Adapted Physical Activity Quarterly, (Ahead of Print)
https://doi.org/10.1123/apaq.2021-0019

First Published Online: Nov. 5, 2021

Human Kinetics
ORIGINAL RESEARCH

Rhythm and Reaching: The Influence of Rhythmic Auditory Cueing in a Goal-Directed Reaching Task With Adults Diagnosed With Cerebral Palsy

Jacqueline C. Ladwig, Tamires C. do Prado, Stephanie J. Tomy, Jonathan J. Marotta, and Cheryl M. Glazebrook
University of Manitoba

Improvements in functional reaching directly support improvements in independence. The addition of auditory inputs (e.g., music, rhythmic counting) may improve goal-directed reaching for individuals with cerebral palsy (CP). To effectively integrate auditory stimuli into adapted teaching and rehabilitation protocols, it is necessary to understand how auditory stimuli may enhance limb control. This study considered the influence of auditory stimuli during the planning or execution phases of goal-directed reaches. Adults (with CP = 10, without CP = 10) reached from a home switch to two targets. Three conditions were presented—no sound, sound before, and sound during—and three-dimensional movement trajectories were recorded. Reaction times were shorter for both groups in the sound before condition, while the group with CP also reached peak velocity relatively earlier in the sound before condition. The group with CP executed more consistent movements in both sound conditions. Sound presented before movement initiation improved both the planning and execution of reaching movements for adults with CP.

Keywords*:* developmental disability, motor control, RAS, rhythmic auditory stimulation

Cerebral palsy (CP) is a neurodevelopmental diagnosis that results from pre-, peri-, or postnatal trauma to the brain. CP encompasses several plegias that include varied muscle tone, musculoskeletal issues, and various comorbidities, often leading to large amounts of sedentary time (Cremer, Hurvitz, & Peterson, 2017; Eunson, 2012; Lundy-Ekman, 2013). Sensorimotor and perceptual challenges that limit voluntary motor control can make activities of daily living more challenging

Ladwig, do Prado, Tomy, and Glazebrook are with the Perceptual Motor Integration Lab, Faculty of Kinesiology and Recreation Management, University of Manitoba, Winnipeg, Manitoba, Canada. Marotta is with the Perception and Action Lab, Department of Psychology, University of Manitoba, Winnipeg, Manitoba, Canada. Ladwig (ladwigj@myumanitoba.ca) is corresponding author.

(Straub & Obrzut, 2009; Trevarrow, Kleinsmith, Taylor, Wilson, & Kurz, 2021). Although CP is nonprogressive, decreased mobility can lead to increased health issues in adulthood (Cremer et al., 2017; Eunson, 2012; Thorpe, 2009). Developing adapted opportunities and instructional approaches that challenge multisensory perception, proprioception, and postural control can aid in the maintenance of functional ability and overall fitness throughout both child- and adulthood (Cremer et al., 2017; Damiano, 2006; Liptak, 2008).

Overwhelmingly our current understanding of the performance of reaching tasks in the presence of CP is based on children (Johansson, Domellof, & Ronnqvist, 2012, 2014; Ju, Hwang, & Cherng, 2012; Ju, You, & Cherng, 2010). Johansson et al. (2012, 2014) proposed that reach kinematics become more efficient in the presence of a continuous auditory stimulus, such as a metronome. When children diagnosed with CP practiced upper limb movements to a synchronized metronome the researchers observed positive effects on spatio-temporal movement organization, with smoother and faster movement trajectories (Johansson et al., 2014). In posttest interviews (6 months), participants reported a sense of improved limb control and decreased spasticity (Johansson et al., 2012). As sensorimotor development continues throughout childhood and adolescence, it remains unclear how adults diagnosed with CP perform functional reaching movements with varying auditory stimuli. Reaching is a goal-directed action that is especially relevant as it supports both communication and independent living. Therefore, the present study focused on how movement efficiency and accuracy during a seated, goal-directed reaching task were impacted by auditory cueing in adults with CP.

