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Visual dependence modifies postural sway responses to continuous visual field motion in individuals with Cerebral Palsy

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Abstract

The current study aimed to explore the impact of visual dependence on sensorimotor coupling of postural sway and visual motion in adults and teens with spastic cerebral palsy (CP). We hypothesized that individuals with CP would exhibit greater magnitudes of sway than healthy individuals, and the presence of visual dependence (VD) would produce instability in the direction of visual motion. Participants stood in a virtual environment in which the visual scene remained static or continuously rotated 30 degree/second in pitch-up or pitch-down. Increased center of pressure and center of mass responses were observed in the direction of visual scene motion in those with CP. Those with VD exhibited reduced frequency responses in anterior-posterior direction than those who were visually independent. VD suggests deficient sensorimotor integration that could contribute to postural instability and reduced motor function. Individuals with CP who are visually dependent may benefit from more sensory focused rehabilitation strategies.

Keywords

balance; virtual reality; visual dependence; sensorimotor integration

1. Introduction

Visual impairment is not strictly a loss of vision. Neuropsychological testing has revealed that a wide range of visual impairments alter accurate processing of visual information.¹ Visual perceptual impairment (VPI) is associated with reduced visual acuity, a reduced visual field, oculomotor incoordination, and complex sensory associative disorders.² VPI behaviours have been identified through paper and pencil tests for cognitive tasks; motor

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tasks, however, could also be significantly affected. Visual field dependence could fall under the category of VPI as it indicates an inability to filter out visual distraction and properly integrate vestibular, proprioceptive, and visual signals. The impact of visual field dependence would be exhibited as an overreliance on visual field information during a motor task, and an inability to respond appropriately to self-motion feedback³. An inability to select and respond to the stimuli most relevant to the task at hand could make the behavioural outcome less successful.

Influence of visual information on perceptual performance (i.e., accuracy of judgment about subjective visual vertical) and postural performance (i.e., variability and orientation during upright stance) has been studied in healthy young adults⁴ and in children with cerebral palsy (CP).⁵ A number of studies have revealed that individuals with visual field dependence (primarily those who are elderly or with neurological trauma) exhibit greater postural sway variability as a consequence of relying heavily upon visual cues, as opposed to visually independent adults.^{6,7} Children with CP tend to stand in a crouched position. When visual input was removed, flexion of hips and knees as increased in children who could not stand unsupported. Enhancing visual attention improved maintenance of quiet stance in children who could stand unsupported.⁵

Sensory inputs, particularly vision, vestibular and proprioceptive, must be dynamically re-weighted by the central nervous system in order to maintain upright stance in a mutable environment.^{5,8} But the visual system is an ambiguous resource because it provides noisy feedback that is not perfectly matched to somatosensory feedback.³ Reliance on such an ambiguous sensory resource over time could result in compromised postural control strategies and an increased risk of falling.

Appropriate coupling of sensory and motor behaviours has been observed in the postural reactions of healthy children as young as 4 years old. However, the magnitude of motor adaptation to changes in the visual environment was less in young children than in older children and adults.⁹ Children with CP placed in a moving room were able to adapt their body sway to the amplitude and velocity of the moving room similarly to that of typical developing participants.¹⁰ Individuals with CP exhibited larger and more variable body sway than the healthy subjects. It was concluded that children with CP were not able to down-weight the visual influences. This result would be suggestive of the presence of a VPI in the form of visual dependence in this population.

Nearly half the individuals with CP have been identified as exhibiting VPI and VPI occurs more frequently in spastic diplegia than in other forms of CP.² Adults with CP have also been found to exhibit greater dependence on visual stimuli as opposed to typically developing adults.⁶ Potentially, deficits in the proprioceptive system,^{11,12} vestibular system,¹³ and perception¹⁴ could precipitate the emergence of overweighting or dependence on visual sensory information in individuals with CP. A growing body of literature has demonstrated that impairments in the control of posture and balance in children with spastic CP may originate from the disruption of sensory connections outside the classic pyramidal motor pathways.¹⁵ As individuals with CP grow into adulthood, deterioration in the overall mobility function may occur before the age of 35 years and becomes more pronounced in

those with diplegic or quadriplegic presentation.¹⁶ Such self-reported deterioration includes increased fatigue and joint pain, decreased quality of life, and decreased balance.¹⁶ Thus understanding the mechanisms of postural control in the adults with CP would help guide appropriate interventions to sustain functional independence in this population.

