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Immersive Real-Time Biofeedback Optimized With Enhanced Expectancies Improves Motor Learning: A Feasibility Study

Ashley M. Williams[1], **Jennifer A. Hogg**[2], **Jed A. Diekfuss**[3,4,5], **Samantha B. Kendall**[6], **Colton T. Jenkins**[7], **Shellie N. Acocello**[2], **Yu Liang**[8], **Dalei Wu**[8], **Gregory D. Myer**[3,4,5,9], **Gary B. Wilkerson**[2]

[1]Progressive Health, Smyrna, TN, USA

[2]Department of Health and Human Performance, The University of Tennessee Chattanooga, Chattanooga, TN, USA

[3]Emory Sport Performance and Research Center, Flowery Branch, GA, USA

[4]Department of Orthopaedics, Emory University School of Medicine, Atlanta, GA, USA

[5]Emory Sports Medicine Center, Atlanta, GA, USA

[6]Music City Orthopedics and Sports Medicine, Nashville, TN, USA

[7]Covenant Health, Leconte Medical Center, Knoxville, TN, USA

[8]Department of Computer Science and Engineering, The University of Tennessee Chattanooga, Chattanooga, TN, USA

[9]The Micheli Center for Sports Injury Prevention, Waltham, MA, USA

Abstract

Context: An Optimizing Performance through Intrinsic Motivation and Attention for Learning theory-based motor learning intervention delivering autonomy support and enhanced expectancies (EE) shows promise for reducing cognitive-motor dual-task costs, or the relative difference in primary task performance when completed with and without a secondary cognitive task, that facilitate adaptive injury-resistant movement response. The current pilot study sought to determine the effectiveness of an autonomy support versus an EE-enhanced virtual reality motor learning intervention to reduce dual-task costs during single-leg balance.

Design: Within-subjects 3 × 3 trial.

Methods: Twenty-one male and 24 female participants, between the ages of 18 and 30 years, with no history of concussion, vertigo, lower-extremity surgery, or lower-extremity injuries the previous 6 months, were recruited for training sessions on consecutive days. Training consisted of 5 × 8 single-leg squats on each leg, during which all participants mimicked an avatar through virtual reality goggles. The autonomy support group chose an avatar color, and the EE group received positive kinematic biofeedback. Baseline, immediate, and delayed retention testing consisted of single-leg balancing under single- and dual-task conditions. Mixed-model analysis

corresponding author. Hogg (jennifer-hogg@utc.edu).

of variances compared dual-task costs for center of pressure velocity and SD between groups on each limb.

Results: On the right side, dual-task costs for anterior–posterior center of pressure mean and SD were reduced in the EE group (mean Δ = −51.40, Cohen *d* = 0.80 and SD Δ = −66.00%, Cohen *d* = 0.88) compared with the control group (mean Δ = −22.09, Cohen *d* = 0.33 and SD Δ = −36.10%, Cohen *d* = 0.68) from baseline to immediate retention.

Conclusions: These findings indicate that EE strategies that can be easily implemented in a clinic or sport setting may be superior to task-irrelevant AS approaches for influencing injury-resistant movement adaptations.

Keywords

OPTIMAL; cognitive-balance control; cognitive load; autonomy support

Approximately 23% to 25% of patients with anterior cruciate ligament (ACL) reconstruction patients will retear the previously injured or contralateral ACL in the early return to play phase.[1] Increased reinjury or secondary ACL injury rates may result from traditional ACL rehabilitation that fails to address the primary injury risks factors that led to the initial injury that are compounded with demands of a dynamic competitive environment. For instance, an athlete following ACL reconstructed may demonstrate an acceptable level of dynamic joint stability in a controlled clinical environment, but deficient neuromuscular control may be exposed in a chaotic sport environment that imposes rapidly changing cognitive and motor demands. Similar phenomena are observed in concussed individuals, in which postconcussive assessments reveal motor impairments when burdened with an additional cognitive load.[2] Scenarios during which cognitive and motor demands occur simultaneously are often termed “dual-tasks,” and robust evidence demonstrates that primary motor task performance is impaired when completed concurrently with a secondary cognitive task.[3,4] The relative difference in primary task performance when completed with and without a secondary cognitive task is termed the “dual-task cost.” A greater dual-task cost is considered undesirable, as it signifies more neuromotor resources are being allocated to the secondary cognitive task rather than the primary motor task. Furthermore, primary task performance decrements are further pronounced during cognitive dual tasking in individuals with a history of sport-related injury relative to noninjured matched controls.[5]

The incorporation of motor learning principles is promising for improving dual-tasking capabilities. Specifically, focusing externally, while minimizing internal focus, is a purported benefit for ACL injury risk reduction. An external focus of attention, or directing the learner’s attention to their effect on the environment rather than to internal body movement cues,[6] has shown promise for improving biomechanics associated with ACL injury risk.[7,8]

