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The Short-Term Effects of Real-Time Virtual Reality Feedback on Motor Learning in Dance

Abstract

Does virtual reality (VR) represent a useful platform for teaching real-world motor skills? In domains such as sport and dance, this question has not yet been fully explored. The aim of this study was to determine the effects of two variations of real-time VR feedback on the learning of a complex dance movement. Novice participants ($n = 30$) attempted to learn the action by both observing a video of an expert's movement demonstration and physically practicing under one of three conditions. These conditions were: full feedback (FULL-FB), which presented learners with real-time VR feedback on the difference between 12 of their joint center locations and the expert's movement during learning; reduced feedback (REDUCED-FB), which provided feedback on only four distal joint center locations (end-effectors); and no feedback (NO-FB), which presented no real-time VR feedback during learning. Participants' kinematic data were gathered before, immediately after, and 24 hr after a motor learning session. Movement error was calculated as the difference in the range of movement at specific joints between each learner's movement and the expert's demonstrated movement. Principal component analysis was also used to examine dimensional change across time. The results showed that the REDUCED-FB condition provided an advantage in motor learning over the other conditions: it achieved a significantly greater reduction in error across five separate error measures. These findings indicate that VR can be used to provide a useful platform for teaching real-world motor skills, and that this may be achieved by its ability to direct the learner's attention to the key anatomical features of a to-be-learned action.

1 Introduction

Advances in wireless technology, motion capture systems, and virtual environments have inspired numerous attempts to develop virtual reality (VR) training environments that improve the teaching of sports-related motor skills. The efficacy of training sports skills in virtual environments has been examined, but not conclusively, in domains as varied as snowboarding (Spelmezan, Jacobs, Hilgers, & Borchers, 2009), martial arts (Yang & Kim, 2002), golf (Honjo, Isaka, Mitsuda, & Kawamura, 2003), target-driven aiming tasks (Huegel, Celik, Israr, & O'Malley, 2010; Huegel & O'Malley, 2010), tai chi (Patel, Bailenson, Jung, Diankov, & Bajcsy, 2006), aerobic exercise training (Ruttkay & van Welbergen, 2008), and dance (Yang, Yu, Diankov, Wu, & Bajscy, 2006; Nakamura,

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Tabata, Ueda, Kiyofuji, & Kuno, 2005; Drobny, Weiss, & Borchers, 2009). However, caution should be taken when using intuitively designed VR training environments, as it is clear that they may not always benefit motor learning, or reliably facilitate the transfer of motor skills from VR to more naturalistic settings (Li, Patoglu, & O'Malley, 2009). Addressing this issue, researchers have manipulated various practice components, such as virtual fixtures (Rosenberg, 1993), shared control (Huegel & O'Malley, 2010) and other haptic feedback mechanisms (Tzafestas, Birbas, Koumpouros, & Christopoulos, 2008), such as vibromotors attached to limbs that cue action within prespecified time constraints (Drobny & Borchers, 2010). However, a complementary approach involves manipulating real-time VR feedback while learners observe an expert's movements in a visual demonstration.

Previous attempts to manipulate real-time VR feedback have used motion capture systems to create a real-time virtual model of the learner (typically as a moving stick figure). This has then been superimposed on top of a previously obtained avatar of an expert's performance, and displayed within a 3D VR environment (e.g., Honjo et al., 2003; Yang & Kim, 2002). The intention of this technique is to provide learners with information feedback about the limb location and timing discrepancies between their own and a desired action. However, the presentation of biological motion information in this format is arguably difficult for learners to interpret effectively for error reduction purposes; it may also provide no greater learning advantage over simply observing and then imitating a demonstrator (see Chua, Daly, Schaaf, & Camill, 2003). Consequently, it is not yet clear how best to provide real-time VR feedback to learners about their technique to bring about a series of desired and relatively permanent changes in their motor behavior that enhance their real-world performance. Therefore, we take a more fundamental motor learning approach to investigating the key anatomical features of human biological motion that, when presented as real-time VR feedback, might best promote motor skill learning. To this end, we introduce our novel method of using a point light display (PLD) to provide learners with real-time VR feedback.

In order to display real-time VR feedback about movement to learners in an intuitive way, it is necessary to first understand how the visual perception system might pick up information from the visual field. One proposal is Scully and Newell's (1985) visual perception perspective (VPP). This view was based on Gibson's (1979) notion of direct perception-action coupling and Newell's (1985) constraints-led approach. Scully and Newell (1985) predicted that, when performers observe and attempt to replicate a demonstrated movement, they attend to the relative motion information between certain key anatomical components. Relative motion is the movement of one body part (e.g., the wrist) relative to other body parts (e.g., the shoulders) across time and space. Scully and Newell's reasoning was predicated on evidence that the visual perception system is highly sensitive to the invariant features of human biological motion when this is presented in a dynamic PLD (Johansson, 1973). A PLD is generated using a motion tracking system, firstly to detect the temporal-spatial locations of joint center markers that are placed on the main joints of the body, and secondly, to visually depict both the absolute and relative motion of these markers in the form of white dots displayed against a black background. A PLD represents kinematic information that specifies an actual or desired behavioral property of movement, or knowledge of performance (Newell, 1991). Therefore, if learners received real-time motion-based feedback about their own movements in PLD form, this should present visual information that is intuitive to their visual perception system's means of information pickup. We refer to this form of visual information as *real-time VR feedback*. Despite the intrinsic appeal of this approach, to our knowledge no previous research exists that has examined the effects of this kind of real-time VR feedback on motor learning.

The VPP broadly described human relative motion as an important variable that is picked up concurrently by the visual perception system for use when reproducing an observed action (Scully & Newell, 1985). On this basis, our first experimental condition (FULL-FB) provided real-time VR feedback to learners about the temporal-spatial differences between 12 of their major joint centers and an expert's demonstration during practice.