Postural control is the result of a direct interaction between sensory information and motor action. An inability to adapt to changes in a dynamic visual environment combined with visual dependence would suggest impaired sensory-motor integration in the CP population. To examine postural responses in a dynamic visual environment, we employed virtual reality technology.^{17,18} Virtual reality environment provides the opportunity to investigate the role of spatial perception on postural behaviour because it provides a visually immersive experience with experimenter control of the visual field even when the performer moves through the environment and alters their orientation with respect to the visual feedback.¹⁹ The immersive virtual environment has been shown to produce strong perceptual effects on postural behaviour through the psychophysical processes of vection (self-motion induced by visual field motion in stationary observers) and immersion.²⁰

Previous studies have shown that postural compensation to virtual visual field motion is primarily observed in movements of the head and trunk and not in the ground reaction forces.^{21,22} Thus, in order to distinguish between body orientation and whole body sway we recorded both center of mass (COM) and center of pressure (COP) responses, respectively. Although related, these are distinctly different variables during active motion. COM characterizes whole body position, whereas COP is the summed projection of forces on the ground.²³ We hypothesized that individuals with CP would be more sensitive to environmental feedback and, therefore, produce larger and more variable COP amplitudes when exposed to continuous motion of the visual field compared to typically developing (TD) adults. Furthermore, we hypothesized that this variability could be explained larger amplitudes of COM motion in the same direction as the visual environment in individuals who are visually dependent, compared to smaller amplitudes in the direction opposite that of the visual environment in those who were visually independent.^{6,7}

2. Methods

2.1 Participants

A sample of convenience of 23 individuals with bilateral spastic CP (12 females; mean [SD] age: 32.3 [11.4] years) and 23 individuals with TD (11 females; mean [SD] age: 29.6 [11.0] years) participated in this current study. Recruitment was carried out locally in the greater Philadelphia Metro area, and a national search using the Cerebral Palsy Research Registry (<http://www.cpregistry.org>). Inclusion criteria were: minimum of 20/40 corrected vision in each eye; ability to follow simple instructions; ability to stand independently without assistive devices or support for at least 2 minutes; minimum of 15 degrees of motion at the ankle joint. In the current study, we adopt the definition of CP as a group of developmental motor disorder due to non-progressive disturbances to the developing brain.²⁴ Additionally, a diagnosis of spastic subtype, defined as bilateral hypertonia with the lower limbs more greatly affected, was required for individuals with CP.²⁵ Children with unilateral effects of

CP were excluded. All subjects reported that they had no known visual impairments other than corrections for acuity.

Participants were excluded if they had any neurological disorders other than CP; presence of visual acuity deficit not corrected by eyewear; current use of benzodiazepines as these drugs may affect balance. At the time of participation, no participants were taking intrathecal Baclofen or had Botulinum toxin treatment in the past 3 months. In addition, all participants with CP could ambulate with, at most, minimal assistance and were classified on the Gross Motor Function Classification System (GMFCS) as level I or II. The institutional review board at Temple University approved this study. Written informed consent was obtained from participants and parents of minors with written assent from all minors. Demographic data and characteristics of all participants are presented in Table 1.

2.2 Apparatus

The immersive virtual environment consisted of three screens facing the front, left, and right of the subject; the overall dimension of the virtual environment was 3.5 m (width), 3.5 m (depth), and 6.1 m (height). Two Panasonic PT-D5600U DLP-based projectors positioned behind each screen projected a full-color field with the resolution of $1,024 \times 768$ pixels at a 60 Hz refresh rate. Stereovision was created by polarized filters placed in front of the projector lens to provide left eye and right eye views of the image on each screen, and polarized glasses that delivered the correct view to each eye. Three computers created the images projected in the virtual environment (Figure 1) and were synchronized through the CAVELib software (MechDyne, Virginia Beach, VA, USA). All participants verbally confirmed the detection of visual field motion through the polarized glasses.

2.3 Procedures

All subjects were evaluated for integrity of light touch and pain sensation on the plantar surface of both big toes and the lateral border of the feet. Failure to identify the Semmes-Weinstein 4.31 monofilament (2 grams force) was considered to indicate diminished light touch sensation.²⁶ Failing to detect a pinprick was considered to indicate impaired pain sensation. Detection of a 128 Hz tuning fork was tested on bilateral posterior calcaneus and failure to detect such vibration was considered to indicate impaired vibration sense.²⁷

A Snellen chart was used to test visual acuity,²⁸ and a non-instrumented Dynamic Visual Acuity test was employed to assess function of the vestibulo-ocular reflex (VOR) in response to rotational head movement in all participants according to a standard protocol.^{29,30} The VOR was considered impaired if the ability to read the visual chart while the head was in motion deteriorated by 0.2 logMAR or greater than when the head was stationary.³⁰ No psychometric properties of clinical Dynamic Visual Acuity tests have been reported in individuals with CP, however this Dynamic Visual Acuity test has excellent test-retest reliability and criterion validity in individuals with unilateral or bilateral vestibular hypofunction.³¹

A computer-based Rod and Frame Test (RFT) was employed with subjects seated to assess the presence of visual dependence.^{32,33} Visual independence (VI) was assumed if both the average and standard deviation of the signed angular deviations from 8 trials were within

$\pm 4.5^\circ$.³⁴ This indicates a correct perception of verticality/horizontality in the absence of visual cues to vertical. In contrast, visual dependence (VD) was assumed when the mean and standard deviation of the signed angular deviations fell outside of this range, which suggested that the perception of verticality and horizontality was influenced by the tilt of the visual frame.³⁴ As a result of this testing, 13 individuals with CP were separated into a visually dependent group (CPVD) and 10 subjects into a visually independent group (CPVI). All of the subjects with typical development were visually independent.

