

B. FOA

Studies of FOA have shown that an EF that directs attention toward movements enhances motor performance and learning compared to IF on body movements [1]. EF improves the accuracy of aiming in motor tasks other than throwing darts [2], such as throwing balls [30] and frisbees [31], kicking balls [32], and shotgun shooting [33]. In cases of dart throwing, there are various types of EF differing in focus (e.g., bull's-eye and trajectory in distal and proximal EF, respectively) [34]. However, some studies have shown that EF does not always improve performance [12], [35], [36]. A model-based analysis revealed that adjusting the kinematics of throwing is the most important factor in the acquisition of novel throwing skills, mainly because this strategy is more robust to the temporal variability arising from the motor noise associated with neuronal systems compared to adjusting the release timing [37]. Some studies have found that FOA does not improve dart-throwing learning or performance, but FOA indirectly influences dart-throwing through implicit factors that affect eye-gaze behavior [38].

In a previous study, the FOA affected the quiet eye (QE) duration (QED) but not the dart-throwing accuracy [36]. QE refers to gaze fixation and is a key metric for differentiating between expert- and novice-level throwing ability in motor tasks [39]. A longer QED is associated with more accurate dart throwing, although it is difficult to control the QED [38]. EF is associated with a longer QED. Among participants with low expertise, a weak correlation was observed between QED and accuracy; however, this correlation was stronger in the presence of EF. In contrast, other studies have shown that QE is a complex process that depends on the cognitive burden but is unrelated to the accuracy or EF [40].

III. MATERIALS AND METHODS

Dart-throwing performance was compared among experimental conditions in participants who were or were not presented with AR trajectories and were or were not wearing an HMD. All experimental procedures were approved by the Ethics Review Board of the National Defense Academy of Japan.

A. PARTICIPANTS

This study included 20 academy students (all males) aged 19–23 years who had normal or corrected-to-normal vision and no history of neurological or psychiatric conditions. The participants were non-experts in throwing darts and included two left-handed participants. The participants provided written informed consent prior to inclusion in the study.

B. APPARATUS

A commercially available soft dartboard was positioned at a height of 1.73 m. The distance from the throwing line to the dartboard was 2.44 m (Fig. 2a). The participants threw standard plastic-tipped darts of identical size and weight while wearing an AR HMD (HoloLens 2; Microsoft Corp.; Fig. 2b). The system was constructed using the Unity game engine 2019 (Unity Technologies, San Francisco, CA, USA). The darts were tagged with two reflective markers placed on the tip and root of the dart shaft (Fig. 2c). The markers were tracked using a motion capture (MOCAP) system (OptiTrack V120: Trio; NaturalPoint, Corvallis, OR, USA), which consisted of three inline MOCAP cameras. The dart positions were considered to be the center of the two markers.

The dart positions were sampled at 120 Hz and transmitted to the AR HMD using UDP communication via a Wi-Fi network. On the AR HMD, the data were filtered using a sixth order Butterworth low-pass filter at 10 Hz. The dart positions were connected with a straight line and drawn as a blue trajectory with 2-cm width at a refresh rate of 60 Hz. One side of the line was always facing the participant according to the position of the AR HMD. After the dart was struck, the trajectory color changed from blue to green. The green trajectory was displayed until the next dart was thrown.

C. EXPERIMENTAL PROCEDURE

The experiment consisted of three blocks with different experimental conditions ("null," "w/o," and "w/"). Each block comprised 20 dart throws (Fig. 2d). The participants threw the darts with their dominant hand and aimed for the center of the dartboard (the bull's-eye). In the null condition, the participants threw darts without wearing the AR HMD. In the w/o condition, the participants wore the AR HMD, but the dart trajectory was not shown. In the w/ condition, the participants threw darts while wearing the AR HMD, which displayed the dart trajectory of the previous trial.

The participants completed three blocks that were presented in a random order to cancel any order effects. There were six possible block orders, i.e., "null–w/o–w/," "null–w/–w/o," "w/o–null–w/," "w/o–w/–null," "w/–null–w/o," and "w/–w/o–null"; four, two, three, four, three, and four participants were allocated to these orders, respectively. There was an approximately 1-min rest period between the blocks. Before the experiment, the participants completed 5–10 practice throws without wearing the AR HMD (null condition) to familiarize themselves with the task and laboratory environment.

