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Virtual Sensorimotor Balance Training for Children With Fetal Alcohol Spectrum Disorders: Feasibility Study

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Background. Diminished sensory adaptation has been associated with poor balance control for children with fetal alcohol spectrum disorders (FASD). A virtual reality system, Sensorimotor Training to Affect Balance, Engagement and Learning (STABEL), was developed to train sensory control for balance.

Objectives. The purpose of this study was to examine the STABEL system in children with FASD and children with typical development (TD) to (1) determine the feasibility of the STABEL system and (2) explore the immediate effects of the STABEL system on sensory attention and postural control.

Design. This is a technical report with observational study data.

Methods. Eleven children with FASD and 11 children with TD, aged 8 to 16 years, completed 30 minutes of STABEL training. The children answered questions about their experience using STABEL. Sensory attention and postural control were measured pre- and post-STABEL training with the Multimodal Balance Entrainment Response system and compared using repeated-measures analysis of variance.

Results. All children engaged in game play and tolerated controlled sensory input during the STABEL protocol. Immediate effects post-STABEL training in both groups were increased postural sway velocity and some changes in entrainment gain. Children with FASD showed higher entrainment gain to vestibular stimuli. There were no significant changes in sensory attention fractions.

Limitations. The small sample size, dose of STABEL training, and exploratory statistical analyses are study limitations, but findings warrant larger systematic study to examine therapeutic effects.

Conclusions. Children completed the training protocol, demonstrating the feasibility of the STABEL system. Differences in postural sway velocity post-STABEL training may have been affected by fatigue, warranting further investigation. Limited immediate effects suggest more practice is needed to affect sensory attention; however, entrainment gain changes suggest the STABEL system provoked vestibular responses during balance practice.

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Balance is achieved by the cooperative interaction of motor and musculoskeletal systems and 3 sensory subsystems: visual, vestibular, and somatosensory (proprioceptive and cutaneous information).[1,2] These sensory subsystems interact to cue the neuromuscular system to produce appropriate postural muscle activation to maintain postural control for specific tasks and environments.[3–6] The inefficient use or control of sensory information has been described as a potential mechanism for balance impairments in children with neurodevelopmental disabilities.[7–11]

Fetal alcohol spectrum disorders (FASD) and moderate-to-heavy prenatal alcohol exposure have been associated with a 3-fold risk for gross motor impairments.[12] These gross motor impairments include diminished balance and postural control. Compared with children with typical development (TD), children with FASD are reported to demonstrate poorer balance during stationary tasks (eg, standing) and increased postural sway following balance perturbations.[10,11] Increased postural sway under altered (inaccurate somatosensory) versus accurate sensory (visual and vestibular) information also has characterized balance responses in this population.[10] Diminished sensory control may be a mechanism of poorer balance ability in children with FASD.

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- **eTable 1:** Personal and Demographic Characteristics by Group
- **eTable 2:** Multi-Modal Balance Entrainment and Response (MuMBER) Protocol: Visual, Samatosensory, and Vestibular Conditions
- **eTable 3:** Sensory Attention Fractions: Sensory Condition by Group

Poor balance and postural control can impede participation in childhood play, learning, and daily living activities (eg, sitting with control in school, playing safely on the playground, engaging in team sports).[13] Underlying motor and postural impairments in children can present as negative behaviors (eg, inattention, clumsiness)[14,15] and lead to psychosocial difficulties (eg, frustration, poor self-esteem, avoidance, anxiety),[16–18] compounding an already high risk for secondary behavior problems and disabilities in children with FASD.[19] Yet, recent research reviews have yielded no published motor intervention studies for this population,[20] despite the positive effects of therapeutic motor training reported in studies of alcohol-exposed rodent models.[21–23]

We developed a novel virtual reality (VR) intervention: the Sensorimotor Training to Affect Balance, Engagement and Learning (STABEL) system, designed to train sensory control during balance. This article describes the STABEL system and rationale for development. We also report the feasibility of the STABEL system for children with FASD and a nonclinical comparison group of children with TD and the immediate effects of STABEL training on sensory attention and postural control during standing balance.

STABEL System: Rationale for Development

The STABEL system uses VR technology that facilitates task-specific balance practice under altered sensory conditions. Task-specific practice has been shown to improve neural organization[24] and postural control and motor coordination.[25–30] These improvements have been demonstrated in: (1) repetitive practice recovering from repeated perturbations of the support surface in children with cerebral palsy during standing,[25,26] (2) children with TD in sitting,[27] (3) repetitive practice reaching beyond the base of support in children with TD,[28] (4) compensatory training emphasizing enhancement of visual and somatosensory function in children with hearing impairments,[29] and (5) a "Retraining for Balance" program that included vestibular and auditory perceptual stimulation in children with attention and motor difficulties.[30]

Virtual reality technology can provide a complex, enriched motor practice environment whereby many repetitions can be completed within a controlled environment with real or distorted feedback, or both, during the practice. In alcohol-exposed animal models, complex therapeutic motor training in enriched environments has shown positive effects on motor performance and neural organization.[21–23] Pilot studies, primarily in children with cerebral palsy,[31–35] have shown that improvements in motor ability and balance occur following VR-based intervention. Neuroplastic changes measured by functional magnetic resonance imaging also have been reported, as described in one child with hemiparesis following completion of a VR protocol that focused on upper extremity control.[33] Maintenance effects at 14 months postintervention also were seen, suggesting the potential for long-lasting changes in motor performance.[33]

Virtual reality game technology can engage and motivate children to increase motor practice. Improved exercise adherence and reports of greater enjoyment when using a VR system versus a conventional therapeutic exercise program have been described.[36–38] Children, parents, and rehabilitation therapists also are interested in VR-based interventions, suggesting that treatment using computer game platforms is clinically acceptable.[39,40]

Specific VR-based interventions that target sensory control as a mechanism of change for balance ability are novel in pediatric rehabilitation. Rine et al[29] examined the impact of an exercise intervention on sensory organization and motor outcomes in children with sensorineural hearing loss and vestibular impairment. The exercise intervention included compensatory training, balance training, and visual and somatosensory enhancement activities. Treatment effects included significant gains in developmental motor performance. Changes in visual, vestibular, and somatosensory outcomes derived from posturography stability scores also were reported, demonstrating sensory adaptation as a plausible mechanism of change for balance control.