An external focus of attention is a key pillar within the Optimizing Performance through Intrinsic Motivation and Attention for Learning (OPTIMAL) theory[9]—the most current motor learning framework. Recent application frameworks have expanded on the potential for OPTIMAL theory pillars to be particularly beneficial within injury prevention strategies, injury rehabilitation, exercise, and play by capitalizing on neural principles associated with movement mechanics (OPTIMAL prevention strategies, injury rehabilitation, exercise, and play).[10–12] In addition to an external focus, OPTIMAL prevention strategies, injury rehabilitation, exercise, and play theorize that autonomy support (AS) and enhanced expectancies (EE) will further support injury-resistant movement by increasing motivation and movement automaticity through dopaminergic principles for more robust retention,[9] though these pillars have been studied to a lesser degree than external focus. AS refers to allowing participants control over their practice conditions; for example, allowing participants to choose the color of golf ball for a putting task.[13] Specific to balance, giving participants the option of when to use a physical assistance device to maintain stability promoted learning[14] and giving participants control over stance order contributed to improved (lower) center of pressure (COP) velocity during a standardized Balance Error Scoring System assessment.[15] EE refers to an increase in participants’ expectation of success, which often takes the form of positive feedback. Previous literature supports investigating the potential benefits of EE for lower-extremity movement and postural control tasks, as well as supplementing previous autonomy-supportive literature using single rather than dual-leg balance tasks.

The purpose of this pilot study was to determine the relative effectiveness of OPTIMAL-based, single-leg squat interventions to promote single-leg balance control, as indicated by reduced dual-task costs (less impairment when completed concurrently with a complex cognitive task) among individuals exhibiting excessive 2-dimensional knee valgus angle. We hypothesized (1) lower dual-task costs in balance control at immediate and delayed retention for athletes who additively trained with EE compared with athletes who trained with the standard biofeedback stimulus (control) and (2) lower dual-task costs in balance control at immediate and delayed retention for athletes who additively trained with AS compared with athletes who trained with the control biofeedback.

Methods

Study Design

This was a 2 session repeated-measures design. Each participant attended sessions on consecutive days. All data were collected between November 2019 and February 2020. Day 1 included baseline and immediate retention testing, and day 2 included delayed retention testing. Independent variables were group membership and session, resulting in a 3 × 3 research design. Dependent variables were the dual-task costs of anterior–posterior (AL) COP mean velocity, AL COP SD, medial–lateral (ML) COP SD, and ML COP mean velocity.

Patients or Participants

A total of 45 subjects (21 male and 24 female) were recruited through email and word of mouth. Exclusion criteria were history of concussion, vertigo, lower-extremity surgery, and any lower-extremity injuries within the previous 6 months. Inclusion criteria were between the ages of 18 and 30 years and suboptimal frontal plane biomechanics, as determined by a prescreening session. Frontal plane biomechanics were selected as screening criteria. Determination of frontal plane biomechanics was assessed by video-recorded performance of single-leg squats bilaterally. Frontal plane angles of 2-dimensional knee valgus angle, contralateral pelvic drop, and lateral trunk lean at the point of maximum knee flexion were assessed offline with ImageJ software (National Institutes of Health).[16] Exhibiting 2 of the 3 following criteria defined suboptimal frontal plane biomechanics: 2-dimensional knee valgus angle >10° for males or >13° for females,[17] contralateral pelvic tilt >5°, and ipsilateral trunk lean >5°. Only individuals exhibiting suboptimal prescreening biomechanics were included in the study. All participants provided written informed consent approved by the University of Tennessee at Chattanooga's institutional review board. Participants were quasi-randomly assigned to 1 of 3 groups (control, AS, and EE) such that each group contained 15 participants, and the ratio of male to female participants was constant across groups. Group randomization was based upon order of recruitment, wherein the first participant was allocated to the control group, the second participant to the AS group, and so on. Each participant attended 2 sessions, which included baseline testing, intervention, and immediate retention (~5–10 min following the cessation of the intervention) on day 1, and delayed retention (24 h postintervention) on day 2.

Testing Instrumentation

Outcome data (COP velocity and SD) were collected using Vicon Nexus software synced with 2 side-by-side embedded Bertec force plates recording COP data during baseline and posttesting. Kinetic data were sampled at 1000 Hz. The cognitive component of the dual task was delivered with VR goggles (Vive Pro, HTC, with Pupil Labs' HTC Vive Binocular Add-on eye tracker) and consisted of the Eriksen flanker test.[18] Each flanker test consisted of 20 trials that generated randomly ordered presentation of 5-arrow sets (ie, incongruent: <<><< or congruent: >>>>>). The participant was instructed to react only to the middle arrow in the set by directing their gaze to a target that corresponded with the direction of the central arrow. The stimulus was shown every 2000 milliseconds, disappearing when the participant hit the target or 250 milliseconds passed—whichever occurred first. Targets were positioned 30° horizontally left and right from the center of the participant's field of view. The flanker test was used solely for its cognitive load and dual-tasking application and was thus not analyzed. Adherence to and completion of flanker cognitive task was monitored real time via pupil tracker streaming.