2.4 Visual Flow

Subjects stood barefoot with feet placed at a comfortable distance apart, arms resting at sides, eyes open, in the center of the virtual environment (Figure 1). Subjects were instructed to look straight ahead at the central screen and to maintain an upright posture. Prior to each trial, subjects were instructed to stand quietly for at least 5 seconds while the visual scene was kept stationary. During each 30-second trial, the visual scene was either kept stationary or continuously rotated about the inter-aural axis; thus, the visual perturbation occurred only in the sagittal plane. All subjects were examined in the following visual scene conditions: (1) stationary visual scene (static), (2) continuously rotating visual scene at $30^\circ/\text{s}$ in the pitch-up or nose up (PU) direction, and (3) continuously rotating visual scene at $30^\circ/\text{s}$ in the pitch-down or nose down (PD) direction. A $30^\circ/\text{s}$ velocity of the visual scene was chosen because it has been shown to produce strong coupling between visual velocity and sway amplitude in adults.³⁵ The order of these testing conditions was pseudo-randomized across subjects. Subjects were allowed rests as needed between trials.

2.5 Data Collection and Analysis

Given the stationary, symmetrical standing task, coordinates of a marker placed at the L4/L5 joint was used as a proxy for COM location.³⁶ Three-dimensional coordinates of this marker were collected at 60 Hz using the Motion Analysis Hawk System (Motion Analysis Inc., Santa Rosa, CA, USA) and low-pass filtered at 6 Hz using a fourth-order Butterworth digital filter. COP data were collected from a 45cm x 45cm AMTI force platform (AMTI Inc., Watertown, MA, USA) force plate at 200 Hz across the 30-second testing period of each trial. Foot position was marked on the platform for reproduction across trials. Using MATLAB (MathWorks, Natick, MA, USA), several parameters were calculated to quantify the relationship between the visual field motion and postural sway. Root-mean-square (RMS) of COM and COP in the anterior-posterior (AP) and mediolateral (ML) directions provided a measure of magnitude of postural sway variability in the upper body and in the ground reaction forces, respectively. Median frequency (MDF) of COM and COP was calculated as a measure of body sway in the frequency domain. Frequency characteristics of sway in healthy young adults during quiet stance tend to fall within a low frequency band (0.02–0.2 Hz) and are lower than healthy elderly adults, young children, and those with neurological disorders.^{37,38}

COP and COM AP trajectories were also plotted across the 30-seconds test period and fitted onto a straight line using a least-square model. The slope of this fitted line (SLP) specifies the direction of deviation from the vertically aligned position thereby indicating whether the

postural sway was moving in the same or opposite direction from visual field motion. Absolute value of SLP was used to quantify the magnitude of that deviation.

2.6 Statistical Analyses

Fisher exact tests on categorical data were employed to determine the association between visual dependence and participant characteristics such as light touch sensation, pain sensation, vibration sensation, and VOR function. Significance level was set at 0.05.

Group differences on the RFT were tested with a one-way ANOVA with the significance level at 0.05. Tukey's Post Hoc test was performed to examine group difference with corrected significance level at 0.016 ($=0.05/3$).

Distribution of the postural data was skewed, thus in order to execute parametric analyses, data transformation was performed based on application of Tukey's ladder. Natural log transformation was applied to the COM in the AP direction. After data transformation, mixed model repeated-measure ANOVAs were employed with group (TD, CPVI, CPVD) as a between-subject factor and visual field condition (static, PU, PD) as a within-subject factor. The effect of visual field motion on group COP and COM responses was examined with a separate mixed repeated-measure ANOVA for AP and ML motion. F -values based on Wilks' Lambda and a significance level at 0.05 was adopted. A large effect size was reported at partial $\eta^2 > 0.14$. Post hoc difference contrasts were employed for determining the effect of group: TD vs. CPVI and VI (TD and CPVI) vs. VD (CPVD). Simple contrasts were employed for determining the effect of condition: PU vs. static and PD vs. static. The corrected significance level was set at 0.025 ($=0.05/2$). Paired t tests were employed to compare means of visual field conditions (static vs. PU; static vs. PD; PU vs. PD) within each group with significance level set at 0.05. Statistical analyses were performed using SPSS 22.0 for Macintosh (SPSS Inc., Chicago, IL, USA).