However, it is possible that certain aspects of full-body real-time VR feedback would become less relevant to learners as a consequence of their visual perception system's inherent selective attention toward task-relevant information. Accordingly, learners might also benefit from real-time VR feedback that emphasizes only certain key anatomical features that are directly related to goal achievement (see Janelle, Champenoy, & Coombes, 2003), rather than merely receiving global representations of their movement form.

According to the VPP, novices in the initial phases of motor learning might identify one source of perceptual information from the multitude of available sources to guide their actions (see also Savelsbergh & van der Kamp, 2000). The emergence of this coupling between perceptual information and action would be induced by the interaction of constraints (i.e., environmental, organismic, and task; see Newell, 1991), through the demands and goals of the task (Savelsbergh, van der Kamp, Oudejans, & Scott, 2004; see Eaves, Hodges, & Williams, 2008). This process is termed the education of perception (Gibson, 1979), whereby a learner must progressively focus or center perception on the critical aspects of an observed movement that specifies action, and attend less to the less relevant, nonspecifying aspects (Jacobs & Michaels, 2002).

Initial research has examined the effects of removing specific visual features from a display to determine the key visual perceptual variables that constrain observational learning. Scully and Carnegie (1998) showed that removing markers from end-effector locations in a PLD, that is, the toe and ankle positions, disrupted the observational learning of a complex dance movement. This finding indicates that, for their task, distal features (e.g., wrists and ankles) were more relevant for perceiving the to-be-learned action than other kinematic variables (Hodges, Williams, Hayes, & Breslin, 2007). Importantly, in Scully and Carnegie's (1998) experimental task, these distal features traveled through greater motion trajectories than the proximal features (e.g., shoulders and hips). Other research has also shown that information about movement goals is prioritized over relative motion or specific motor segments (i.e., Bekkering, Wohlschlager, & Grattis, 2000). Therefore, goal representation (i.e., an objective criterion) and the visual representation of the agents involved in achieving the goal (e.g., a particular limb) may influence learning over and above a demonstrated behavioral strategy (see Bekkering et al., 2000). By design, our experimental task required the learner's wrists and right ankle to travel through greater motion trajectories than all other kinematic variables. Therefore, it was predicted that the extremities of our demonstrator's limbs would convey the most crucial perceptual information and, as such, be the most relevant features for learning the action. Similarly, it was conceivable that these distal features would also be perceived by learners as being those that were most closely associated with goal achievement. Therefore, our second experimental condition (REDUCED-FB) only provided real-time VR feedback on wrist and ankle positions.

Previous research investigated the visual perceptual information that minimally constrains observational learning. In contrast, the effect of augmenting this crucial information as real-time VR feedback has not yet been explored. We provided real-time VR feedback to learners about the difference between their own relative motion and an expert's movements when imitating a complex dance movement. Our aim was to assess the impact of two variations of this real-time VR feedback on motor learning. It was hypothesized that learners would be advantaged under the REDUCED-FB condition. In order to test this prediction, learning was assessed as a function of changes in the participants' kinematic variables toward a kinematic representation of an expert's complex dance movement. The two experimental conditions (FULL-FB and REDUCED-FB) were compared in this way to a no-feedback condition (NO-FB), where learners carried out the same physical practice and observed the same number of demonstrations but received no real-time VR feedback during learning.

2 Method

2.1 Participants

Thirty novice participants (17 male, 13 female, $M_{\text{age}} = 21$ years, age range = 20–29 years) volunteered for the study. All had normal or corrected-to-normal vision and reported having no previous dance training. Informed consent was provided before participation and the experiment was conducted with research ethics approval from Teesside University.

2.2 Creating the Demonstration Video and Kinematic Model

A professional female dancer demonstrated the experimental task. The dancer had trained on average 5–6 hr per week for 10 yr, held the highest grade (Level 8) accredited by the Royal Academy of Dance (RAD) and had passed a further Advanced 1 Major Exam with RAD. Retroreflective markers were placed on all major joint centers on both sides of the expert's body: the acromion process (shoulder), lateral epicondyle (elbow), ulnar styloid (wrist), greater trochanter (hip), lateral condyle of the femur (knee), lateral malleolus (ankle), and the distal head of the fifth metatarsal (toe). The demonstrated task was a complex full-body dance sequence performed at a medium pace in the frontal plane (for maximal visibility for the learner). The expert's proximal joint centers (shoulders and right hip) displayed a large range of angular motion, while the position of these joints remained relatively stable throughout the movement. In contrast, the reverse was true for the three corresponding distal joints (see Table 1). A professional dance tutor deemed the movement appropriately challenging (physically and cognitively) for a novice learning the movement during the experiment.

The expert performed 10 repetitions of the movement. Temporal-spatial positions were gathered using a computer running motion-capture software (Nexus 1.2.103, Vicon Motion Systems, Oxford, UK) linked to six motion-sensitive infrared cameras sampling at 100 Hz (MX13, Vicon Motion Systems, Oxford, UK) (cf. Breslin, Hodges, Williams, Curran, & Kremer, 2005; Breslin, Hodges, Williams, Kremer, & Curran, 2006). Positional data from six of the expert's major joint centers (ankle, knee, hip, shoulder, elbow, wrists) on both sides of her body in 3D (i.e., in the X, Y, and Z planes) were tracked during her performance of the task. The range of motion over time was calculated for each of the 36 dependent variables (that is, $6 \times 2 \times 3$). These data were filtered using a Woltring routine before being linearly interpolated and normalized to 100 data points (see Winter, 1990). Principal component analysis (PCA) was used to determine the dependent variables for inclusion in the main analysis. This identified the proportional contributions of each dependent variable (i.e., each joint in each plane of motion) to the global variance within each trial (Jolliffe, 2002). The results confirmed that three components contributed at least 73% to the global variance that was observed in each of the expert's trials: Component (1) the left and right elbows in the X axis and left and right shoulders in the Y axis (48%); Component (2) the right knee and right hip in the X axis (16%); and Component (3) the right ankle in the X axis (9%). These seven dependent variables were selected for further analysis.