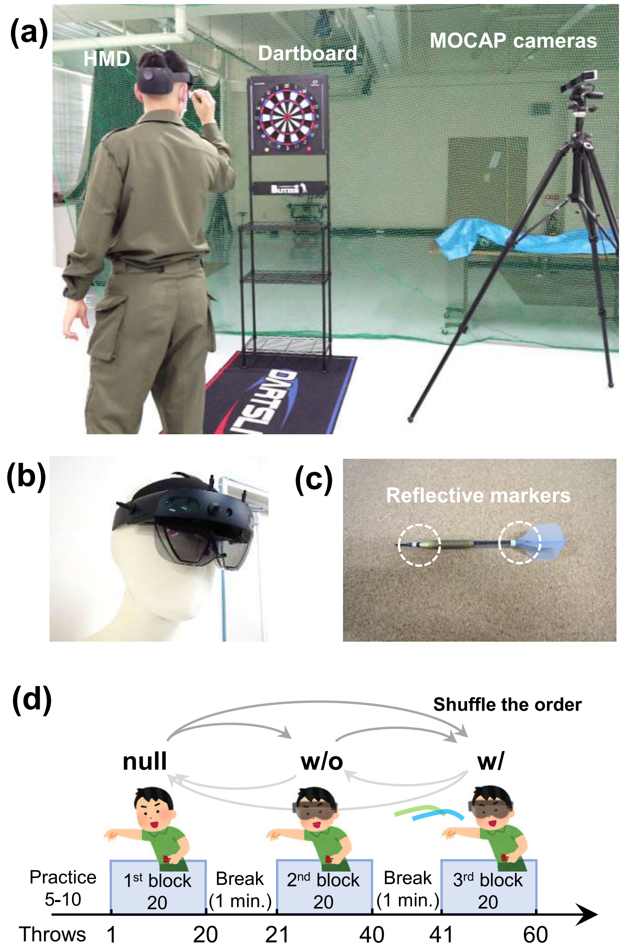

FIGURE 2. Experimental setup. (a) Experimental setting. (b) Microsoft HoloLens 2 AR HMD. (c) Darts with reflective markers. White dashed circles indicate marker locations. (d) Experimental sequence and conditions.

D. DATA ANALYSES

We calculated the absolute error for the dart positions on the dashboard with respect to the bull's eye. The first 4 of 20 throws in each block were excluded from the analysis to rule out any effects of adaptation to the experimental conditions. Thus, the mean and standard deviation (SD) of the error were calculated for the latter 16 throws in each block for each participant. Additionally, we computed the variance of the dart position from the latter 16 throws.

A standard bootstrap technique was used to generate boot-strap confidence intervals for the mean error and variance across participants. Then, the data were resampled by a factor of 10, i.e., 200 samples.