Ashkenazi et al[41] used off-the-shelf VR game technology in combination with different standing surfaces as a sensorimotor intervention for children with developmental coordination disorder (n=9). The children showed significant postintervention improvements on balance and motor outcomes on the Movement Assessment Battery for Children (2nd edition). Results demonstrated the feasibility of balance training using components similar to our STABEL system. The intervention also had positive effects on motor outcomes in a clinical group with motor impairments similar to children with FASD.

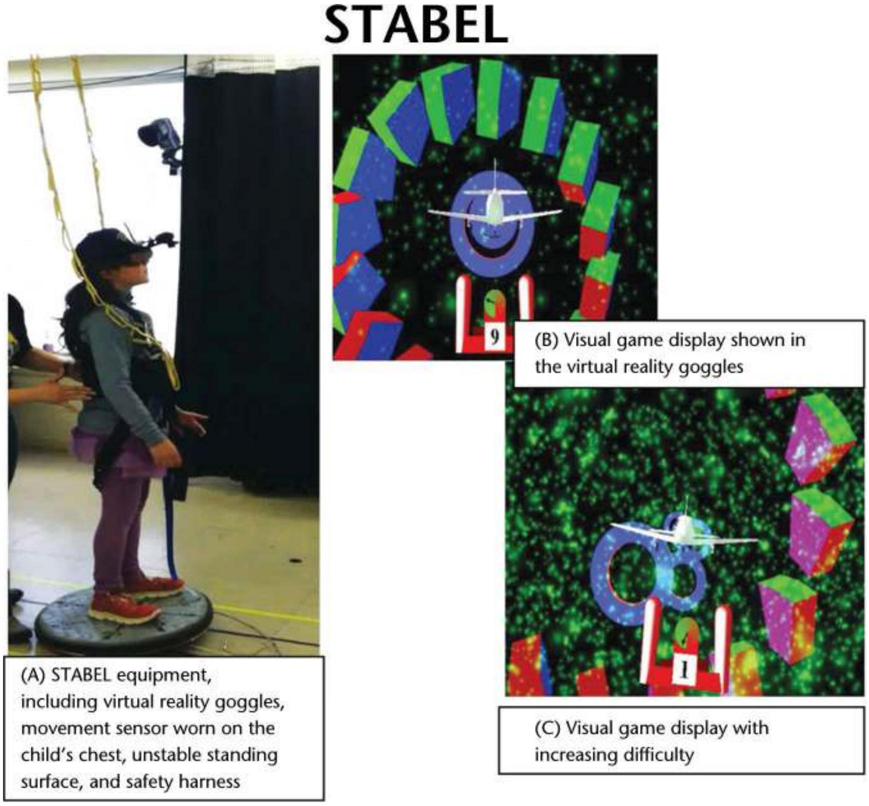

Figure 1.
Sensorimotor Training to Affect Balance, Engagement and Learning (STABEL) system: (A) STABEL equipment, consisting of the virtual reality goggles, movement sensor worn on the child's chest, unstable standing surface, and safety harness; (B) visual game display shown in the virtual reality goggles; (C) visual game display of increasing difficulty.

Technical Description

Physical therapists, occupational therapists, rehabilitation engineers, and computer scientists developed the STABEL system. The STABEL system is novel with respect to other commercially available game devices used for rehabilitation in that it uses a combination of VR and game technology coupled with an unstable standing surface, which allows for controlled manipulation of sensory information in measureable doses during balance practice. The VR goggles and an unstable standing surface allow for the distortion of visual, vestibular, and somatosensory input while children move their bodies (bending in anterior-posterior and medial-lateral directions) to play a game piloting a virtual airplane through hoop targets (Fig. 1). The required body movements to "pilot the plane" and maintain standing balance under changing sensory conditions provide a task-specific goal and motivating context for repeated standing balance practice. The game progresses from easy to more difficult, and the child is rewarded by accruing points for piloting the plane through the hoops. During game play, the child's body segment motion is tracked with a chest sensor using inertial measurement units (IMUs). The IMUs consist of 9-degree-of-freedom sensors that track acceleration, angular velocity, and geomagnetic field orientation in 3 dimensions. An onboard microcontroller computes the final 3-dimensional orientation from the 9-degree-of-freedom sensors. The child controls the direction of the plane by leaning forward and backward to alter the pitch of the plane and by leaning left and right to alter the yaw. The gain for amount of movement (body lean) to change plane direction can be adjusted. For this feasibility study, we adjusted the difficulty level (amount of leaning required to pilot the plane) once at the beginning of the STABEL play session for each child. The gain was set so play was challenging, but children were successful on the easier conditions (ie, the "just right" challenge). With greater times playing STABEL games, we suggest that the adjustment of gain of body movement to plane control will be a key element for provoking greater postural control improvement.

Visual sensory input is delivered with a small, head-mounted video camera combined with computer-generated imagery projected through VR goggles. The visual input is systematically varied during game play by the optical flow of the visual scene. The difficulty of the visual input is progressed by manipulating the screen background and speed and the path of the obstacles during the game. Screen background settings in order from easiest to more difficult include a referenced background in which the children see the real environment through the camera, a pure black background, and a black background with different numbers of looming objects. In addition, obstacles (eg, hoops) appear in varying orientations beginning with a straight line at the easiest level and a corkscrew orientation at a more difficult level.