Kinematic data for biofeedback delivery were collected using the Microsoft Azure Kinect DK. Through kinect, we obtained joints' transient position $\langle x, y, z \rangle_t^k$ and corresponding Quaternion rotation $\left\langle \theta, \overrightarrow{v} \right\rangle_t^k$, where θ is an angle around unit axis vector $\overrightarrow{v}$, t is the time step, and k is the joint identifier. Quaternions are considered to represent the rotation of a rigid body in 3-dimensional space using 4 degrees of freedom. Preprocessing included noise removal, temporal, and spatial normalization, occlusion fixing using a Kalman filter and spherical linear interpolation and 3D kinematic data format transformation (from Kinect version to Unit3D version). Following which, the resulting kinematic data $\left(\langle x, y, z \rangle_t^k, \left\langle \theta, \overrightarrow{v} \right\rangle_t^k \right)$ were reconstructed over virtual reality goggles using Unit3D software.

Testing Procedures

Participants were instructed to complete a single-task balance assessment for 20 seconds followed by a dual cognitive-balance task assessment for 20 to 25 seconds at 3 different time points: baseline, immediate retention (~5–10 min following the cessation of the intervention), and delayed retention (24 h postintervention). The first session consisted of baseline testing, the intervention, and immediate retention testing. Delayed retention testing was conducted on the following day. The balance task consisted of a single-leg squat hold and was conducted for the left limb first and then the right. With their eyes open and standing on the force plate, participants placed their hands on their hips and flexed their knee to approximately 30°. Instructions were given to remain as still as possible for 20 seconds. For the dual task, participants wore VR goggles and performed the Eriksen flanker cognitive task while maintaining the single-leg squat hold balance task. The same was done for a retention test the following day.

Intervention Procedures

We employed a 1-day intervention consisting of single-leg squats while participants viewed a visual biofeedback stimulus that was mapped onto participants' lower-extremity kinematics and displayed in real time through a virtual reality headset. The same investigator delivered all interventions to reduce bias in the delivery of feedback to participants. This investigator could not be blind to group allocation but intentionally delivered standardized instructions to all participants. The intervention consisted of 5 sets of 8 single-leg squats on each leg, with adequate rest between sets. During the single-leg squats, participants wore VR goggles on which were displayed an avatar. All participants were instructed to mimic the avatar as closely as possible. The control group received no other feedback or autonomy. The EE group received real-time biofeedback in the form of green highlights strategically placed on the avatar. The highlights remained on as long as the participant did not exceed knee valgus or pelvic drop thresholds. Participants in the EE group were instructed to move in such a way as to retain the green lights on the avatar but were given no explicit feedback on how to do so (Figure 1). The AS group was allowed to choose the color of their avatar for each set but did not receive feedback (Figure 2). In keeping with OPTIMAL theory, both the EE and AS manipulations were designed to maximize learner motivation.

Postural Control Data Processing

Alterations to participants' COP are commonly used to quantify performance during balance tasks. Specifically, COP mean velocity, and SD in the AP and ML planes have been used as indicators of change in dual-task costs.[19] Greater COP mean velocities and SDs reflect poorer balance control. For the present study, analog data were exported from Vicon Nexus into Visual 3-D, where data were filtered with a low-pass 5-Hz fourth-order Butterworth filter. Filtered COP coordinates were trimmed to the middle 10 seconds of each trial and exported. The COP displacement time series was converted to a velocity time series using the formula, $v_i = \frac{d_i - d_{i-1}}{t_i - t_{i-1}}$, where $v = \text{velocity}$, $d = \text{displacement}$, and $t = \text{time}$. Means and SDs were then computed for the velocity time series in both the AP and ML directions, resulting in the variables APVel, APSD, MLVel, and MLSD. All variables were computed in R.

Dual-Task Costs

Consistent with previous literature, we defined dual-task costs as the difference in single-leg postural control with (dual task) and without (single task) the secondary cognitive task at a given testing interval (baseline, immediate retention, and delayed retention). This difference was then normalized to single-task performance and thus represents a percentage change from single-task performance. The formula for dual-task costs is provided below, and each dependent variable of interest was entered as a dual-task cost for all statistical analyses.

$$\text{Dual-taskcost} = \frac{\text{DTperformance}_{\text{session}} - \text{STperformance}_{\text{session}}}{\text{STperformance}_{\text{session}}} \times 100\,.$$

As we were interested in the relative pretraining to posttraining changes in dual-task costs following the respective interventions (ie, baseline dual-task cost – immediate retention dual-task cost), a *reduction* in dual-task cost was signified with a *negative* delta percentage value to indicate *improvements* in dual-task costs. Conversely, an *increase* in dual-task cost was noted with a *positive* delta percentage value to indicate *worsening of* dual-task costs. For example, Δ = −200.00% would be interpreted as a desirable, 2-fold improvement in dual-task cost from baseline to retention; whereas, Δ = +200.00% would be interpreted as an undesirable, 2-fold deterioration in dual-task cost from baseline to retention.