The temporal-spatial location of peak angular displacement was identified for each dependent variable in each of the expert's 10 trials. The single trial that was selected as the criterion movement was defined as the trial that contained the most median peak angular displacement values (cf. Al-Abood, Davids, Bennett, Ashford, & Marin, 2001; Mullineaux, Bartlett, & Bennett, 2001). Variability (*SD*) across the peaks was minimal in each variable across all 10 trials (see Table 2). A digital video camera (Panasonic NV-MX500B, Matsushita Electric Industrial Co. Ltd, Japan) was used to film these 10 trials. The video trial selected for demonstration was altered using video editing software (Pro 1.5, Adobe Premier Systems, San Francisco) so that it was preceded by a "3-2-1-Ready?" prompt.

2.3 Task

For kinematic data collection, retroreflective markers were placed on the novice participants' joint centers, as described above for the expert. Participants performed a 5-min warm-up routine, stretching muscle groups relevant to the task, before assuming a start position 4 m from a projection screen (height = 3 m; width = 3 m). A life-sized video demonstration of the expert's actions was presented in blocks of three repetitions on the screen using a projector (Hitachi CP-X445 Multimedia LCD Projector, Hitachi Ltd., Japan) linked

Table 1. *Experimental Task Described from Participant's Perspective (i.e., in Mirror, Not Anatomical Symmetry) Using Classical Ballet (Warren, 1989) and Anatomical Terms*

Order	Classical ballet terminology Soviet Syllabus: Dévelopé à la seconde	Anatomical posture required for imitation	Image
1	Feet: 1st position Arms: preparatory position	Place both heels together, feet turned outward. Extend both shoulders slightly, flex both elbows slightly.	
2	Right leg: lift into retiré Arms: pause briefly in 1st position	Flex right hip and right knee, and point right toe simultaneously. At the same time extend both shoulders slightly and flex both elbows in synchrony to maintain bilateral symmetry in the upper limbs.	
3	Right leg: extend à la seconde Arms: raise into big pose	Flex right hip further, maximally extend right knee and point right toe simultaneously. At the same time maximally extend right shoulder to a vertical position and extend left shoulder to midpoint in range. Maximally extend both elbows in synchrony.	
4	Right leg: lower to point à la seconde Arms: open to 2nd position	Extend right hip while maintaining maximal right knee extension and pointed right toe. At the same time flex right shoulder to midpoint in range with maximally extended elbow to achieve bilateral symmetry in upper limbs.	
5	Right Leg: close to place both feet in 1st position Arms: lower into preparatory position	Place both heels together, feet turned outward. At the same time flex both shoulders and slightly flex both elbows in synchrony to maintain bilateral symmetry in the upper limbs.	

to a computer running the Adobe Premier Pro 1.5 video editing software. Participants remained still when observing the first block of three demonstrations. Kinematic data were then sampled at a pretest that required participants to replicate the movement three times in the absence of both the video demonstration and any feedback (consequently, this was self-paced). The data gathered across these three trials were collectively termed

Table 2. *Median Kinematic Trial Used in Main Analysis (SD)*

Dependent Variable	Timing of peak angle (%)		Amplitude of peak angle (°)	
Right hip	39	(1.3)	110	(5.1)
Right knee	26	(1.6)	138	(0.9)
Right ankle	25	(2.2)	–46	(1.0)
Right shoulder	38	(3.2)	76	(2.2)
Left shoulder	16	(1.9)	79	(3.3)
Right elbow	51	(2.3)	150	(3.2)
Left elbow	32	(1.3)	75	(6.6)

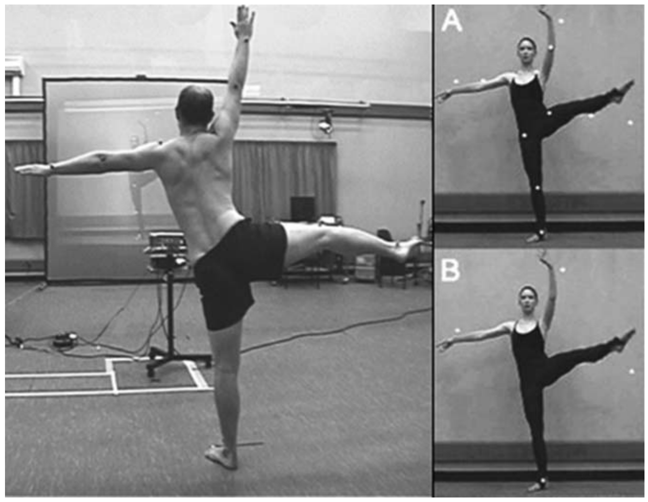

Figure 1. *Experimental setup: real-time VR feedback presented under (A) the FULL-FB condition; (B) the REDUCED-FB condition (currently in position 3: see Table 1).*

sample time point 1. The learning period was then composed of five blocks of three repetitions of the movement with 2-min rest periods interspersed between blocks to minimize any effects of fatigue. Practice trials were externally paced as participants were required to synchronize their movements in time and space with the expert's prerecorded demonstration (see Figure 1). Kinematic data sampling conditions identical to sample time point 1 were replicated at the end of learning (sample time point 2) and in a 24-hr retention test (sample time point 3). Participants undertook the same pretest warm-up routine immediately before the retention test. Additionally, they did not observe the demonstration or the real-time VR feedback before or during sample time point 3 (consequently, this was self-paced). This protocol of conducting a single training session followed by a 24-hr retention test was consistent with other experiments in the sports science/motor learning literature, which have similarly examined the short-term effects of action observation plus physical practice on motor learning (see Al-Abood et al., 2001; Breslin et al., 2005; Breslin et al., 2006). For alternative and longer training durations, see other published work on virtual training environments (e.g., Huegel et al., 2010).