3. Results

3.1 Visual Dependence (Rod and Frame Test – RFT)

Thirteen of the 23 CP subjects tested positive for visual dependence (Table 1). Averaged angular deviations on the RFT differed significantly between the three groups ($p < .01$, $F(2, 43) = 51.81$). The CPVD group made larger errors (mean [SD]: 15.16° [7.48°]) than the CPVI group (mean [SD]: 2.03° [0.74°], $p < .01$) or the TD group (mean [SD]: 1.77° [0.71°], $p < .01$). There was no significant difference between the CPVI and TD groups on the RFT. Larger angular deviation in the CPVD group indicates a greater sensitivity to visual inputs as compared to CPVI and TD.

3.2 Association between Visual Dependence and Mobility and Sensory Functions

Thirteen out of the twenty-three (56.5%) participants with spastic CP exhibited an impaired VOR. Not all of the subjects with impaired VOR demonstrated visual dependence; results of a Fisher exact test on these data imply that visual dependence was significantly associated with impaired VOR function ($p = .04$). Visual dependence was not significantly associated with light touch sensation ($p = .49$), pain sensation ($p = .41$), or vibration sensation ($p = .43$).

3.4 Effect of Visual Field Motion on Postural Responses

Pitch rotation of the body is expressed as anterior (nose down) or posterior (nose up) sway, and the COM and COP motions followed the direction of visual scene motion for all groups (Figure 2a). Directionality of visual flow was reflected in the slope of the COM and COP for all three groups (Table 2). Response trajectories moved posteriorly as individuals were exposed to a pitch up visual scene, and anteriorly as individuals were exposed to a pitch down visual scene.

In the AP direction, MDF of COP increased significantly across groups ($p < .01$) with visual field motion compared to the static visual field (Figure 3). In contrast, MDF of COM did not differ significantly except with PD visual field motion in the CPVI group.

In the ML direction, subjects with CP either with or without VD moved more than did the TD subjects (Figure 2b). Although there were no significant effects of group on any of the movement variables in the ML direction (Table 2), an emerging effect of group was found on the RMS of the ML COP ($p < .07$, $F(2, 43) = 2.89$, partial $\eta^2 = 0.12$). Difference contrast tests demonstrated that there was no difference between the two CP subgroups on the RMS of COP in the ML direction (i.e., CPVI and CPVD, $p < .73$), but lesser variability in the TD group approached a significant difference from the two CP subgroups ($p = .02$).

3.5 Effect of Visual Dependence on Postural Responses

Visual dependence emerged as a distinguishing factor in the AP postural responses of the CPVD population (Figure 2a). After approximately 10 seconds of immersion in the virtual environment, both COM and COP deviated in the direction of visual flow much more than in those who were visually independent (TD and CPVI).

A significant main effect of group appeared in the absolute value of the slope of the line fitted to COM ($p < .05$, $F(2, 43) = 3.32$, partial $\eta^2 = 0.13$, Figure 4). Difference contrast tests confirmed that while the absolute value of slope of this fitted line of COM was not different between the TD and CPVI groups ($p = .84$), it was significantly greater in the CPVD group than both TD and CPVI groups ($p = .01$) signifying a greater shift of COM motion with motion of the visual field for the CPVD group (Figure 4 bottom).

TD only demonstrated significant RMS differences in AP COP between the pitch up direction of the moving visual field and the static scene. CPVI exhibited a significant increase in RMS of both AP COM and COP responses between pitch down of the visual field and the static scene; this could be due to their more backward leaning position with a static visual field (Figure 4). CPVD, however, exhibited significantly larger magnitudes of movement variability in AP COP and COM with both directions of visual field motion compared to the static scene (Figure 5). Responses in AP were larger than responses in the ML direction (Figure 2) for each group.

4. Discussion

Approximately half of the individuals with spastic CP have an associated visual perceptual impairment which can result in deficient higher order visual processing and visual attention.

^{2,39} Individuals with CP that exhibit visual dependence (expressed as a greater perceptual reliance on visual information) are at risk of impaired development in spatial awareness, posture and movement skills.³⁹ In this study we examined postural behaviours of adolescents and young adults with and without spastic CP when the visual environment was either kept stationary or moved in two directions of rotation in sagittal plane. We hypothesized that individuals with CP would be more sensitive on environment feedback and, therefore, less stable when exposed to continuous motion of the visual field compared to typically developing adults.¹⁰ Furthermore, we hypothesized that this instability could be explained by a finding of visual dependence that would make individuals with CP less able to compensate for motion of the visual field than individuals with visual independence.