Statistical Analyses

One-way analysis of variances for each of the 4 cost variables (APVel, MLVel, APSD, and MLSD) was conducted to determine the presence of baseline differences. Mixed-model (between-factor: group, within-factor: session) 3 × 3 repeated-measures analysis of variances was used to determine differences between groups over time. Left and right sides were analyzed separately to avoid potential confounding effects associated with limb dominance for motor control and learning. Tukey post hoc testing was conducted where appropriate. As this was a pilot study, effect sizes were used to determine clinical meaningfulness instead of *P* values. The omnibus generalized eta-squared $\left(\eta_g^2\right)$ effect size was considered meaningful when greater than or equal to .04 (small to moderate effect). In the event of a meaningful η_g^2, Cohen d values were also computed and reported to aid in interpretability. All analyses were conducted in R using the ggpubr[20] and rstatix[21] packages.

Results

Demographic characteristics for each group are presented in Table 1. No dual-task costs for any dependent variables were significantly different between the 3 groups at baseline (*P* range = .11–.63; Table 2).

For APVel, there was a main effect for time on the left side $\left(\eta_g^2 = .04\right)$. Post hoc testing revealed this effect to occur between baseline (dual-task cost = 103.43% [66.43%]) and immediate retention (dual-task cost = 79.07% [48.63%]) (Δ = −24.36%; Cohen $d = 0.42$). There was a group by time interaction on the right side $\left(\eta_g^2 = .04\right)$. Post hoc testing revealed this effect to occur between the control and EE groups primarily between baseline (control dual-task cost = 100.00% [74.00%]; EE dual-task cost = 102.00% [82.10%]) and immediate retention (control dual-task cost = 77.01% [63.90%]; EE dual-task cost = 50.60% [38.60%]) (control Δ = −22.09, Cohen $d = 0.33$; EE Δ = −51.40, Cohen $d = 0.80$) (Figure 3).

With regard to APSD, there was a main effect for time on the left side$\left(\eta_g^2 = .08\right)$. Post hoc testing revealed this effect to occur between baseline (dual-task cost = 128.13% [79.63%]) and immediate retention (dual-task cost = 99.70% [58.47%]) (Δ = −28.43%, Cohen $d = 0.41$) and baseline and delayed retention (dual-task cost = 89.87% [71.43%]) (Δ = −38.26%, Cohen $d = 0.51$). There was a group by time interaction for the right side$\left(\eta_g^2 = .07\right)$. Post hoc testing revealed this effect to occur between the control and EE groups primarily between baseline (control dual-task cost = 111.00% [58.5%]; EE dual-task cost = 143.00% [87.00%]) and immediate retention testing (control dual-task cost = 74.90% [46.5%]; EE dual-task cost = 77.00% [60.50%]) (control Δ = −36.10%, Cohen $d = 0.68$; EE Δ = −66.00%, Cohen $d = 0.88$) (Figure 4).

There were no meaningful interactions or main effects for MLSD or MLVel (all$\left(\eta_g^2 = .04\right)$).

Discussion

The purpose of this pilot study was to determine the relative effectiveness of OPTIMAL-based, single-leg squat interventions to promote learning of single-leg balance control (as indicated by reductions in dual-task costs) among individuals exhibiting excessive 2-dimensional knee valgus angle. Dual-task cost was chosen because reductions in dual-task costs indicate automaticity, which is a key mediator identified by the OPTIMAL theory. As the beneficial effects of visual biofeedback for injury-resistant movement has been established with respect to an external focus, we additively included either AS or EE through manipulation of the biofeedback stimulus during single-leg squat training to uncover the unique effects of these motivational, OPTIMAL-based factors. In support of our first hypothesis, the additive inclusion of EE, in the form of positive feedback, to a real-time biofeedback intervention enhanced motor learning relative to the control intervention. However, contrary to our second hypothesis, providing individuals AS, in the form of a task-irrelevant choice, during the intervention was not additively beneficial to motor learning compared with the control intervention.

These preliminary data may provide novel insights to inform ACL injury risk reduction strategies, particularly through (1) the inclusion of positive feedback and (2) future exploration of more relevant and effective methods of supporting an individual’s autonomy. The present findings also support the extant literature regarding the benefits of visual biofeedback systems, which are theorized to induce an external focus and reinforce injury-resistant movement mechanics.[7,22,23] There is strong evidence supporting EE for improving motor learning, but prior literature is generally constrained to *performance-based* outcome measures. The present data expand previous findings by indicating EE—specifically by providing positive feedback when participants achieved the desired movement—to also support the retention of global *biomechanical-based* dual-task cost outcome measures in those who exhibit poor frontal plane knee motor control. Enhancing individual expectancies through simple green highlights on the knee and hip of the avatar stimulus during single-leg squatting elicited ~50% improvement in dual-task costs relative to the control intervention. Providing positive feedback in response to desirable motor performance adds to previous motor learning literature typically constrained to discrete tasks (eg, dart throwing) and expands its potential utility for use during continuous tasks (balance control).