Task instructions that use auditory cues to decrease the effort of voluntary actions may also decrease the physical and mental effort required to perform motor tasks. Initial evidence demonstrates that rhythmic auditory stimuli (RAS) may facilitate reaching movements for hemiparetic stroke survivors (Thaut, Kenyon, Hurt, McIntosh, & Hoemberg, 2002); where pacing reaches to a continuous RAS improved kinematic stability of the reach trajectories. The authors suggest that the clear smoothing of the velocity curve in the rhythmic condition, with the associated decrease in the number of movement reversals, is evidence of more efficient movements (Malcom, Massie, & Thaut, 2009; Thaut et al., 2002). Similar results were found using synchronized metronome training during a reaching task for children with hemiplegic CP (Johansson et al., 2012, 2014). Despite the above evidence to support a benefit of RAS for reach performance, it is still unclear as to how RAS elicit changes in movement control that result in greater kinematic stability.

Specifically, the literature reviewed above reflects the use of a continuous RAS from movement planning through movement execution, as one entity. The use of the continuous RAS makes it unclear how and why a RAS leads to improvement in movement performance. It is important to understand which aspects of movement control are improved by the presence of the auditory stimuli in order to maximize the benefits of adapted instruction and rehabilitative protocols with auditory stimuli. Hatfield, Wyatt, and Shea (2010) examined the use of an auditory stimulus in a reciprocal aiming task and found that movement times (MT) were shorter when auditory feedback was received at target acquisition. This is evidence that the addition of an auditory stimulus reduced the expected increase in endpoint variability. The authors proposed that the incorporation of auditory input frees the visual system from the task of assessing target acquisition, which may allow participants who are neurotypical to direct their attention to planning future actions. The present study used a similar approach and focused on the effect of a RAS presented either before movement initiation (during movement planning), or while the reach was being executed (movement execution). This approach allowed us to investigate if, and when, the influence of the auditory stimulus was most effective in coordinating and smoothing movements during either movement planning, movement execution, or both.

Given the reports of improved reach trajectories with continuous auditory stimuli (Ju et al., 2012; Thaut et al., 2002), it was predicted that if the RAS had greater benefit when presented during movement preparation, then more efficient and smoother movement profiles would be demonstrated when the sound was presented before movement initiation. The reverse would also be true: If the RAS had a greater benefit during movement execution, then movement profiles would demonstrate greater efficiency and smoother trajectories in the sound during condition. Based on the inherent differences in movement control between the two groups, it was predicted that in all conditions, the group with CP would show greater variability, longer reaction times (RTs), and MTs. It was also predicted that the benefits of the RAS would be greater for the group with CP due to underlying differences in motor control.

Method

Participants

Participants were recruited from the University of Manitoba campus and the surrounding community through posters and e-mail (see Figure 1). The group with CP included 10 adults (eight females, two males; $\text{mean}_{\text{age}} = 30$; $SD = 7.79$ years) with Gross Motor Functional Classification Scale (GMFCS) levels ranging from 2 to 4; this range includes individuals who are able to ambulate independently for short distances, require mobility devices when walking indoors and/or outdoors, or may require the use of a wheelchair for activities of daily living in the home and community (Livingston, Rosenbaum, Russell, & Palisano, 2007; Palisano et al., 1997). Inclusion criteria for the group with CP were (a) a diagnosis of CP, GMFCS level 1 to 4, and (b) vision and hearing normal or corrected-to-normal. Exclusion

Figure 1 — A visual representation of the recruitment process. *Note.* Of the 14 study participants recruited through the university, two were participants with cerebral palsy (CP), two participants without CP were not included in the final data set due to technical error. All eight participants recruited through community organizations were participants with CP.

criteria were (a) any orthopedic surgeries within the past 6 months, and (b) any botulinum injections within the past 6 months. The group without CP (10 adults; seven females, three males; $\text{mean}_{\text{age}} = 24.1$; $SD = 5.9$ years), were matched on handedness to the group with CPs less-impaired upper limb, had no neurological or orthopedic conditions, and had normal, or corrected-to-normal, vision and hearing. Strength of handedness for the group without CP was reported and scored using the revised Waterloo Handedness questionnaire (Elias, Bryden, & Bulman-Fleming, 1998). Prior to testing a demonstration of the task was provided, and informed consent was given by participants. A support person was available to assist with informed consent as needed. All procedures were approved by the Education/ Nursing Research Ethics Board of the University of Manitoba, in accordance with the Declaration of Helsinki (2002).