Sensory integration uses information from all sensory modalities simultaneously with the result that a change in one sensory input will lead to change in the response to all sensory inputs. Impaired sensory integration has been shown to impact postural behaviour in both healthy^{9,40} and neurologically impaired^{41,42,43} adults. In the development of postural control, visual inputs initially dominate sensory integration. Dominance of somatosensory (i.e., proprioceptive and vestibular) receptors gradually emerges with age.^{44,45} Healthy 7 to 12-year-old-children were found to be unable to use somatosensory inputs to limit the body sway generated by dynamic visual cues to the same extent as adults, suggesting that the sensory integration of the somatosensory cues was still developing at 12 years of age.⁴⁶ Improved postural control with maturity may, therefore, be reflective of the acquired ability to adaptively reweight, i.e., to be able to switch between self-motion feedback and environmental feedback.⁴⁷

Self-motion induced by visual field motion, orvection, emerges 8–10 seconds after the immersion in the virtual environment; such delay in time is required for generating the perceptual process ofvection.^{35,48} In corroborative with previous findings, individuals who were visual dependent (i.e., CPVD) exhibited pronounced deviation in both COM and COP after approximately 10 seconds of exposure to visual field motion. Because of thevection phenomenon that governs responses in virtual environment, we would expect body motion in the same direction as the visual field.²¹ If proprioceptive information were governing the response to the virtual environment motion, we would expect a compensatory response in the direction opposite of the visual field motion.²² All groups did shift their COM in the direction of visual field motion. Furthermore, the directional shift and the magnitude of sway were much greater in the individuals who were visually dependent compared to the healthy young adults and to those with spastic CP who were visually independent (Figure 2).

The change in magnitude combined with the reduced power spectral bandwidth of body motion in the plane of visual motion is demonstrative of the greater sensitivity to visual field motion in the individuals who were visually dependent. That visually dependent individuals are more locked into the visual flow field implies that using constrained visual feedback could provide an informational structure to their postural behaviors that has been associated with improved balance and equilibrium.⁴⁹ Individuals who were visually independent responded with lower amplitude but an increased frequency bandwidth of their sway suggesting that visual field motion was being processed as additional noise to their system.^{3,50}

When available, task appropriate and reliable sensory information should be weighted more strongly than less reliable (impaired or noisy) information.⁵¹ If visual dependence were a result of decreased signals from vestibular and somatosensory systems, an increased perceptual reliance on the relatively intact visual system would be expected, even if the visual information were not appropriate for the task at hand. Children with spastic CP have been shown to exhibit decreased or absent vestibular evoked myogenic potentials,⁵² and oculomotor responses induced by caloric stimulation suggest a link between the VOR and perception.⁵³ The retention of visual dependence with maturation could also be related to an impaired ability to integrate sensory information stemming from damage to the periventricular white matter in children with CP.¹⁵ The majority of our CPVD participants did not exhibit deficiencies in somatosensory function (e.g., light touch, pain, vibration) at the foot, but did exhibit impaired VOR function. Thus, we might infer that vestibular dysfunction contributed to the impaired VOR and the resulting visual dependence in this group. Our results argue that postural instability and, by extension, impaired functional activity in adults with cerebral palsy, are a consequence of impaired sensory integration and not just an expression of motoric limitations.

Intriguingly, while most of our participants did not exhibit difference in the frequency component of the upper body as the visual field motion varied, our participants with CPVI did exhibit difference between static and pitch-down visual field motion condition. We might infer from this that although postural adjustments increased in frequency when the environment was in motion, overall body stability was not affected. The significant change in the CPVI group with pitch-down rotations could be reflective of their backward leaning position in the static condition (Figure 4). A pitch-down visual field appears to correct the posture alignment of the CPVI group; however, whether this could be used to facilitate treatment awaits further in depth investigation.

There are limitations in our current study. First, our subjects with CP were relatively few in number (23 in total) and were only in the GMFCS I and II levels. Individuals with decreased functional mobility (higher scores on the GMFCS) may respond differently to visual flow perturbations while standing. Future work is planned to look at a more heterogenic group, possibly including sitting tasks for those individuals with CP that are unable to maintain stance. Also, we used only sagittal plane visual perturbations. Visual motion in the frontal or transverse planes, or multiplanar visual motion, may have differential impact and is worthy of future investigation.

Conclusions

The purpose of this study was to examine the influence of visual dependence on postural behaviour in a population of adults with spastic CP. Individuals with visual dependence might be expected to depend more greatly on visual information for orientation cues to control and adapt their postural control to the demands of a particular task. We have demonstrated that visual dependence produces differential effects on postural responses in the plane of the visual field motion compared to responses of those with visual independence. The greatest effect was observed as larger magnitudes of anterior-posterior sway in the direction of visual field motion in the visually dependent subjects; little effect

emerged in lateral sway. Our results suggest that assessing the ability to maintain upright stance within a dynamic visual environment would distinguish subgroups within a CP population. Identifying these sensory weighting capabilities would help better target interventions to improve balance through sensory experience training.

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Abbreviations:

AP	anterior-posterior
CP	cerebral palsy
COM	center of mass
COP	center of pressure
MDF	median frequency
ML	mediolateral
PD	pitch down (nose down) rotation
PU	pitch up (nose up) rotation
RFT	rod and frame test
RMS	root mean squares
SLP	slope of the fitted line
TD	typical development
VD	visual dependence
VI	visual independence
VOR	vestibulo-ocular reflex
VPI	visual perceptual impairment

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Figure 1.