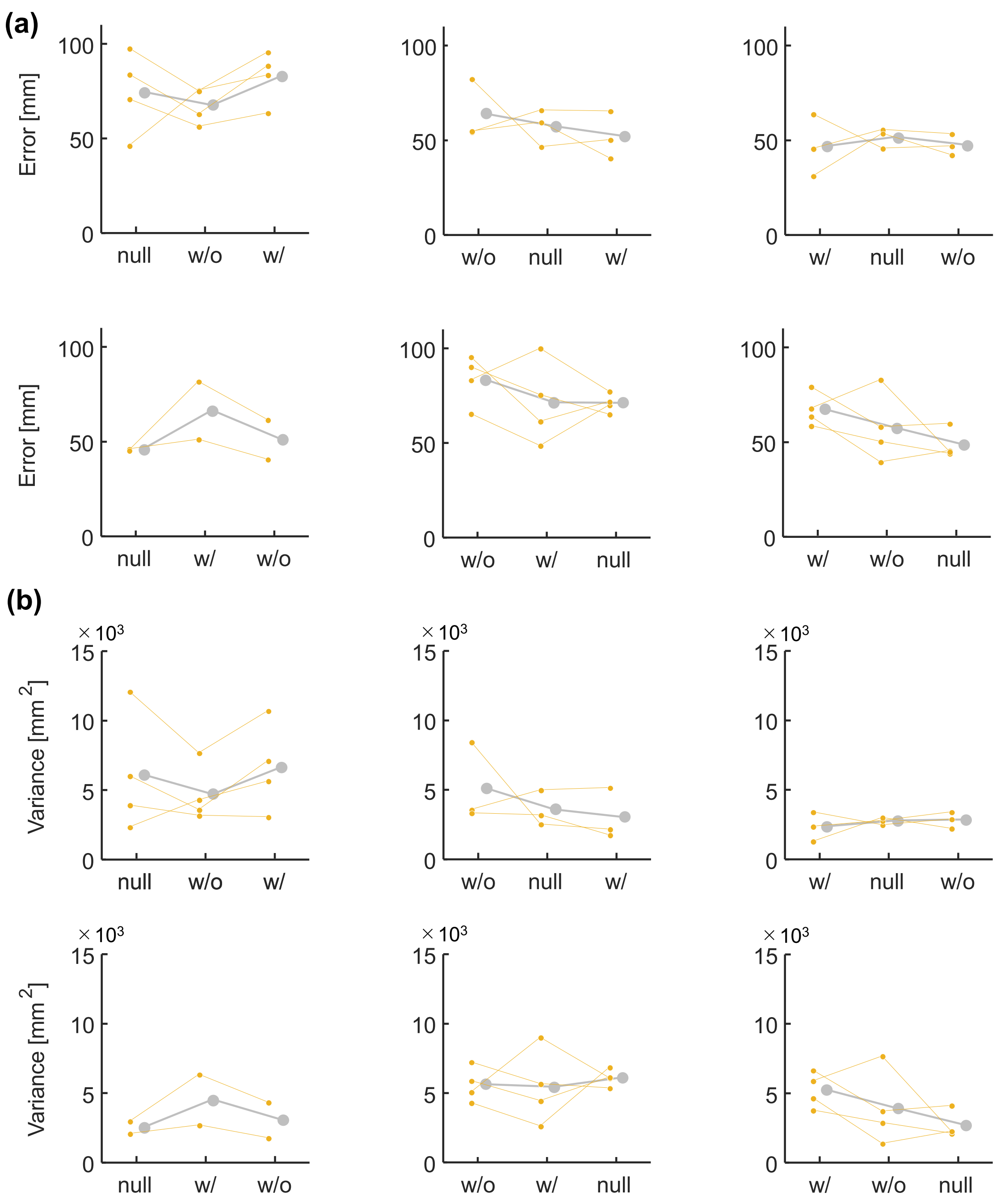

FIGURE 3. Data collected for each block order. Small yellow dots represent data of individual participants. Large gray dots represent the mean values for participants in each block order. The (a) mean error and (b) variance of the dart positions are shown. In each panel, the presentation of the data from left to right data indicates the group order.

A two-way repeated measures analysis of variance (ANOVA) was used to compare blocks and block orders, and to evaluate the interaction effect of block order and condition. An alpha level of 0.05 was used for the analysis.

IV. RESULTS

The experiment included three block conditions for six groups (Fig. 3). The two-way repeated measures ANOVA revealed no significant order × condition interaction effect on error ($F_{(4,51)} = 2.46$, $p = 0.057$, $\eta^2 = 0.15$; Fig. 3a) or variance ($F_{(4,51)} = 1.38$, $p = 0.26$, $\eta^2 = 0.10$; Fig. 3b). We organized the data according to block order and condition, and evaluated the main effects thereof on error and variance (Fig. 4).

Error (mean ± SD) decreased from the first to third block (first: 66.4 ± 18.8, second: 62.5 ± 15.3, third: 60.7 ± 16.7 mm; Fig. 4a, left panel), although the difference was not statistically significant ($F_{(2,51)} = 0.85$, $p = 0.43$, $\eta^2 = 0.03$). Similarly, there was no significant difference among block conditions (Fig. 4a, right panel; $F_{(2,51)} = 0.73$,

$p = 0.49$, $\eta^2 = 0.02$), although the error in the w/ condition was larger than that in other conditions (null: 59.9 ± 15.3, w/o: 63.7 ± 17.0, w/: 65.9 ± 18.5 mm).

There was no significant difference in variance in dart position according to block order (first: 4.79 ± 2.54, second: 4.23 ± 2.07, third: 4.30 ± 2.35 × 10^3 mm^2 [mean ± SD]; $F_{(2,51)} = 0.44$, $p = 0.65$, $\eta^2 = 0.00$; Fig. 4b, left panel). Regarding block condition, the w/ condition showed larger variance than the other conditions (null: 4.20 ± 2.45; w/o: 4.37 ± 2.04; w/: 4.74 ± 2.48 × 10^3 mm^2; Fig. 4b, right panel), although the difference was not significant ($F_{(2,51)} = 0.38$, $p = 0.69$, $\eta^2 = 0.00$).