2.4 Real-Time VR Feedback

Participants were randomly assigned to one of three learning conditions that differed only in the nature of visual information available during learning. Two groups received real-time VR feedback about their movements at a frequency that reduced across the learning period (see Table 3). The guidance hypothesis (Salmoni, Schmidt, & Walter, 1984) predicted that motor learning can be enhanced by reducing the frequency of feedback presentations relative to the number of practice trials across the learning period. This can negate the development of feedback dependencies detrimental to learning: an effect that is robust in both action generation (cf. Winstein & Schmidt, 1990) and observational learning tasks (cf. Badets & Blandin, 2004, 2005). Participants in the current study received feedback on six practice trials. This created a feedback frequency of 29% relative to the 21 physical practice trials on the first day (cf. Hodges, Hayes, Eaves, Horn, & Williams, 2006), and was presented as a faded frequency.

Two projectors (Hitachi CP-X445 Multimedia LCD Projector, Hitachi Ltd., Japan) were used to create the real-time VR feedback. The first projected an image of the expert's prerecorded video demonstration onto the large screen 4 m in front of the participants. The second projector was used to superimpose a second image onto the same screen at the same location as the prerecorded video demonstration. The second image was a real-time dynamic PLD, which depicted only the participant's white joint center markers. This PLD was created using a computer running the motion capture software linked

Table 3. *Research Design for All Conditions, with Additional Feedback Schedule Across the Learning Period for the Two Experimental Conditions Only*

	Pretest: Sample time point 1			Learning period															End of learning: Sample time point 2			24-hour retention: Sample time point 3		
				Block 1			Block 2			Block 3			Block 4			Block 5								
Trials	1	2	3	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	1	2	3	1	2	3
Feedback				✓	✓	✓		✓	✓				✓											

to the six motion-sensitive cameras. This system was sufficiently sensitive to detect the 3D locations of the reflective markers that were selectively placed on the participant's joint centers. While participants remained in the start position, the dimensions of their PLD were transformed using the simple viewing options in Vicon to accurately match the expert's body dimensions in the prerecorded video, which remained clearly visible underneath the PLD. Together, the two images formed one display that could provide learners with real-time VR feedback. Learners could now attend to the visual discrepancy, in real time, between their own dynamic temporal-spatial body positions (as depicted by their real-time white joint center locations in the PLD) and the expert's actions in the prerecorded image (see Figure 1).

The quantity of joint center markers presented as real-time VR feedback on practice trials was manipulated to achieve the experimental conditions. Learners under the FULL-FB condition received real-time VR feedback on 12 (2×6) joint center locations during practice. These were positioned on both sides of their bodies on their ankles, knees, hips, shoulders, elbows, and wrists. Learners under the REDUCED-FB condition received real-time VR feedback on only four (2×2) joint center locations: the wrists and ankles. Learners under the NO-FB condition carried out the same procedures as the other two groups, but received no augmented feedback about joint marker information. In order to collect full-body kinematics at each sample time point, the full set of reflective markers had to be replaced on all participants' bodies, as described in Section 2.2, after each set of practice trials.

2.5 Kinematic Data

2.5.1 Relationship Properties. Assessing the degree of correlation between two limb segments, as a function of learning, is an analysis technique "particularly suited to human movement" (Mullineaux et al., 2001, p. 752; see also Brick & Boker, 2011). Therefore, cross-correlation coefficients with zero time lags were calculated for each combination of joint pairings in the expert's data using the seven dependent variables employed in the main analysis (see Section 2.2) and

Table 4. *Highly Correlated Joint Pairings Identified in the Expert's Movement Trial*

Joint pairings	Cross-correlation scores
Right hip to right knee	1.0
Right hip to left elbow	0.8
Right hip to right elbow	0.8
Right knee to left elbow	0.9
Right knee to right elbow	0.8
Left shoulder to right shoulder	0.8
Left elbow to right elbow	0.9

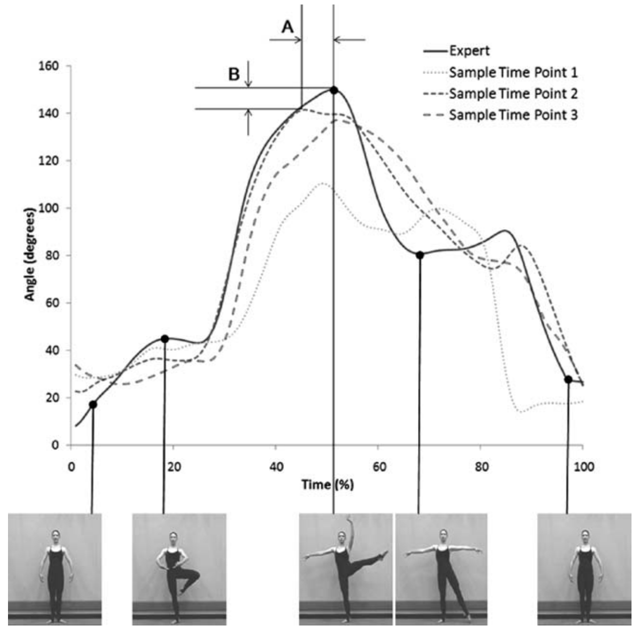

Figure 2. *Example data illustrating how timing (A) and amplitude (B) errors were quantified for one participant's mean movement trace at the right shoulder in the* Y axis at sample time point 2.

transformed to Fisher *z* scores (cf. Hodges, Hayes, Horn, & Williams, 2005). Highly coupled joint angles that moved simultaneously in the same (positive correlation) or different directions (negative correlation) were characterized by correlation coefficient values between 0.8 and 1, as described by Franzblau (1958). Seven joint pairings were identified in the expert's data as having a highly correlated (positive) relationship (see Table 4). The linear relationship within each of these pairs was calculated for each participant. This was achieved by calculating individual mean Fisher *z* scores for each participant for each joint pair from the three trials performed within a single sample time point. Error was defined as the difference between individual mean scores and the expert's score. Group mean error scores were then calculated for each joint pair at the three sample time points.

2.5.2 Absolute Properties. To assess the contribution of each joint, the range of motion in all seven dependent variables was examined across time. This provided a detailed insight into the differences in continuous, temporal, and peak angular displacement between the expert's criterion movement and the learners' movements across the learning period, which is an analysis protocol recommended by Mullineaux et al. (2001; see Figure 2).