Somatosensory and vestibular input is altered by varying the standing surface stability, progressing from a more to less stable floor surface. The standing surface consists of a piece of firm foam and an adjustable pressure tilt board set at low- and high-pressure levels. Stability is adjusted via inflation of an annular pneumatic inner tube supporting the omnidirectional tilt board. Children wear a gait belt with a therapist standing close by to prevent falls during game play.

By manipulating both the visual scene and the support surface, we hypothesized that we were provoking balance practice under altered sensory conditions, essentially "forcing" the children to attend to and use vestibular sensory information during standing balance. Our focus on vestibular sensory attention was informed by previous research findings suggesting that children affected by prenatal alcohol exposure had inefficient postural control with less attention to vestibular input when somatosensory conditions were inaccurate.[10,11] We tested sensory attention and postural control behaviors in children with FASD and children with TD before and immediately after a short STABEL session to explore immediate effects. We expected that the STABEL training would be feasible for school-aged children and that postural control and vestibular sensory attention would change following STABEL practice.

Method

Sample

A convenience sample of 11 children with FASD (27% female; mean age=137.0 months, SD=23.0) and 11 children with TD (33% female; mean age=133.5 months, SD=26.9) participated. Participant characteristics are shown in eTable 1 (available at ptjournal.apta.org). All parents and children signed approved consent and assent forms, vely, prior to participating in the study.

Children with FASD were recruited from a clinical registry with more than 2,000 patients with FASD who have been systematically diagnosed by an interdisciplinary team using the 4-digit diagnostic code, a validated, objective, case-defined approach that uses quantitative Likert scales to measure and report outcomes. The 4 digits of the code reflect the magnitude of expression of the key diagnostic features of FASD: (1) growth deficiency, (2) facial features, (3) central nervous system damage/dysfunction, and (4) maternal alcohol consumption during pregnancy.[42,43]

Inclusion criteria for children with FASD were: (1) ages 8.0 to 16.0 years, (2) male or female, (3) any race or ethnicity, (4) confirmed prenatal alcohol exposure at any level, (5) a diagnosis on the fetal alcohol spectrum (fetal alcohol syndrome, static encephalopathy, or neurobehavioral disorder),[42,43] and (6) a previously identified sensorimotor impairment based on clinical diagnostic assessment results. Children with FASD were excluded if they: (1) had an IQ of <60, (2) had a severe co-occurring neuromotor condition that impaired ambulation or independent standing for ≥2 minutes, (3) had a history of serious head injury or seizures, (4) had a visual acuity impairment not corrected by glasses, (5) reported any lower limb or back injury within the previous 6 months, or (6) currently lived in an unstable home placement. Children were recruited and enrolled in accordance with institutional review board requirements and Health Insurance Portability and Accountability Act (HIPAA) guidelines.

Children with TD were recruited from the community via flyers, word-of-mouth, and a university research participant pool. Inclusion criteria were: (1) aged 8.0 to 16.0 years, (2) male or female, and (3) any race or ethnicity. Exclusion criteria were: (1) an identified sensory or motor impairment, (2) current or past special education services, (3) history of serious head injury or seizures, (4) prenatal alcohol exposure (mothers reported ≥3 drinks over the duration of the pregnancy), (5) visual acuity impairment not corrected by glasses, and (6) report of any lower limb or back injury within the previous 6 months. Caregivers in both groups were interviewed by phone using an enrollment questionnaire to determine if their child was eligible for the study.

Procedure

Study procedures were conducted in one 3-hour laboratory visit by a physical therapist, who was a PhD student at the time of study. The examiner was not blinded to FASD or TD status for this feasibility study. Participants were assessed with the Multimodal Balance Entrainment Response (MuMBER) system, then completed 30 minutes of STABEL training, and then were reassessed with the MuMBER system. The training protocol entailed three 6-minute blocks of STABEL practice with short rest breaks between blocks. Each 6-minute block progressed in difficulty by altering the stability of the standing support surface from stiff foam to a high-pressure (relatively stable) surface that could tilt in multiple directions and finally to a low-pressure (relatively unstable) tilting surface. Following each training block, children answered questions from a short questionnaire about their STABEL experience to assess feasibility.

Instrumentation

The MuMBER system is a noninvasive, kinematic laboratory methodology designed to measure sensory attention within a complex environment where multiple external sensory stimuli are provided that can affect postural control. This measurement system was developed by this research team based on the work of Oie and colleagues.[44] Based on our examination of validity and reliability, we suggest that construct validity is supported and intertrial reliability is fair (unpublished data; July 17, 2015). The MuMBER system measures postural responses and sensory attention across 3 sensory subsystems during standing balance under varying sensory conditions. Further details about the MuMBER assessment system and outcomes are reported elsewhere.[11]

The assessment protocol required participants to stand on the MuMBER apparatus while 3 types of sensory stimuli (movable dots on a visual screen, finger touch to a moveable pole, and a movable platform surface) were manipulated simultaneously. Participants wore a loose support harness during the assessment protocol for safety. Sensory stimuli were provided in combinations of low (L), medium (M), and high (H) frequencies for visual (dots on screen), somatosensory (touch pole), and vestibular (tilt board surface) inputs. For example, a condition labeled HHL indicates a combination of high-frequency visual stimuli, high-frequency somatosensory stimuli, and low-frequency vestibular stimuli. All stimuli were triggered to move in a medial-lateral direction at consistent small amplitudes. Each stimulus was moved at a specific frequency, which was unique for each sensory system. Stimulus conditions were grouped into 2 sequences where the frequency of one or more sensory systems was varied (eTab. 2, available at ptjournal.apta.org).