Image of a young healthy adult standing on the force plate in the virtual environment with the stationary image projected on the center screen. The scene was either kept stationary or, after 5 sec, it was rotated in the pitch up or pitch down direction for 30 sec at 30 deg/sec.

(a)

(b)

Figure 2.

Center of mass (COM, left column) and center of pressure (COP, right column) displacement data from three visual scene conditions: Static (bold line), Pitch Up (PU, thin line), and Pitch Down (PD, dashed line), (2a) in the anterior-posterior (AP) direction and (2b) in the mediolateral (ML) direction from a representative subject with typical development (TY, top row), cerebral palsy without visual dependence (CPVI, middle row), and cerebral palsy with visual dependence (CPVD, bottom row).

(a)

(b)

Figure 3.

Averaged median frequency (MDF) of (a) center of pressure (COP) and (b) center of mass (COM) in the anterior-posterior (AP) direction for each visual scene condition in subjects with typical development (TD), cerebral palsy who were visually independent (CPVI) and cerebral palsy who were visually dependent (CPVD).

Figure 4.

Top row: Averaged slope of (a) center of pressure (COP) and (b) center of mass (COM) in the anterior-posterior (AP) direction in each visual scene condition for subjects with typical development (TD), cerebral palsy who were visually independent (CPVI), and cerebral palsy who were visually dependent (CPVD). Bottom row: Averaged absolute values of slope of (c) COP and (d) COM in the AP direction in each visual scene condition for each group.

(a)

(b)

Figure 5.

Averaged root-mean-square (RMS) of (a) center of pressure (COP) and (b) center of mass (COM) in the anterior-posterior (AP) direction in each visual scene condition for subjects with typical development (TD), cerebral palsy who were visually independent (CPVI), and cerebral palsy who were visually dependent (CPVD).

Table 1.

Demographic data and participant's characteristics

	Age (years)	Sex(F/M)	Weight (kg)	Height (m)	Diagnosis	Group	RFT (°)[Mean (SD)] ^a	VOR function ^b	GMFCS –E&R ^c	Light Touch ^d	Pain ^e	Vibration ^f
S01	37	M	61.8	1.66	Spastic Quadriplegia	CPVI	1.44 (1.76)	Intact	I	Intact	Impaired	Intact
S02	44	F	88.5	1.61	Spastic Diplegia	CPVI	0.31 (1.03)	Impaired	II	Intact	Impaired	Impaired
S03	25	F	47.5	1.56	Spastic Diplegia	CPVI	0.13 (1.85)	Intact	I	Intact	Intact	Intact
S04	15	F	74.0	1.76	Spastic Quadriplegia	CPVI	-0.50 (2.90)	Intact	I	Intact	Impaired	Intact
S05	21	F	48.0	1.58	Spastic Diplegia	CPVI	-0.50 (3.37)	Intact	I	Intact	Intact	Intact
S06	17	M	67.0	1.64	Spastic Diplegia	CPVI	-1.25 (1.00)	Intact	II	Intact	Intact	Intact
S07	30	M	109.5	1.82	Spastic Diplegia	CPVI	-1.81 (1.98)	Impaired	II	Intact	Intact	Intact
S08	20	M	64.5	1.67	Spastic Diplegia	CPVI	0.69 (4.33)	Intact	I	Intact	Intact	Intact
S09	28	M	78.0	1.61	Spastic Diplegia	CPVI	-0.88 (2.63)	Impaired	II	Intact	Impaired	Intact
S10	43	F	70.0	1.68	Spastic Diplegia	CPVI	0.00 (1.87)	Intact	I	Intact	Intact	Intact
S11	27	F	56.0	1.64	Spastic Diplegia	CPVD	0.19 (30.86)	Impaired	I	Impaired	Impaired	Intact
S12	48	M	93.5	1.76	Spastic Quadriplegia	CPVD	5.56 (10.12)	Impaired	II	Impaired	Impaired	Intact
S13	23	M	60.5	1.76	Spastic Quadriplegia	CPVD	0.94 (22.39)	Impaired	I	Intact	Intact	Intact
S14	19	F	54.0	1.56	Spastic Diplegia	CPVD	-4.56 (21.51)	Intact	I	Intact	Impaired	Intact
S15	45	F	55.6	1.53	Spastic Quadriplegia	CPVD	-10.06 (21.08)	Impaired	II	Intact	Impaired	Intact
S16	45	F	89.0	1.62	Spastic Diplegia	CPVD	-3.44 (6.86)	Impaired	I	Intact	Intact	Intact
S17	39	F	70.0	1.65	Spastic Diplegia	CPVD	0.38 (11.28)	Impaired	II	Intact	Intact	Intact
S18	31	M	87.5	1.82	Spastic Diplegia	CPVD	2.19 (25.90)	Impaired	I	Intact	Impaired	Intact
S19	35	M	118.5	1.66	Spastic Diplegia	CPVD	-5.06 (4.37)	Intact	I	Intact	Intact	Intact
S20	45	F	67.5	1.58	Spastic Diplegia	CPVD	0.44 (20.88)	Impaired	II	Intact	Intact	Intact
S21	50	M	61.5	1.58	Spastic Quadriplegia	CPVD	3.81 (6.26)	Impaired	I	Intact	Impaired	Intact
S22	38	F	77.0	1.60	Spastic Diplegia	CPVD	-6.00 (31.25)	Impaired	I	Intact	Impaired	Intact
S23	17	M	47.5	1.58	Spastic Diplegia	CPVD	0.75 (27.04)	Intact	I	Intact	Impaired	Intact
T01	23	F	60.5	1.64	-	TD	-0.50 (1.10)	Intact	-	Intact	Intact	Intact
T02	28	M	68.0	1.63	-	TD	-0.38 (0.92)	Intact	-	Intact	Intact	Intact
T03	23	M	89.5	1.76	-	TD	1.25 (1.63)	Intact	-	Intact	Intact	Intact
T04	22	F	43.5	1.64	-	TD	-0.44 (1.52)	Intact	-	Intact	Intact	Intact