Apparatus

Participants sat at a height-adjustable table (74.5 cm × 150 cm) in a chair or their own wheelchair, where their midline was aligned with the home switch located at the center anterior edge of the table. Two targets were custom built using snap action switches with long lever actuators (LKG Industries, Rockford, IL) embedded into a dense foam tube that was cut in half lengthwise into two smaller, square support surfaces (8 cm × 8 cm × 4 cm) (see Figure 2a). A light emitting diode was placed directly beneath each target switch. Each target was located within participants' peripersonal space, was 5 cm in diameter, and made of dense foam that was weighted with a coin. To provide a supportive surface for the hand, the home switch (4.5 cm in diameter) was threaded through a dense foam tube cut in half lengthwise. Both the base of the home switch and target switches

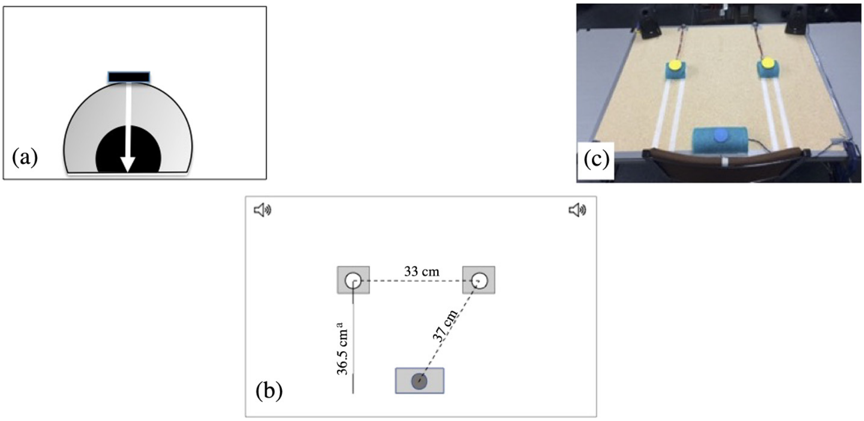

Figure 2 — A visual representation of the apparatus. (a) Lateral view of switches: each was attached to the top of a foam tube, wiring was drawn through and drawn out the side of the tube; (b) target amplitudes (indicated by the solid line) measured from anterior edge of table; and (c) photo of apparatus. *Note*. Home switch (in gray) and the two targets (in white; 4.2 cm in diameter). [a]Adjusted target amplitudes occurred in the same anterior–posterior axis.

were attached to a (75 cm × 89 cm) wood surface using heavy duty Velcro® (Velcro Canada, Inc., Brampton, Canada) and the entire surface was secured to the table with four clamps (see Figure 2b and 2c). The auditory stimulus was presented using two Logitech® (Newark, CA) audio speakers placed on either side corner of the apparatus surface, facing toward the participant. Volume was set at a level that was comfortable for each participant (~70 dB). The table height was adjusted for each participant to ensure a comfortable reach to the home position and targets. Target amplitudes were set at a maximum of 36.5 cm following a pilot study with one adult with CP and adults without CP. At the beginning of their practice session, each participant with CP was asked to demonstrate their comfortable maximum reach and target amplitude was adjusted accordingly (see "Data Analysis" section for details regarding how target distance was accounted for). Target amplitudes for the group with CP ranged from 6.3 to 36.5 cm.

Procedure

To ensure understanding of the task, each session began with a series of familiarization trials. The familiarization trials included six reaches with each hand (12 trials) to both targets in a sound condition where one tone was presented 6 s after the target light appeared. Participants were instructed to reach naturally to the target switch and then press the target switch in time with the auditory stimulus. One additional set of practice trials was given if participants required more practice to be comfortable pressing the home and target switches.

At the start of each trial, participants placed a hand on the home switch. Participants were then instructed to reach "naturally and accurately" to the target (indicated by the target light). Twenty trials were performed with each hand, in each of the three conditions. The first condition was no sound (NS), followed by sound before (SB), or sound during (SD). Two blocks of 10 trials were conducted, in each of the three conditions, for a total of 60 trials. This series was repeated for a total of 120 trials. The second block was presented in a randomized order where the NS condition could not be first. Explicit instructions were provided for each condition. For the NS and SB conditions, participants were instructed to move to the target at a natural and comfortable pace when they saw the target light illuminate. In the SD condition, the instructions given were, "You will see the target light first, and when you begin to move you will then hear the auditory stimulus. Try to time your movement to the sound by pressing the target on the third beep." To protect against practice effects and fatigue, handedness was blocked (10 trials per block) within each condition, and within each block of trials, target direction was randomized. Rest breaks were provided between conditions and if requested by the participant. The whole procedure took approximately 30–60 min to complete, depending on the number and duration of breaks.