Series LLL, LLM, and LLH evaluated responses to 3 frequencies of tilt board stimuli to measure attention to vestibular stimuli. Series LLL, MML, and HHL evaluated responses to increasing frequencies of visual (visual dots) and somatosensory (touch pole) stimuli to determine if children increased their attention to the vestibular (tilt board) stimuli when frequencies of visual and touch stimulation were higher. A final condition, XXL (where X denotes no visual or touch pole stimulation), assessed responses to tilt board stimuli alone.

A Qualisys Oqus 300 motion capture system (Qualisys AB, Gothenburg, Sweden)[45] captured body sway movements at 120 Hz through 5 cameras located posterior and lateral to the child. The system tracked 5 reflective markers located on the occiput of the head (marker on a helmet), seventh cervical (C7) vertebra, sacrum between the posterior superior iliac crests, and Achilles tendons, approximately 5 cm above the inferior surface of each heel. Postural sway was tracked in response to the changing sensory stimulation to determine the children's postural stability and the proportion that the children attended to each sensory stimulus. Specific variables are described below.

Data Reduction

All data were examined frame by frame for missing data. If markers momentarily disappeared due to the child's body movements (eg, if the child extended his or her head, the helmet could obscure the C7 marker; if the child's safety vest shifted, it could obscure the C7 or sacral marker), those segments were interpolated. Any trials with a marker gap >300 milliseconds) were discarded. Each marker component was centered, by subtracting the mean, before further processing.

Two kinematic postural control variables were derived by sensory condition using MATLAB software (The MathWorks Inc, Akron, Ohio): (1) velocity of medial-lateral and anterior-posterior body sway movement (root mean square [RMS] mm/s) and (2) ellipse area of body sway (mm^2). The mean of 2 trials per sensory condition was used. Two kinematically derived measures of sensory (visual, tactile, and tilt board) attention were analyzed: (1)

entrainment gain and (2) sensory attention fraction.

Entrainment gain. Entrainment gain for each sensory system was defined as response amplitude divided by stimulus amplitude at the stimulus frequency of the respective sensory system. Gain is a common measure in the engineering disciplines to compare system behaviors. Comparisons between gains reveal the relative response amplitudes while normalizing to the stimulus amplitudes. Entrainment gain is a variable that has been used in previous, similar studies examining visual and tactile contributions to balance control.[6,44] Spectral analysis was used to isolate the portion of the body sway occurring at the stimulus frequencies. As only the trajectory data near the stimulus frequencies were of interest (ranging from 0.24 to 1.11 Hz), a fourth-order Butterworth band-pass filter was applied.[46] A Welch smoothing window was applied to avoid spectral leakage, along with a tolerance interval to detect response peaks within 0.02 Hz of the stimulus. To detect phase wrapping, phase (timing of response) was calculated from the timing of the peak cross-correlation of stimulus and response signals and converted to degrees. Some analyses were restricted to a prescribed range of phases (ie, phase-restricted) to ensure that the body sway responses used to determine entrainment gain were temporally related to the sensory stimuli.

Sensory attention fraction. Sensory attention fraction (SAF) was defined as the ratio of the medial-lateral body sway response amplitude (at each respective sensory stimulus frequency) to the sum of all peaks of body sway movement over the pass-band of frequencies. The SAF is a novel measure intended to reveal the contribution of each balance subsystem and measure the relative attention to each sensory subsystem when all 3 stimuli were provided. Gains were statistically analyzed to calculate visual, tactile, and tilt board SAFs if the phase of the child's response was not greater than ±360 degrees to the sensory stimuli (this approach precluded a large temporal/phase mismatch of stimulus and response).

Data Analysis

Children's responses to the post-STABEL questionnaire were collated using descriptive statistics. Data analysis and graphs for the pretraining-posttraining analysis of STABEL were completed using IBM SPSS version 20 (IBM Corp, Armonk, New York) and Excel (Microsoft Corp, Redmond, Washington). Variables were calculated for each sensory stimulus using the sacrum and head (marker on helmet) markers. Because sacrum and head marker data showed similar pretraining-posttraining results in comparisons of gain and SAFs, only sacrum marker data are presented. Individual children's data and descriptive data were examined to explore postural control (ellipse area of body sway and RMS velocity) and sensory attention (entrainment gain and SAF) outcomes before and after STABEL training. We analyzed outcome variables with a repeated-measures analysis of variance (ANOVA), using a within-group analysis across the 6 MuMBER conditions. Two-tailed significance levels were set at $\alpha=.10$, and corrections for multiple comparisons were not applied due to the exploratory aims of this study.

Results

Feasibility

Descriptive data from the child questionnaire completed immediately after each STABEL training block describe the feasibility of STABEL in children with and without FASD (Tab. 1). All participants with FASD and TD interacted with the STABEL system and completed all 3 training blocks within the 30-minute practice session. The majority of the children reported STABEL was fun to play; however, a small proportion (18%–27%) of children in both groups reported session 3 was "too hard to have fun." Approximately one-third of the children with TD and one-fourth of the children with FASD reported dizziness during or immediately after using STABEL; however, the dizziness resolved within 5 to 10 minutes of rest.

Immediate Effects: Postural Control

Postural control kinematic variable distributions by group and condition (ellipse area of body sway and anterior-posterior and medial-lateral RMS velocity) are plotted in Figure 2. Descriptive statistics and repeated-measures ANOVA comparisons of postural control outcomes are presented in Table 2. The repeated-measures ANOVA yielded no significant interactions for ellipse area of body sway or velocity outcomes. The children with FASD showed significantly higher medial-lateral RMS velocity than children with TD across all 6 conditions. Significantly higher medial-lateral and anterior-posterior RMS velocities were seen after STABEL training compared with before STABEL training across all conditions in both groups, with the exception of condition XXL. There were no significant differences in ellipse area of body sway before versus after STABEL training or by group (data not shown).