Age (years)	Sex (F/M)	Weight (kg)	Height (m)	Diagnosis	Group	RFT (°) [Mean (SD)] ^a	VOR function ^b	GMFCS –E&R ^c	Light Touch ^d	Pain ^e	Vibration ^f
T05	20	F	49.0	1.60	-	TD	-1.44 (1.92)	Intact	-	Intact	Intact
T06	41	M	110.5	1.80	-	TD	0.13 (2.05)	Impaired	-	Intact	Intact
T07	27	M	77.6	1.79	-	TD	-0.56 (1.29)	Impaired	-	Intact	Intact
T08	19	F	53.0	1.52	-	TD	0.25 (2.15)	Intact	-	Intact	Intact
T09	22	F	78.0	1.63	-	TD	-0.50 (1.77)	Intact	-	Intact	Intact
T10	45	M	64.5	1.74	-	TD	-1.56 (3.06)	Intact	-	Intact	Intact
T11	48	M	58.0	1.66	-	TD	0.81 (2.33)	Intact	-	Intact	Intact
T12	27	M	88.0	1.85	-	TD	-0.44 (1.02)	Intact	-	Intact	Intact
T13	26	F	50.0	1.50	-	TD	-0.88 (1.69)	Intact	-	Intact	Intact
T14	44	F	60.0	1.61	-	TD	0.94 (1.08)	Intact	-	Intact	Intact
T15	18	M	86.0	1.86	-	TD	0.75 (1.56)	Intact	-	Intact	Intact
T16	31	M	67.0	1.76	-	TD	-0.44 (1.32)	Intact	-	Intact	Intact
T17	20	M	63.5	1.86	-	TD	-1.31 (3.27)	Intact	-	Intact	Intact
T18	18	F	64.0	1.63	-	TD	-0.31 (2.10)	Intact	-	Intact	Intact
T19	21	F	72.0	1.67	-	TD	-1.25 (3.54)	Impaired	-	Intact	Intact
T20	50	M	76.5	1.82	-	TD	0.56 (3.48)	Intact	-	Intact	Intact
T21	21	F	51.5	1.54	-	TD	-1.88 (3.01)	Impaired	-	Intact	Intact
T22	43	M	82.0	1.87	-	TD	-2.25 (2.10)	Impaired	-	Intact	Intact
T23	44	F	64.5	1.63	-	TD	1.81 (2.80)	Impaired	-	Intact	Intact

Abbreviation: GMFCS-E&R, gross motor function classification system – expanded and revised; CPVD, cerebral palsy with visual dependence; CPVI, cerebral palsy with visual independence; RFT, rod and frame test; SD, standard deviation; TD: typical development; VOR: Vestibulo-ocular Reflex

^aRFT results are a mean report of the angular deviation from true vertical and horizontal

^bVOR function was tested via non-instrumented dynamic visual acuity. VOR function is considered as impaired if the visual acuity during head motion is worse than that when the head remained stationary by 0.20 logMAR (or 2 lines on the vision chart).

^cGMFCS-E&R is a 5-level classification system that describes the gross motor function of children with cerebral palsy up to 18 years of age on self-initiated movement with the focus on walking ability in the current study. Our evaluation is based on the description made for the age band of 12–18 years of age. *Level I* represents the ability to walk without restrictions, while *Level II* represents the ability to walk with some limitation especially in some of the more advanced motor skills such as running, jumping, and climbing up and down stairs.