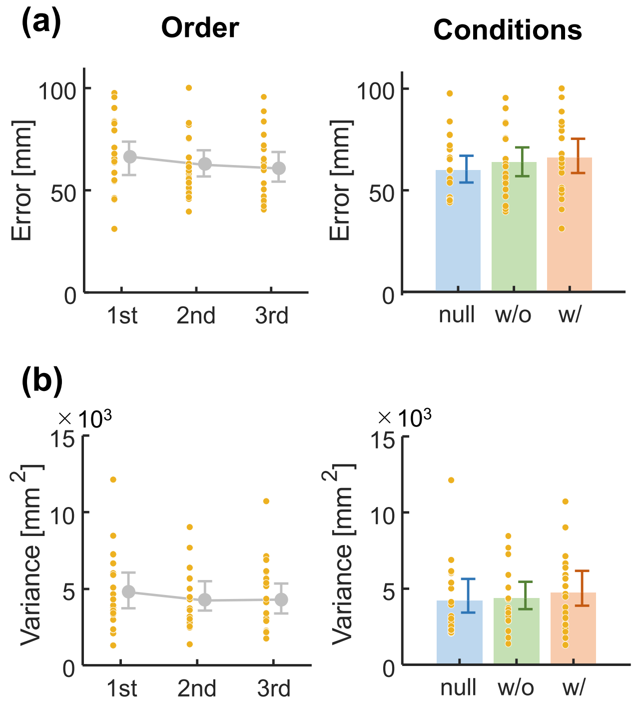

FIGURE 4. Effects of block order and conditions. The (a) mean error and (b) variance of dart positions are shown. Left and right columns indicate block order and conditions, respectively. Small yellow dots represent the data of individual participants. Vertical bars indicate 95% bootstrap confidence intervals. No significant differences were observed among the conditions.

V. DISCUSSION

Previous studies have suggested that the EF plays a crucial role in the training of dart-throwing skills [1]. Furthermore, in line with the motor learning theory in computational neuroscience [3], [4], explicit error effectively facilitates the acquisition of motor skills. Thus, we hypothesized that presenting a dart trajectory using AR would enhance performance in dart-throwing tasks. To test this hypothesis, we evaluated an AR system and found no improvement of dart-throwing performance with AR trajectory feedback. Thus, trajectory feedback did not affect performance during or after training.

Although our approach was in line with the EF and motor learning theory, it did not improve dart-throwing performance. This may be because of variations in the presented trajectories and, consequently, participant gaze behavior, i.e., QE. Although several studies have explored the relationship between QED and motor performance, QE affects motor learning directly [41] and indirectly [38], [42], [43]. In this study, performance in the condition with AR trajectory was worse in terms of error and variance, although the difference was not significant. This may be due to the QE disruption induced by varying the presented trajectory.

Because EF can improve the QED [36], other trajectory feedback systems may produce different result from our study. For example, an optimal trajectory to the target appears to be the best candidate. Using a trajectory that avoids QE variation may prevent trajectory variability. However, it is difficult to determine the optimal dart-throwing trajectory using computation because optimization requires the following information: release point, throwing speed, and dart launch posture. If the release point is fixed during a dart-throwing simulation, the optimal dart launch posture and throwing speed can be determined based on the presence of motor noise [23]. The motor plan is optimized according to the motor noise, i.e., planning and execution noise [24]. Planning noise can induce exploration of the motor plan and is equivalent to exploration noise. A good balance between noise types is essential for optimal reinforcement learning [44]. Therefore, modulating motor noise is essential to improve performance in aiming motor tasks, such as dart throwing.

A limitation of this study is the small sample size of 20 participants. Although there were no significant order × condition interaction effects, the effect sizes (η^2) were large at 0.10 or greater. According to a post-hoc statistical power analysis, the statistical powers for the error and variance were 0.83 and 0.53, respectively, at the 0.05 significance level. Thus, we could not exclude the possibility of the interaction effects due to insufficient of the statistical power caused by the small sample size. On the other hand, we assume that the results of the main effects were not significantly affected by the sample size, because the effect sizes of the main effects on the error and variance were small at 0.03 or less. Therefore, we confirm that the block order and condition had no direct effect on the dart throwing performance.

VI. CONCLUSION

We developed an AR-based trajectory feedback system to improve dart throwing ability. We evaluated the improvement in aiming accuracy after use of the feedback system. Based on studies of EF [1] and motor learning theory in computational neuroscience [3], [4], the feedback system was developed to improve dart-throwing performance. However, our results showed that trajectory feedback did not affect dart-throwing performance. Our results will provide a basis for further studies on AR.

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AUTHOR CONTRIBUTIONS

Yuki Ueyama designed this study, prepared the materials, performed the experiments, analyzed the data, and wrote the manuscript. Yuki Ueyama and Masanori Harada discussed the results and approved the final manuscript.

SUPPLEMENTARY MATERIAL

The supplementary material includes a video (S1.mp4).

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