Immediate Effects: Sensory Attention

Entrainment gain. Table 3 shows means, standard deviations, and repeated-measures ANOVA comparisons for visual, touch pole, and tilt board entrainment gains. Two significant interactions were found in the LLM condition ($P<.10$); visual screen gain and tilt board gain

Table 1.
Summary of Sensorimotor Training to Affect Balance, Engagement and Learning (STABEL) System Feasibility by Group[a]

STABEL Sessions	TD Group (n=11)	FASD Group (n=11)
STABEL practice block 1 (easy, standing on the solid floor)		
1. Playfulness (%)[b]		
Feels fun	90.9	81.8
Feels OK	9.1	18.2
Feels too hard to have fun	0.0	0.0
2. Dizziness (%)[b]		
Feel dizzy	9.1	0.0
Feel a little dizzy	27.3	18.2
No dizziness	63.6	81.8
STABEL practice block 2 (moderate, standing on a fully inflated air tube)		
1. Playfulness (%)		
Feels fun	72.7	100.0
Feels OK	27.3	0.0
Feels too hard to have fun	0.0	0.0
2. Dizziness (%)		
Feel dizzy	9.1	9.1
Feel a little dizzy	27.3	9.1
No dizziness	63.6	81.8
STABEL practice block 3 (hard, standing on a partially inflated air tube)		
1. Playfulness (%)		
Feels fun	63.6	54.5
Feels OK	18.2	18.2
Feels too hard to have fun	18.2	27.3
2. Dizziness (%)		
Feel dizzy	27.3	18.2
Feel a little dizzy	9.1	0.0
No dizziness	63.6	81.8

[a] TD=typical development, FASD=fetal alcohol spectrum disorders.
[b] Specific questions that children answered: (1) How did the game make you feel? and (2) Did you feel dizzy or did your stomach feel funny?

increased from before to after STABEL training in the TD group only. Exploration of pretraining and posttraining outcomes by condition showed that children in both groups had significantly higher touch pole entrainment gain (conditions LLL and LLH) and visual screen gain (condition LLH) and significantly lower entrainment gain for condition HHL. Examination of entrainment gain by group indicated that the children with FASD consistently showed a higher tilt board gain across all 6 conditions.

Sensory attention fraction. Individual and group SAFs were examined across conditions. A comparison of SAFs by group and condition with a repeated-measures ANOVA showed no significant interaction or pretraining-posttraining differences for SAF in any sensory condition (eTab. 3, available at ptjournal.apta.org). Four significant group differences were seen. In condition LLL, the children with FASD had a lower SAF to touch pole stimuli compared with children with TD (P=.03). In condition MML, the children with FASD had a slightly higher SAF in response to visual screen and to touch pole frequencies than children with TD (P=.07). In condition LLH, the tilt board SAF was slightly higher for the children with FASD compared with children with TD (P=.05).

Figure 3 provides line plots of individual tilt board SAF responses by group before and after STABEL training. The upper 2 quadrants of Figure 3 illustrate a lower tilt board SAF for both groups in response to increasing tilt board frequency (conditions LLL to LLM to LLH). The children with TD showed more variability in the tilt board SAFs, whereas the children with FASD showed minimal change in the tilt board SAFs. In response to increased frequency of visual and touch pole stimuli in conditions LLL to MML to HHL (Fig. 3, lower quadrants, a combination that hypothetically should force attention to the low-frequency tilt board stimuli), variable response patterns for children in both groups were seen.

Discussion

The STABEL system was designed as a rehabilitation intervention for children to develop balance control under altered sensory conditions through the use of VR and game technology. We tested the feasibility of the STABEL system and examined immediate results on postural control and sensory attention among children with and without FASD. The results are described below by study objective.

Feasibility

We sought to determine if children were able to engage and use the STABEL system and if they were able to tolerate component features (VR