2.5.2.1 Continuous Error. Participants performed three movement trials at each sample time point. A mean movement trace was calculated from these three trials for each joint angle at each sample time point. Error was defined as the absolute difference between each individual mean trace and the expert's temporal-spatial movement pattern at every time point (i.e., continuously) throughout the duration of each trial, which was normalized to 100 data points. This was calculated using 95% confidence intervals (95% CI), which is similar to the root mean squared difference technique, but shows a greater magnification of effects for trial sizes where $n \leq 3$ (Mullineaux et al., 2001). Group mean error scores were then calculated from individual means for each joint angle at each sample time point. This index of coordination is a measure of within-participant variability, which is sensitive to both constant errors (the average deviation of the participants' mean pattern from the goal pattern) and within-participant variability (Schmidt & Wulf, 1997).

2.5.2.2 Mean Timing Error for Peak Angle (%). Normalizing each trial length to 100 data points allowed the timing of a peak angle to be identified for each joint and expressed as a percentage of the total time taken to perform the movement. Individual mean timing scores were calculated for the three trials each participant performed at each sample time point. Error was calculated as the difference between individual mean scores and the timing of the expert's peak angle (see Table 2). Group mean timing error was then calculated from the individual means for each dependent variable at each sample time point. This method was employed by Scully and Carnegie (1998) and described in detail by Mullineaux and colleagues (2001).

2.5.2.3 Mean Angular Displacement at Peak Angle (°). The amplitude of peak angular displacement was located within each participant's kinematic data. Individual mean scores were calculated across the three trials at each sample time point for each participant in each dependent variable. These individual mean scores were compared to the expert's data to derive group mean error scores at the three sample time points for each of the seven dependent variables.

2.5.2.4 Standard Deviation. Standard deviation was calculated separately on each of the positional data involved in the three error measures above. This index was an indication of the level of movement pattern stability across trials.

2.6 Statistical Analysis

Parity across the three groups' initial level of ability in the task at sample time point 1 (i.e., prior to practice) was confirmed by the nonsignificant results from each one way ANOVA (1×3) that was conducted on each dependent variable. All dependent variables were then individually subjected to a 3×3 mixed measures ANOVA, wherein group and time were the two factors analyzed. All analyses were assessed and adjusted for sphericity when necessary using a Greenhouse–Geisser correction. Effect sizes were calculated for each ANOVA using partial eta squared (η_p^2) values. Comparisons of interest between two mean values involved in main effects and interactions were investigated using Tukey HSD procedures with a Bonferroni-adjusted alpha level of .008 per test (.05/6).

3 Results

3.1 Relationship Properties

Analyses of variance performed on the group mean error in Fisher z scores for the seven paired joints showed a main effect for time for the following four pairings: right hip to left elbow $F(2,54) = 17.38$, $p = 0$, $\eta_p^2 = .39$, right hip to right elbow $F(2,54) = 15.3$, $p = 0$, $\eta_p^2 = .36$, right knee to left elbow $F(2,54) = 14.34$, $p = 0$, $\eta_p^2 = .35$ and right knee to right elbow $F(2,54) = 17.15$, $p = 0$, $\eta_p^2 = 3.9$. Post hoc analyses showed significant differences between sample time points 1 and 2. There were also significant differences between sample time points 1 and 3 for the REDUCED-FB condition (right hip to left elbow; right hip to right elbow; right knee to left elbow; right knee to right elbow), the FULL-FB condition (right hip to right elbow; right knee to left elbow; right knee to right elbow), and the NO-FB condition (right knee to right elbow). There were no further main effects for group. There were also no group $\times$ time interactions for the data. However, observation of Table 5 shows that in the REDUCED-FB condition there were more changes from either low or moderate levels of coupling to high levels ($n = 3$) than the FULL-FB ($n = 2$) and the NO-FB condition ($n = 1$). In addition, for the REDUCED-FB condition there were more changes from low to moderate levels of coupling ($n = 2$) than the FULL-FB ($n = 1$), but not for the NO-FB condition ($n = 3$).

3.2 Absolute Properties

The error in the range of movement at each joint was examined. Analyses of variance identified a number of significant main effects for time as well as group $\times$ time interactions (see Table 6). Results from the post hoc t tests used to investigate these effects further are reported below. Unless otherwise stated, all main effects involving time were due to differences between sample time point 1 and 2. No main effects for group were identified.

3.2.1 Continuous error (°). Post hoc tests examining the significant group $\times$ time interaction for the left

Table 5. *Mean Coefficients for Key Joint Pairings as a Function of Time*

Cross-correlation comparison	Condition	Learning period: Sample time point 1	Learning period: Sample time point 2	Retention: Sample time point 3
Right hip to right knee	NO-FB	0.9	0.8	0.8
	FULL-FB	0.7	0.7	0.7
	REDUCED-FB	0.7	0.8	0.8
Right hip to left elbow	NO-FB	0.4	0.6*	0.5
	FULL-FB	0.1	0.5*	0.4
	REDUCED-FB	0.1	0.5*	0.6*
Right hip to right elbow	NO-FB	0.4	0.7*	0.6
	FULL-FB	0.2	0.6*	0.6*
	REDUCED-FB	0.3	0.5*	0.6*
Right knee to left elbow	NO-FB	0.5	0.9*	0.8*
	FULL-FB	0.4	0.9*	0.8*
	REDUCED-FB	0.4	0.7*	0.8*
Right knee to right elbow	NO-FB	0.4	0.7*	0.7*
	FULL-FB	0.4	0.8*	0.8*
	REDUCED-FB	0.5	0.7*	0.8*
Left shoulder to right shoulder	NO-FB	0.8	0.8	0.8
	FULL-FB	0.8	0.9	0.9
	REDUCED-FB	0.9	0.9	0.8
Left elbow to right elbow	NO-FB	0.8	0.9	0.9
	FULL-FB	0.7	0.7	0.7
	REDUCED-FB	0.8	0.9	0.9

*Significant difference between this number and the corresponding number at sample time point 1. Changes from low or moderate levels of coupling to highly coupled pairings are shaded.

elbow revealed that only the REDUCED-FB group made a significant improvement between sample time points 1 and 2. This group was also significantly better than the FULL-FB group in retention (see Figure 3). A similar trend was observed in the right elbow data, but this finding was not significant.