^dLight touch sensation was tested with Semmes Weinstein monofilament examination on the plantar part of big toes and lateral border of the feet. The test force includes 2g (4.31 monofilament), 4g (4.74 monofilament), and 10g (5.07 monofilament). Protective sensation is considered as impaired if a given subject failed to detect the stimuli from 2g (4.31 monofilament).

^ePain sensation was evaluated using the pinprick test on the plantar part of big toes and lateral border of the feet.

Vibration sensation was evaluated using the 128 hertz tuning fork on the calcaneus bone of both heels.

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Table 2.

Mean (SE) of the movement variables of center of pressure (COP) and center of mass (COM) in the anterior-posterior (AP) and mediolateral (ML) directions in three groups in response to different visual scene conditions

	TD	CPVI	CPVD	Statistics		
				effect	p	F
COP:AP						
RMS ^{a*}	Static	0.521 (0.067)	0.509 (0.101)	0.602 (0.089)	COND	.001
	Pitch Up	0.722 (0.106)	0.567 (0.161)	0.987 (0.141)		
	Pitch Down	0.638 (0.090)	0.721 (0.136)	0.972 (0.119)		
MDF ^{a*}	Static	0.284 (0.023)	0.256 (0.035)	0.243 (0.031)	COND	<.001
	Pitch Up	0.406 (0.031)	0.347 (0.047)	0.363 (0.041)		
	Pitch Down	0.390 (0.025)	0.325 (0.038)	0.285 (0.033)		
SLP [*]	Static	−0.010 (0.006)	0.004 (0.009)	−0.014 (0.008)	COND	<.001
	Pitch Up	0.019 (0.011)	0.026 (0.016)	0.022 (0.014)		
	Pitch Down	−0.036 (0.011)	−0.026 (0.016)	−0.029 (0.014)		
absSLP [*]	Static	0.021 (0.004)	0.014 (0.007)	0.025 (0.006)	COND	<.001
	Pitch Up	0.042 (0.008)	0.036 (0.013)	0.054 (0.011)		
	Pitch Down	0.030 (0.008)	−0.032 (0.012)	0.056 (0.011)		
COP:ML						
RMS ^a	Static	0.277 (0.079)	0.465 (0.121)	0.398 (0.106)		
	Pitch Up	0.281 (0.079)	0.486 (0.120)	0.530 (0.105)		
	Pitch Down	0.250 (0.053)	0.374 (0.080)	0.497 (0.070)		
MDF	Static	0.370 (0.032)	0.330 (0.048)	0.333 (0.042)		
	Pitch Up	0.392 (0.030)	0.413 (0.045)	0.328 (0.039)		
	Pitch Down	0.423 (0.035)	0.415 (0.053)	0.373 (0.046)		
COM:AP						
RMS ^{a*}	Static	0.586 (0.076)	0.585 (0.116)	0.702 (0.102)	COND	.008
						5.385
						0.204

	TD	CPVI	CPVD	Statistics		
				effect	p	η^2
MDF ^a	Pitch Up	0.760 (0.178)	1.461 (0.237)			
	Pitch Down	0.673 (0.098)	1.067 (0.131)			
	Static	0.201 (0.017)	0.204 (0.023)			
SLP [*]	Pitch Up	0.218 (0.020)	0.177 (0.027)			
	Pitch Down	0.229 (0.018)	0.168 (0.024)			
	Static	0.007 (0.011)	-0.009 (0.010)	COND	.002	7.570
absSLP [*]	Pitch Up	0.021 (0.012)	0.027 (0.016)			
	Pitch Down	-0.039 (0.019)	-0.072 (0.025)			0.265
	Static	0.023 (0.008)	0.027 (0.007)	COND	.001	8.994
COM.ML	Pitch Up	0.051 (0.015)	0.104 (0.021)	GRP	.046	3.317
	Pitch Down	0.038 (0.009)	0.065 (0.011)			0.134
	Static	0.027 (0.005)				
RMS ^a	Pitch Up	0.293 (0.089)	0.615 (0.135)			
	Pitch Down	0.309 (0.098)	0.576 (0.149)			
	Static	0.285 (0.057)	0.410 (0.086)			
MDF	Pitch Up	0.248 (0.024)	0.249 (0.032)			
	Pitch Down	0.229 (0.021)	0.190 (0.027)			
	Static	0.260 (0.024)	0.222 (0.032)			

* Asterisk denotes the significant differences ($p < 0.05$) observed between visual scene conditions.

^a Natural log transformation was applied before conducting repeated measure ANOVAs.

Abbreviations: AP: antero-posterior; COND: condition; CPVD: cerebral palsy with visual dependence; CPVI: cerebral palsy with visual independence; GRP: group; ML: medio-lateral; MDF: median frequency; RMS: root mean square; SLP: slope of the fitted line from movement trajectory; η^2 : partial eta squared, an index of effect size, of which 0.02 is defined as small, 0.13 as medium, and 0.26 as large effect; F-value: F values are computed based on Wilks' Lambda.