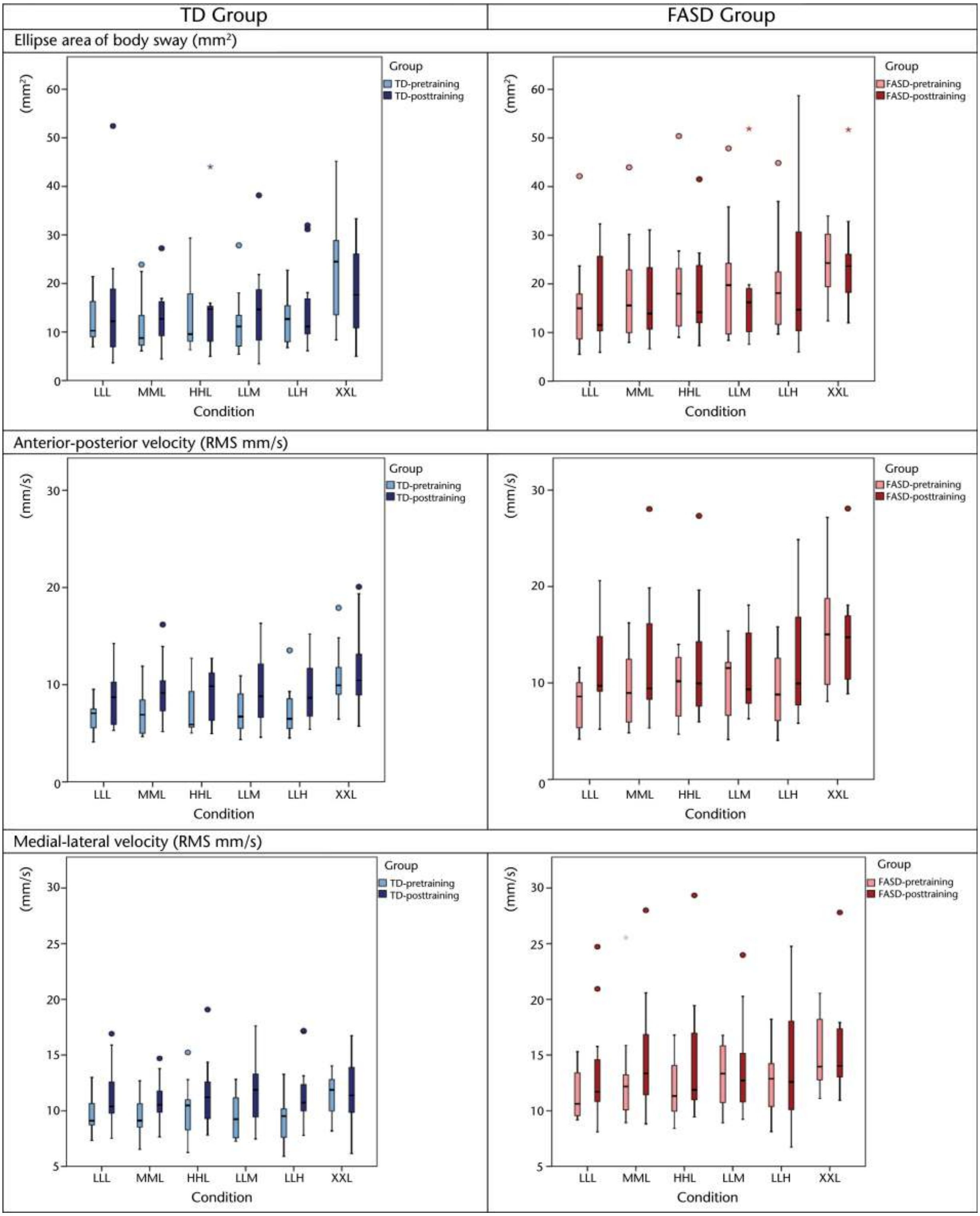

Figure 2.

Postural control distributions by group before versus after Sensorimotor Training to Affect Balance, Engagement and Learning (STABEL) practice. Postural control distributions for each outcome (ellipse area of body sway [mm^2], anterior-posterior sway velocity, and medial-lateral sway velocity [root mean square, mm/s]) are plotted on the x-axis by group (TD=typical development, FASD=fetal alcohol spectrum disorders) and on the y-axis by Multimodal Balance Entrainment Response (MuMBER) system condition pre- and post-STABEL practice. L=low-frequency movement, M=medium-frequency movement, H=high-frequency movement, X=no movement.

Table 2.

Postural Control: Postural Sway Velocity Outcomes for Each Sensory Condition[a]

MuMBER Sensory Conditions	Group $\bar{X}$ (SD)				RM-ANOVA (*P* Value)		
	TD		FASD				
	Pretraining	Posttraining	Pretraining	Posttraining	Pretraining/Posttraining	Group	Interaction
Anterior-posterior velocity (RMS)							
LLL	6.8 (1.7)	8.7 (3.2)	7.9 (2.9)	11.6 (4.9)	<.01*	.13	.21
MML	7.1 (2.3)	9.3 (3.4)	9.5 (3.9)	12.4 (7.0)	<.01*	.15	.60
HHL	7.6 (2.6)	8.9 (2.9)	9.6 (3.4)	12.1 (6.5)	.03*	.11	.45
LLM	7.2 (2.3)	9.6 (4.0)	9.9 (3.7)	11.4 (4.4)	.01*	.14	.53
LLH	7.2 (2.7)	9.3 (3.2)	9.3 (3.9)	12.5 (6.4)	<.01*	.12	.50
XXL	10.9 (3.2)	11.7 (4.6)	15.3 (6.2)	15.1 (5.5)	.47	.08*	.84
Medial-lateral velocity (RMS)							
LLL	9.6 (1.7)	11.4 (2.8)	11.6 (2.3)	13.6 (5.0)	.03*	.08*	.88
MML	9.4 (1.8)	11.0 (2.1)	12.9 (4.7)	14.8 (5.7)	<.01*	.03*	.73
HHL	10.0 (2.6)	11.5 (3.2)	12.1 (2.9)	14.6 (5.9)	.04*	.08*	.57
LLM	9.6 (2.1)	11.7 (2.9)	13.1 (2.9)	13.9 (4.6)	.05*	.03*	.40
LLH	9.3 (2.5)	11.7 (3.0)	12.7 (3.0)	15.6 (8.7)	.03*	.05*	.80
XXL	11.4 (1.9)	11.7 (3.2)	16.6 (6.6)	15.8 (4.7)	.94	.02*	.64

[a] Sensory conditions are presented in the following order: visual, tactile, vestibular (eg, MLL=visual stimulus at medium frequency, tactile stimulus at low frequency, and vestibular stimulus at low frequency). TD=typical development, FASD=fetal alcohol spectrum disorders, MuMBER=Multimodal Balance Entrainment Response system, L=low-frequency movement, M=medium-frequency movement, H=high-frequency movement, X=no movement, RMS=root mean square (mm/s), RM-ANOVA=repeated-measures analysis of variance. * *P* value ≤.1.

goggles, standing surface, and altered sensory input). All children were able to complete the training protocol. Children's self-reported responses to the STABEL system were generally positive, and most study participants reported the game was "fun" to play. The 3 training blocks within our feasibility protocol were designed to progress from easy to more difficult. Although some children noticed that the game was more difficult, they were still able to complete the protocol. Furthermore, based on observations of the children during game play, perturbations provoked postural and balance challenges but did not induce any falls. We designed the sensory input and game parameters to provoke attention to the vestibular system. Children in both groups reported dizziness after using STABEL. Of the children who reported dizziness, symptoms were mild and did not persist for any participant. This finding suggested that the combination of sensory input from the STABEL system elicited a vestibular response. We conclude that the STABEL system was feasible for children 8 to 16 years old in clinical and nonclinical groups, and children were able to practice balance control across changing sensory conditions that progressed from easy to more difficult. Monitoring symptoms of dizziness as a potential side effect will be important in future studies.