Interestingly, in the current pilot study, the benefits of EE for single-leg balance control was uniquely beneficial to the right limb—the preferred stance limb for over 90% of participants. This may be due to participants having greater neuromuscular control of their stance limb; thus, the preferred stance limb may possess a greater likelihood of responsiveness to the biofeedback stimulus providing EE. Further research is warranted to deconstruct why the stance limb may have greater responsiveness; we hypothesize the stance limb to be more finely tuned to postural considerations and thus more adaptable to the EE biofeedback. Importantly, changes in postural capabilities that occur following a single-leg dynamic training intervention would reasonably transfer to other postural single-leg activities.

Unlike EE, AS did not elicit meaningful motor learning improvements in dual-task costs compared with the control intervention; we propose 2 explanations for these null AS findings. First, we *additively* included AS to a standard visual biofeedback stimulus intervention. The existing literature has established such interventions to be effective as they are theorized to capitalize on a primary pillar of OPTIMAL theory: an external focus. An external focus is generally considered the most robust pillar to elicit motor learning and, to the authors' knowledge, is the only pillar with empirical supporting evidence for eliciting desirable biomechanics related to ACL injury risk biomechanics.[23,24] The visual biofeedback system and associated external focus was further present during the entire duration of the intervention, and AS was only provided prior each set. Thus, EF may have simply superseded any unique effect of the presented AS manipulation. As meaningful improvements were observed for EE (also provided throughout the entire duration of the intervention), a higher dosage of AS may be needed to elicit dual-task cost learning benefits. Alternatively, the failure to observe meaningful effects by providing AS to individuals may be attributed to *task relevance.* We manipulated AS by allowing individuals to choose the color of the avatar; however, this would be considered a *task irrelevant* choice, as avatar color reasonably has no direct effect on the task goal of improving single-leg balance control. A recent study revealed that providing AS through the use of *task-relevant* choices is more effective for motor learning than task-irrelevant choices.[25] For instance, letting individuals choose when to receive visual biofeedback during the intervention (eg, letting individuals "turn the stimulus off" as desired) may have elicited more direct, motivational influences on dual-task cost learning. Though we cannot confirm whether task relevance was a contributing factor to the present findings, future research is primed to investigate such a possibility by capitalizing on emergent technologies and associated gamification capabilities that can provide AS with ease.[23,26,27]

The present findings support the additive inclusion of EE—but not AS—to visual biofeedback interventions, which can be readily implemented in a clinical setting. To incorporate EE for instance, following "good" repetitions, a clinician or coach can seamlessly provide positive feedback (eg, "your posture is significantly improved from last week"). There are various forms of EE, including self-modeling and perceived task difficulty. Though comprehensive data on the various forms of EE are lacking, the provision of EE as positive feedback has been demonstrated to improve learner motivation and self-efficacy.[28] This is arguably an important consideration, as fear of reinjury is the most commonly cited reason for not returning to play following ACL injury.[29] Of note, provision of general kinematic feedback, not necessarily positive, has previously been shown to attenuate high-risk lower-extremity biomechanics.[30] Although the OPTIMAL theory has robustly demonstrated positive feedback to maximize learner potential, provision of *any* feedback is likely to result in improvement.

Despite the novel contributions of this pilot investigation, the present findings must be considered in light of study limitations. First, dual-task costs during single-leg balance control does not reflect the rapid acceleration/deceleration and/or landing mechanics associated with typical ACL injury events. However, the purpose of this pilot study was to establish proof of concept effectiveness and or differential effects of isolated EE and AS for motor learning, which necessitated a slow continuous task to provide the real-time biofeedback during the intervention consistent with prior literature,[26] and we are aware that such methods may have implications for other conditions such as patellofemoral pain or concussion. While we did intervene upon angular kinematics and assess static postural balance in a static squat at 30° knee flexion, observing effects on balance as a result of kinematic feedback is encouraging for evidence of transfer between single-leg motor control tasks. Future research should consider more dynamic tasks and associated biomechanical measures to assess the transferability of the present study findings to scenarios more closely associated with ACL injury events. Although common in AS literature, this pilot study did not employ a yoking procedure (linking environmental conditions between participants) between the AS group and the control group. Nevertheless, as we did not observe effects in the AS group, the lack of yoking does not affect the interpretation of our results. The observed large SDs were possibly the result of the cognitive task being performed in VR, which occludes visual orientation and would thus disproportionately affect individuals who heavily rely on vision for balance. Although the large SDs limit our ability to establish strict differences, this represents a prime opportunity for future research to parse out these large variances. Future studies should also expand their data collection procedures to ensure representation of diverse racial and ethnic populations. Finally, we did not assess errors in the cognitive task performance during any testing period; however, as the present pilot aims were to determine *biomechanical-related* improvements associated with OPTIMAL-based motor learning strategies, this did not affect the outcomes of this study.