Post hoc analysis of the main effect for time in the right ankle data revealed an improvement across sample time points 1 and 3. Further post hoc tests showed that the interaction effect for this variable was due to the significant differences between the error scores at sample time points 1 and 3 for both the REDUCED-FB and FULL-FB groups, which was not found for the NO-FB group (see Figure 4).

3.2.1.1 Standard Deviation of Mean Continuous Error. Post hoc tests investigating the group × time interaction for the left elbow revealed that only the REDUCED-FB group made a significant improvement between sample time points 1 and 2, which was retained at sample time point 3. However, the remaining groups did not achieve a performance level in the next-day retention test that was significantly different from their performance at sample time point 1 (see Figure 5).

3.2.2 Mean Timing Error for Peak Angle (%). Post hoc analyses of the group × time interaction for error in the timing of peak right hip angle showed

Table 6. *Main Findings: Significant Main Effects for Time and Significant Group × Time Interactions for Each Dependent Variable*

Error measure	Variable	Significant main effects for time			Significant group × time interactions
Continuous error	Left elbow	$F(2,54) = 7.9$,	$p = .001$,	$\eta_p^2 = .23$	$F(4,54) = 2.5$, $p = .05$, $\eta_p^2 = .16$
	Right elbow	$F(2,54) = 13.8$,	$p \leq .001$,	$\eta_p^2 = .34$	
	Right ankle	$F(1.9,54) = 25.4$,	$p \leq .001$,	$\eta_p^2 = .49$	$F(1.7,54) = 8.4$, $p = .001$, $\eta_p^2 = .24$
	Right knee	$F(1.7,54) = 55.9$,	$p \leq .001$,	$\eta_p^2 = .67$	
	Right hip	$F(1.9,54) = 4.2$,	$p = .002$,	$\eta_p^2 = .13$	
	Left shoulder	$F(2,54) = 10.1$,	$p \leq .001$,	$\eta_p^2 = .27$	
	Right shoulder	$F(2,54) = 36.7$,	$p \leq .001$,	$\eta_p^2 = .58$	
SD of continuous error	Left elbow	$F(2,54) = 7.9$,	$p = .001$,	$\eta_p^2 = .23$	$F(4,54) = 2.7$, $p = .04$, $\eta_p^2 = .17$
	Right elbow	$F(2,54) = 6.3$,	$p = .002$,	$\eta_p^2 = .19$	
	Right ankle	$F(2,54) = 5.6$,	$p = .01$,	$\eta_p^2 = .39$	
	Left shoulder	$F(2,54) = 11$,	$p \leq .001$,	$\eta_p^2 = .29$	
	Right shoulder	$F(1.7,54) = 28.5$,	$p \leq .001$,	$\eta_p^2 = .51$	
Mean timing error	Left elbow	$F(1.7,54) = 4.01$,	$p = .03$,	$\eta_p^2 = .13$	
	Right knee	$F(2,54) = 7.4$,	$p = .001$,	$\eta_p^2 = .22$	
	Right hip	$F(1.9,54) = 4.2$,	$p = .002$,	$\eta_p^2 = .13$	$F(2,27) = 3.5$, $p = .045$, $\eta_p^2 = .21$
	Left shoulder	$F(1.8,54) = 3.9$,	$p = .03$,	$\eta_p^2 = .13$	
	Right shoulder	$F(2,54) = 14.6$,	$p \leq .001$,	$\eta_p^2 = .35$	
SD of mean timing error	Right ankle	$F(1.7,54) = 5.6$,	$p = .01$,	$\eta_p^2 = .17$	
	Right knee	$F(2,54) = 4.7$,	$p = .013$,	$\eta_p^2 = .15$	
	Right hip	$F(1.8,54) = 3.7$,	$p = .04$,	$\eta_p^2 = .21$	
	Left shoulder	$F(2,54) = 11$,	$p \leq .001$,	$\eta_p^2 = .29$	$F(4,54) = 2.7$, $p = .04$, $\eta_p^2 = .17$
	Right shoulder	$F(1.7, 54) = 8.4$,	$p = .001$,	$\eta_p^2 = .24$	
Mean angular displacement error	Right ankle	$F(1.8, 54) = 9.1$,	$p = .001$,	$\eta_p^2 = .25$	
	Left shoulder	$F(2, 54) = 6.4$,	$p = .003$,	$\eta_p^2 = .19$	
	Right shoulder	$F(2, 54) = 5.8$,	$p = .005$,	$\eta_p^2 = .19$	
SD of mean angular displacement error	Right elbow	$F(1, 27) = 6.2$,	$p = .019$,	$\eta_p^2 = .19$	
	Right ankle	$F(1.8, 54) = 3.3$,	$p = .05$,	$\eta_p^2 = .11$	
	Right knee	$F(2, 54) = 4.7$,	$p = .013$,	$\eta_p^2 = .15$	

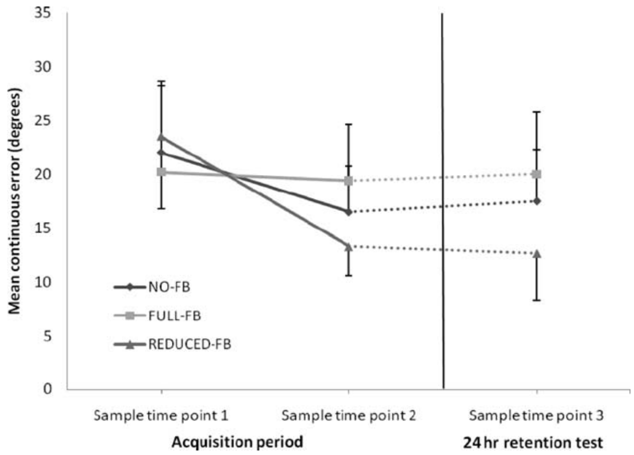

Figure 3. *Mean continuous error at the left elbow joint across time, with* SD.