Immediate Effects: Postural Control

Our second study aim was to explore the immediate effects of the STABEL system on a laboratory measure of postural control and sensory attention. Both groups of children showed significantly higher anterior-posterior and medial-lateral postural sway velocity after STABEL practice. We interpret the increased sway velocity as an indicator of decreased postural stability. We question if fatigue may have been a factor affecting postural control for all participants on the post-STABEL assessment due to the long testing sessions (~2.5 hours). Having the 2 assessments of sensory attention and postural control outcomes and playing the STABEL games in a single session is a limitation of the current study. In future studies, assessments and STABEL play will occur on separate days so fatigue will potentially not affect results. Also, we will consider a reduction of the number of conditions within the MuMBER assessment protocol to reduce the possible effects of fatigue during assessment.

Immediate Effects: Sensory Attention

We hypothesized that the combination of visual and somatosensory stimulation that was manipulated during game play would "force" attention to vestibular input during

Table 3.
Sensory Attention: Entrainment Gain for Each Sensory Condition[a]

Measurements/Sensory Conditions	Group $\overline{X}$ (SD)				RM-ANOVA (*P* Value)		
	TD		FASD				
	Pretraining	Posttraining	Pretraining	Posttraining	Pretraining/Posttraining	Group	Interaction
LLL							
Visual gain	0.7 (0.5)	1.0 (0.6)	1.1 (0.8)	1.0 (0.5)	.26	.33	.30
Touch pole gain	1.1 (0.5)	1.3 (0.6)	1.1 (0.6)	1.2 (0.6)	.06*	.46	.83
Tilt board gain	1.1 (0.7)	1.2 (0.6)	1.5 (0.4)	1.6 (0.4)	.13	.01*	.91
MML							
Visual gain	0.3 (0.2)	0.7 (1.7)	0.6 (0.8)	0.7 (0.9)	.12	.80	.67
Touch pole gain	0.5 (0.3)	0.5 (0.3)	0.9 (1.0)	1.0 (1.5)	.17	.05*	.26
Tilt board gain	1.0 (0.7)	1.2 (0.7)	1.8 (0.5)	2.2 (2.2)	.14	.01*	.49
HHL							
Visual screen gain	3.6 (3.2)	4.0 (3.3)	3.2 (3.6)	4.2 (3.8)	.61	.81	.90
Touch pole gain	6.3 (3.5)	3.1 (4.1)	3.5 (4.0)	3.0 (4.2)	.02*	.15	.12
Tilt board gain	1.1 (0.8)	1.3 (0.7)	1.7 (0.6)	1.9 (0.5)	.20	<.01*	.90
LLM							
Visual screen gain	0.8 (0.5)	1.4 (1.1)	1.1 (0.7)	1.1 (0.7)	.11	.95	.07*
Touch pole gain	1.2 (0.6)	1.6 (1.5)	1.7 (1.8)	1.6 (1.0)	.59	.57	.34
Tilt board gain	0.7 (0.4)	1.1 (0.9)	1.1 (0.3)	1.1 (0.3)	.09*	.08*	.08*
LLH							
Visual screen gain	0.7 (0.3)	1.1 (0.6)	1.1 (0.6)	1.4 (1.2)	.02*	.02*	.88
Touch pole gain	1.2 (0.7)	1.7 (0.7)	1.5 (0.7)	1.6 (1.3)	.09*	.71	.36
Tilt board gain	0.3 (0.2)	0.3 (0.2)	0.5 (0.2)	0.5 (0.3)	.72	<.01*	.36
XXL							
Tilt board gain	1.4 (0.8)	1.4 (0.8)	2.0 (0.6)	2.0 (0.5)	.85	<.01*	.83

[a] Sensory conditions are presented in the following order: visual screen (vision), touch pole (somatosensory), tilt board (vestibular) (eg, MLL=visual stimulus at medium frequency, somatosensory stimulus at low frequency, and vestibular stimulus at low frequency). L=low-frequency movement, M=medium-frequency movement, H=high-frequency movement, X=no movement, RM-ANOVA=repeated-measures analysis of variance, TD=typical development, FASD=fetal alcohol spectrum disorders. * *P* value ≤.10.

STABEL practice. Therefore, we expected that the tilt board entrainment gains and SAFs after STABEL training would be higher than before STABEL training; however, overall, we did not find this pattern. We suggest that the one-time practice with STABEL was not enough to change sensory attention fractions. We did find group differences in entrainment gain between the children with FASD and TD, where children with FASD generally had higher gains than children with TD both before and after training. Higher entrainment gain suggests that either the children with FASD had more body movement in response to the specific sensory stimuli due to poorer balance, or they responded more to the sensory input. To control for general balance body sway when analyzing entrainment gain responses to the sensory stimuli, measurements of body sway without any extra sensory stimulation are needed. We did not perform these measurements within this study. In future research, this information should be collected and considered.

Overall, the SAF responses after the STABEL practice showed no significant mean differences in children in either group. If graphs of individual children are examined, however, several of the children with TD and children with FASD responded in the expected direction of increased sensory attention to the tilt board, as touch pole and visual stimuli increased in frequency (LLL to MML to HHL; Fig. 3). The examination of sensory attention in more children and adults with and without balance and postural control impairments is needed to further interpret whether these are clinically important changes and adaptive responses that improve overall balance and motor ability.