Conclusions

The additive inclusion of EE in the form of positive kinematic feedback to a visual-biofeedback intervention (theorized to promote an external focus of attention) facilitated the retention of desirable dual-task cost reductions during single-leg balance control for those with suboptimal frontal plane knee biomechanics. However, task-irrelevant AS was not additively beneficial for improving dual-task costs relative to a standard visual biofeedback stimulus. These preliminary data support the use of enhanced expectancy strategies for emergent ACL risk reduction programs, but future research is needed to refine how AS is implemented for those at high risk for musculoskeletal injury to enhance its potential efficacy.

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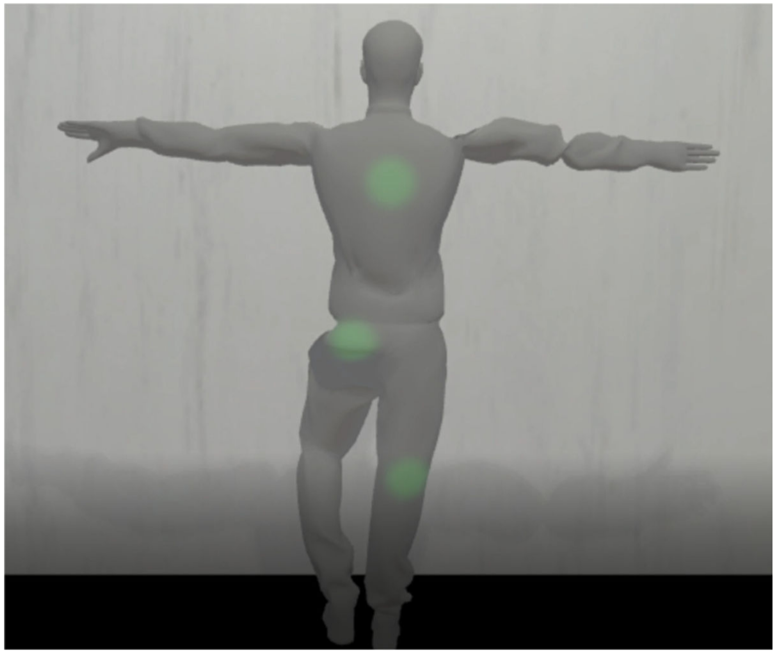

Figure 1 —.
Representation of the avatar with positive feedback (green highlights over the right knee, left hip, and middle of trunk) as seen by the participants in enhanced expectancies group.

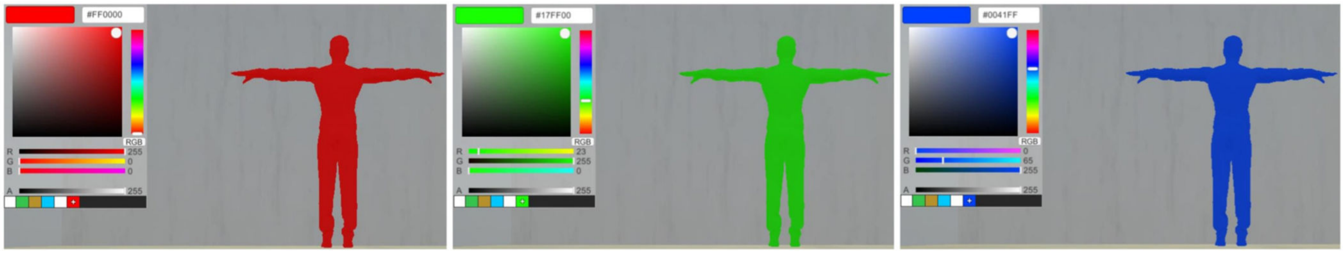

Figure 2 —.

Representation of the avatar with examples of various color choices (red, green, and blue) as seen by the participants in autonomy support group.