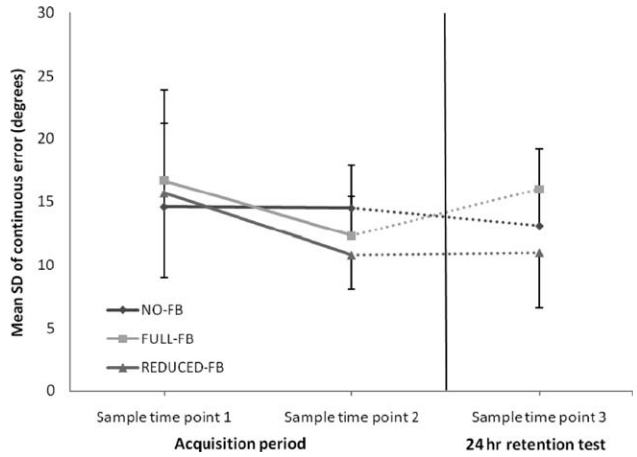

Figure 5. *Mean* SD *of continuous error at the left elbow joint across time, with* SD.

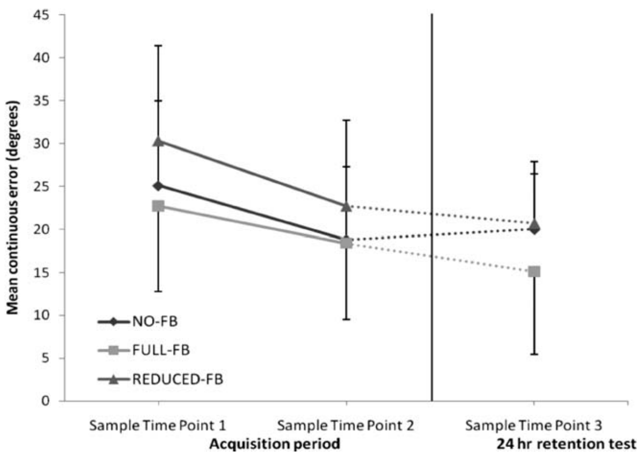

Figure 4. *Mean continuous error at the right ankle joint across time, with* SD.

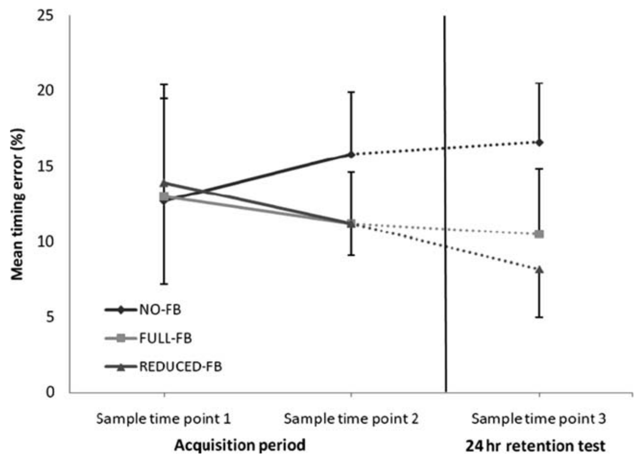

Figure 6. *Mean timing error for peak angle at the right hip joint across time, with* SD.

that the REDUCED-FB condition significantly reduced error when sample time point 1 was compared to sample time point 3 (see Figure 6). Moreover, the REDUCED-FB group had significantly less error than the NO-FB group in retention.

3.2.2.1 Standard Deviation of Mean Timing Error. Post hoc analyses revealed that the group × time interaction in the left shoulder was due to only the REDUCED-FB group improving across sample time points 1 and 2. Both the FULL-FB and the NO-FB conditions did not significantly reduce the *SD* of mean critical timing error in the left shoulder joint during the experiment (see Figure 7).

4 Discussion

The aim of this study was to determine the impact of two variations of real-time VR feedback on motor learning compared to receiving no feedback. Participants simultaneously observed and attempted to replicate a

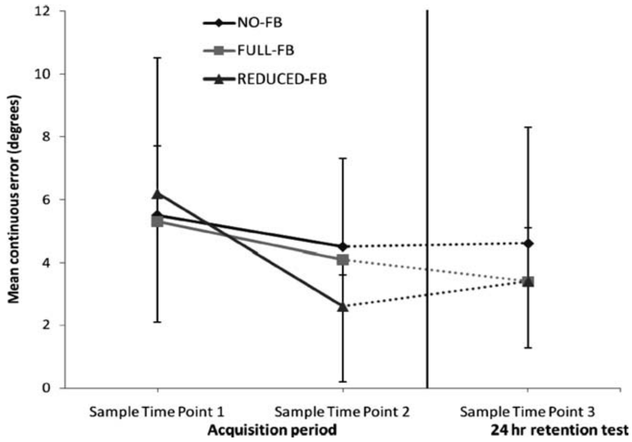

Figure 7. *Mean* SD *of mean timing error for peak angle at the left shoulder joint across time, with* SD.

demonstration of a complex dance movement while receiving real-time VR feedback on the temporal-spatial locations of 12 of their joint centers (FULL-FB), four end-effectors (REDUCED-FB), or while receiving no real-time VR feedback (NO-FB). Changes in participants' kinematic variables were compared with the expert demonstrator's kinematic representation of the movement. It was hypothesized that the REDUCED-FB condition would provide an advantage to learners.

All groups exhibited various improvements in movement form across practice. These improvements were mostly retained. However, the REDUCED-FB condition exhibited more of the required changes in the degree of linear coupling between certain key joints. This was by achieving more changes from either low or moderate levels to high levels of coupling than the other conditions. Furthermore, the interaction of group $\times$ time identified a significant learning advantage for the REDUCED-FB condition in five different measures of absolute range of motion. These advantages were in mean continuous error in the left elbow and right ankle, in the *SD* of this error measure at the left elbow, in the timing of peak critical angle at the right hip, and in the *SD* of this error measure at the left shoulder. In contrast, the FULL-FB condition yielded only one advantage for learners when mean continuous error at the right ankle joint improved after practice, which similarly occurred for the REDUCED-FB condition, but not for the NO-FB condition. These findings support the view that real-time VR feedback about movement kinematics can benefit the motor learning of a complex real-world movement skill, specifically when temporal-spatial discrepancies between end-effector locations are emphasized.