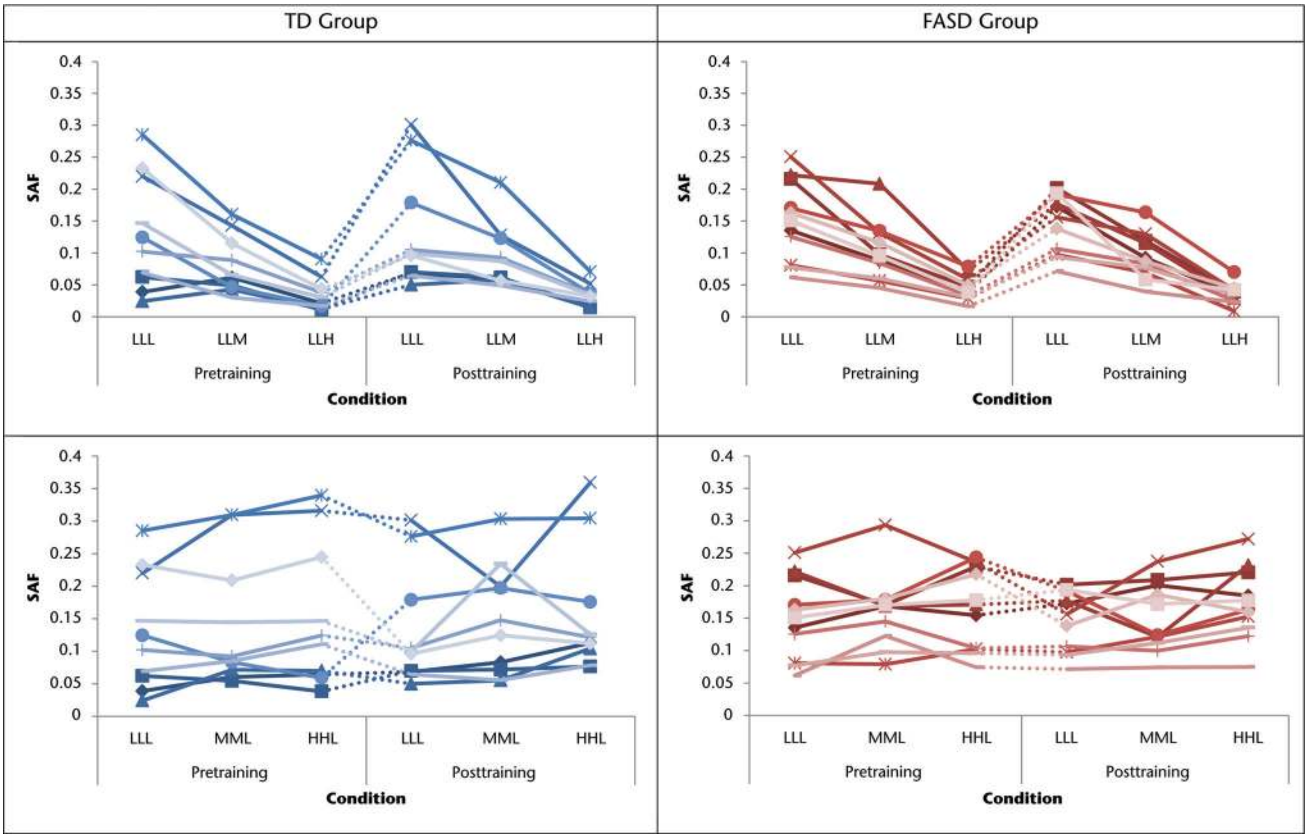

Figure 3.

Sensory attention fraction (SAF) plots: tilt board SAF. Individual children's SAFs as measured by the Multimodal Balance Entrainment Response system (MuMBER) are plotted on the y-axis (ratio of the medial-lateral body sway response amplitude [at each respective sensory stimulus frequency] to the sum of all peaks of body sway movement over the pass-band of frequencies) within each group (TD=typical development, FASD=fetal alcohol spectrum disorders) and shown before and after Sensorimotor Training to Affect Balance, Engagement and Learning (STABEL) practice. The dotted lines connect each child's pretraining-posttraining data for easier visual tracking of the data. The upper 2 quadrants plot individual responses to increasing frequency of the tilt board (vestibular) stimulus (x-axis: LLL, LLM, LLH) to measure attention to changing tilt board stimuli. The lower 2 quadrants plot individual children's responses to increasing frequencies of visual (visual dots) and somatosensory (touch pole) stimuli (x-axis: LLL, MML, and HHL) to determine if children increased their attention to the tilt board (vestibular) stimuli in response to changing visual and tactile stimuli. Sensory conditions were presented in the following order: visual, touch pole (tactile), tilt board (vestibular) (eg, MML=visual stimulus at medium frequency, touch pole stimulus at medium frequency, and tilt board stimulus at low frequency). L=low-frequency movement, M=medium-frequency movement, H=high-frequency movement.

There were several study limitations. Compared with other training interventions for postural control, the 30-minute dose of STABEL training was minimal. Study of a higher dose of STABEL training is needed to draw conclusions about any potential therapeutic effects for children with balance impairments. Studies that examine longer or more frequent STABEL sessions also should account for children's interest in the game over time. We did not use motor performance outcomes for this feasibility study. Including measures of balance and motor performance will be necessary in future studies to complement kinematic measures of sensory attention and postural control to examine effects at the levels of both impairment and function.[47] Finally, as this was a feasibility and exploratory study, the results are limited by our small sample size and multiple comparisons and cannot be generalizable without further studies.

Conclusions

The lack of clinical interventions to address sensorimotor function in children with FASD and the positive effects of therapeutic motor training described in animal models warrant development and study of targeted interventions. The use of VR technology provides a modality that has potential to motivate and engage children in repeated motor practice, factors that increase the probability of skill improvement and generalization. The use of VR computer technology also makes it possible to practice in clinical or home environments, which can increase access to rehabilitation interventions.

We demonstrated that the STABEL system was feasible for school-aged children with and without postural and balance control deficits. Our preliminary results indicated the STABEL system provoked sensory (vestibular) responses during balance practice, but group immediate effects on sensory attention were limited. Analysis of individual responses and patterns of change, however, suggest grounds for further study of the STABEL system using a larger sample and dose. Expanding outcomes to include functional motor performance and participation and examining the relationships between clinical measures and MuMBER sensory attention outcomes are important directions for future research.

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