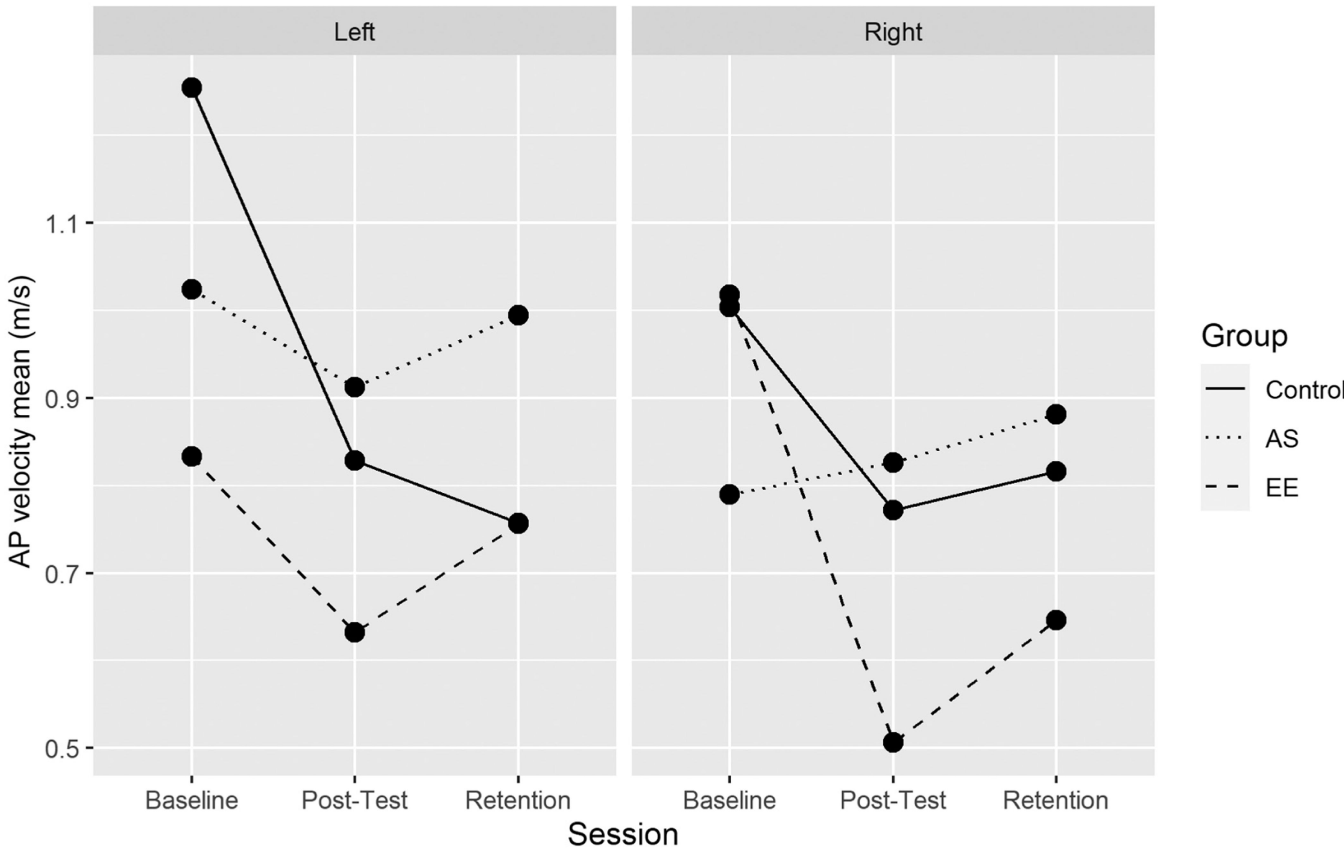

Figure 3 —.

Anterior–posterior velocity dual-task cost changes over time between groups.