Scully and Carnegie (1998) highlighted that, within a demonstration, certain key anatomical features are more useful for perceiving a to-be-learned action than others. Adopting an ecological psychology perspective, Savelsbergh and van der Kamp (2000) predicted that these key sources of perceptual information might be selected by learners on the basis of task-relevant perception-action couplings that emerge due to interacting constraints inherent in the task, the organism, and the environment (see Newell, 1991). Scully and Carnegie (1998) showed that removing end-effectors from a PLD was detrimental to observational learning, suggesting that these areas might be perceived by learners as being the more goal-relevant and perceptually salient features of the to-be-learned action. This was possibly because these features traveled through greater motion trajectories (Hodges et al., 2007). The present experiment adopted a task that was similar in this regard. Therefore, we predicted that the perceptual array surrounding the end-effectors in our display would be similarly rich in information.

In line with these expectations, our results showed for the first time that our novel approach to providing real-time VR feedback can facilitate the education of perception-action couplings (Gibson, 1979), as reflected in the beneficial changes we observed in motor learning. We propose that this effect was because the information that was inherent in the feedback provided learners with a visually clear representation of the spatial-temporal difference between key features of their actions and the expert's. One possibility is that, because the human visual perception system is highly sensitive to human biological motion when it is presented in a PLD (see Johannson, 1973), our real-time VR feedback provided a visual representation of temporal-spatial movement in a mode that was deeply intuitive to the development of task-relevant perception-action couplings. Therefore, the feedback may have afforded learners the ability to pick up information relevant to making corrective movements, in an instinctive and efficient manner.

There are a number of possible reasons why motor learning was advantaged under the REDUCED-FB condition. Perhaps the single emphasis that it placed on the more task-relevant features attenuated the learners' focus on the less pertinent aspects of the action (Jacobs & Michaels, 2002). Similarly, the FULL-FB condition provided temporal-spatial information on eight more joint centers than the REDUCED-FB condition. It was possible that this greater quantity of real-time VR feedback made it difficult for learners to identify the more task-relevant features from the multitude of available sources (Savelsbergh & van der Kamp, 2000). If so, this finding might support previous research on acquiring intra- and inter-limb coordination, which has suggested that information overload can arise early in learning (see Breslin, Hodges, & Williams, 2009). Of course, these two explanations must also acknowledge the participant's stage of learning. We specifically chose to examine the learning of a complex dance movement over a short training and retention period (cf. Al-Abood et al., 2001; Breslin et al., 2005; Breslin et al., 2006). This enabled us to examine the short-term effects of real-time VR feedback on motor learning. Our motivation was that the VPP's predictions relate specifically to learners in the initial phase of motor learning. However, our results now provoke further questions about the potential role of real-time VR feedback manipulations in maintaining this developmental advantage across different stages of motor learning.

We propose that future research could examine the effect of the REDUCED-FB condition on motor learning with longer periods of practice. In this case, the initial burden of information that might be encountered in the early stages of learning would be expected to reduce as the learning progresses (Huegel et al., 2010). Concomitantly, a learner's visual search strategy for information in a demonstration will likely evolve as a function of learning, perhaps toward the detection of more subtle and refined technique characteristics. If so, it could become more difficult to predict the various anatomical features that progressively emerge as information-rich areas. It is clear that professionals wishing to teach motor learning through real-time VR feedback must possess a comprehensive, insightful, and expert knowledge of the particular skill they hope to teach. This should enable them to systematically justify the anatomical features that they provide real-time VR feedback about, and also at which stages of learning these are offered or omitted. We hope future research can now begin to investigate these issues. If progress is not made in this area, however, there is a real danger that real-time VR feedback would become counterproductive if uninformed physical trainers use it to direct learners' attention to task-irrelevant features at inappropriate stages in learning (cf. Li et al., 2009; Huegel & O'Malley, 2010).

As a general principle, our results only suggest that REDUCED-FB can benefit the initial stage of learning in a task involving the direct matching of movement form, wherein end-effectors were predicted to be goal-relevant features due to their evidently larger motion trajectories. Moreover, we specifically examined learning in an action that required a fundamentally different style of learning from those actions that serve to reduce accuracy in hitting an external target (e.g., Huegel et al., 2010; Huegel & O'Malley, 2010). It is widely known that this latter category of skill requires humans to take a conceptually different approach to learning (see Hodges et al., 2007), which might not be best suited to the use of our real-time VR feedback. Therefore, caution should be taken when extrapolating our results to those cases.

5 Conclusion

Our primary contribution is a new paradigm that represents an effective and intuitive way of providing real-time VR feedback. Our protocol is in stark contrast to existing VR training environments, wherein vast amounts of time, effort, and resources are often employed to enhance the fidelity and ecological validity of the learners' experiences. It is conceivable that our finding might also appear somewhat counterintuitive, in that providing less, rather than more, real-time VR feedback can significantly benefit motor learning. However, on the strength of our results, we recommend that the selection and subsequent presentation of motion information to learners in VR training environments be thoroughly scrutinized, in terms of whether it is (a) presented in a format that is intuitive to the visual perception system's means of information pickup, and (b) appropriate, in terms of the informational quantity and content, to both the local task requirements and the performer's stage of learning.

In future, similar training environments could be adapted to capture learners' motion data and compare this in an online fashion to the demonstrator's pre-recorded kinematics. This approach could be used to create supplementary forms of computer-generated error-based feedback, such as motivational crowd noises within specified error tolerances. Overall, our results provide clear and substantial evidence that VR can be used effectively as a platform for teaching real-world motor skills.

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