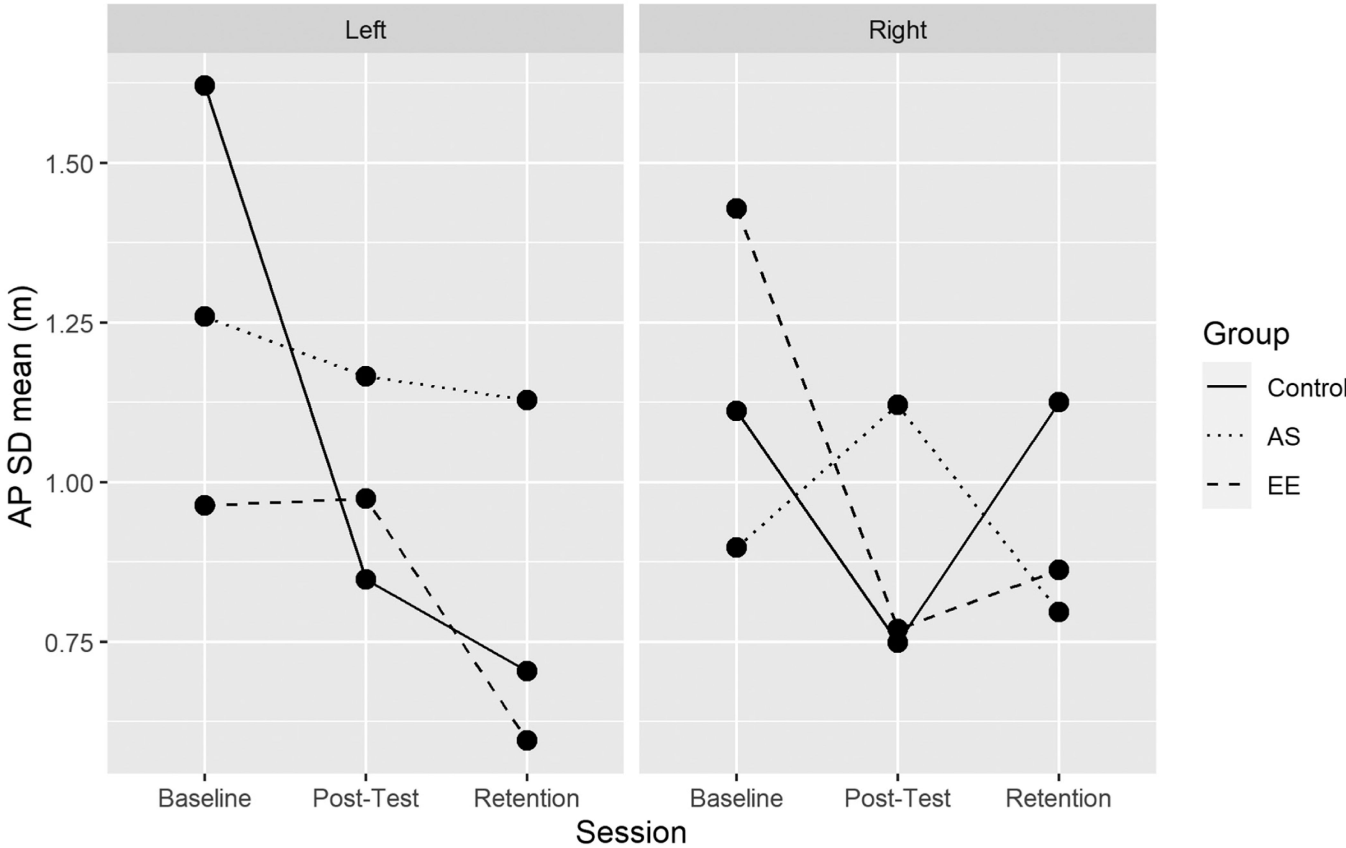

Figure 4 —.
Anterior–posterior SD dual-task cost changes over time between groups.

Table 1

Demographics of Participants by Group

Mean (SD)	Control	Autonomy support	Enhanced expectancies	Analysis of variance *P*
Age, y	21.3 (1.9)	21.8 (1.8)	22.7 (2.1)	.33
Height, cm	172.5 (10.5)	172.2 (9.4)	171.5 (5.3)	.49
Weight, kg	71.1 (17.1)	70.9 (14.3)	70.6 (12.8)	.28

Note: Each group consisted of 8 females and 7 males.

Table 2

Descriptive Statistics (Mean [SD]; 95% Confidence Intervals) for Each Center of Pressure Dual-Task Cost Variable by Group and by Session

	Control group			Autonomy support group			Enhanced expectancies group		
	Baseline	Immediate	Delayed	Baseline	Immediate	Delayed	Baseline	Immediate	Delayed
APVel									
L[1]	125 (50) (100–150)	83 (40) (63–103)	76 (45) (53–99)	102 (82) (61–144)	91 (37) (72–110)	100 (70) (65–135)	83 (67) (49–117)	63 (69) (28–98)	76 (67) (42–110)
R[1,2,5]	100 (74) (63–137)	77 (64) (45–109)	82 (49) (57–107)	79 (42) (55–111)	83 (55) (62–114)	88 (51) (81–123)	102 (41) (31–71)	51 (39) (44–86)	65 (41) (44–86)
APSD									
L[1,3,4,5,*]	162 (77) (123–201)	85 (78) (46–124)	70 (56) (42–98)	126 (85) (83–169)	117 (43) (95–139)	113 (77) (74–152)	96 (77) (57–135)	97 (54) (70–124)	60 (82) (19–101)
R[2]	111 (59) (81–141)	75 (47) (51–99)	112 (79) (72–152)	90 (82) (49–131)	112 (83) (70–154)	80 (45) (57–103)	143 (87) (99–187)	77 (61) (46–108)	86 (70) (51–121)
MLVel									
L[1,*]	193 (103) (141–245)	171 (187) (76–266)	118 (84) (75–161)	192 (153) (115–269)	166 (127) (102–230)	181 (109) (126–236)	152 (124) (89–215)	134 (96) (85–183)	99 (107) (45–153)
R	148 (87) (104–192)	112 (78) (73–151)	185 (115) (127–243)	141 (122) (79–203)	166 (151) (90–242)	167 (124) (104–230)	214 (138) (144–284)	143 (106) (89–197)	166 (145) (93–239)
MLSD									
L	96 (58) (67–125)	117 (163) (35–199)	91 (130) (25–157)	158 (158) (78–238)	123 (117) (64–182)	120 (150) (44–196)	111 (116) (54–168)	90 (72) (54–126)	57 (84) (14–100)
R	98 (54) (71–125)	103 (81) (62–144)	125 (96) (76–174)	90 (105) (37–143)	81 (66) (48–114)	89 (106) (35–143)	122 (98) (72–172)	78 (71) (42–114)	80 (108) (25–135)

Abbreviations: L = left; R = right; APVel = anterior-posterior velocity; APSD = anterior-posterior standard deviation; MLVel = medial-lateral velocity; MLSD = medial-lateral standard deviation. Variables are expressed as percentage increase from single-task condition.

[1] Within-group main effect for time at $P < .10$.

[2] Group by session interaction effect at $P < .10$.

[3] Between-group η_g^2 effect size > .04.

[4] Between-session η_g^2 effect size > .04.

[5] Group by session η_g^2 effect size > .04.

[*] Between-group effect at $P < .10$.