To capture limb displacement infrared markers (IREDs) were placed on the participants' right and left arms on the posterior surfaces of the distal phalanx of the index finger using Blenderm (3M®, London, Canada) surgical tape. IREDs were also attached to the proximal metacarpal joint of the index finger and ulnar styloid of both arms. Each IRED was attached to a small wedge of dense foam to ensure visibility of the markers. A fingerless glove was created from Tensogrip®

elasticated (tube; Essity Medical Solutions, Charlotte, NC) stockinette to facilitate IRED positioning on the knuckle and wrist. The fingerless glove allowed the IREDs to be positioned easily using Velcro. IRED wires were threaded under the glove and up the forearm to secure the wires. Prowrap™ (Mueller Sports Medicine, Inc., Prairie du Sac, WI) was used to secure the IRED wiring to the forearm and upper arm of the participant. Individual stationary target positions (3-s target files) were collected postexperiment at the home position and at each target.

Three-dimensional position data were recorded using the Optotrak 3D Investigator motion capture system (accuracy to 0.4mm; Northern Digital, Inc., Waterloo, Canada) at a collection rate of 250 Hz. The experiment was coordinated via a custom program designed using E-Prime software (version 2.0; Psychological Software Tools, Inc., Sharpsburgh, PA). Specifically, the initiation of the Optotrak was triggered externally and synchronized with the initiation of the visual stimulus that served as the "go signal" (i.e., target light illuminated). The auditory stimulus was a set sequence of three auditory tones: 575 Hz tone for 200 ms (followed by a 1,800 ms pause), a 575 Hz tone for 200 ms (followed by a 1,800 ms pause), and finally a 600 Hz tone for 300 ms. In the SB condition, the visual go signal was paired with the final tone. In the SD condition, the auditory stimulus began once participants initiated their reach.

Data Analysis

Initial analysis of the raw displacement data was processed in a custom reach analysis program by Kinsilico Labs (Ottawa, Ontario, Canada) in MATLAB (MathWorks, Inc., Natick, MA). Any known trial errors, such as marker error (e.g., occlusion) and participant distraction (e.g., loss of attention or environmental distraction), were removed before initial data analysis. Trial errors occurred for 6% of the trials for the group with CP, and in none of the trials for the group without CP. Raw data were smoothed using a five-point moving average. The onset of reach for both groups was defined as the first frame where the velocity exceeded and remained at 30 mm/s for 30 ms. Reach offset was defined as the first frame where the velocity fell below, and remained, at 30 mm/s for 30 ms. To remove any outliers, where the participant stopped short of the target, the position end in the *y*-axis was compared with a target area based on the stationary target files. To establish the target area, the diameter of the target size was added to the target file value to establish an upper limit and subtracted from the target file to establish the lower limit (therefore, participants needed to be within the vicinity of the target for the trial to be included as a successful reach). Any trials that fell outside of the upper and lower limits of the defined target area were removed; thus, 35% of the group with CP trials and 10% of the group without CP trials were removed. The large percentage of the group with CP trials reflects that three participants with CP who chose to solely use their preferred (less impaired) arm throughout testing due to the level of fatigue experienced when using the nonpreferred arm. Similarly, three participants with CP chose to reach only to the ipsilateral target (the less impaired side) throughout testing.

Statistical analysis was performed using Statistica™ (version 12.0; Tibco™, Palo Alto, CA). Preliminary analysis of RT and MT across ipsilateral and contralateral targets for the group with CP did not reach significance—RT,

$F(1, 14) = 0.41$, $p = .531$; MT, $F(1, 14) = 2.67$, $p = .125$; therefore, data were collapsed across target location for all variables, for both groups. Preexisting differences in reach capabilities between the groups with and without CP were expected and observed. Specifically, three participants with CP did not complete the trials with their nonpreferred hand and there was a need to adjust target amplitudes to an achievable location for seven of the 10 participants with CP. To account for these observed differences, two adaptations were made to the data analysis. First, data analysis was based on the preferred hand only, for both groups. Second, the impact of sound on movement performance was assessed by calculating the individualized difference scores (Δ). Specifically, ΔSB = SB − NS condition and ΔSD = SD − NS condition. The decision to assess the difference scores was made because target amplitude has a direct effect on MT and the variability of target endpoints (see Supplementary Figure S1 [available online] for natural means). Also, the primary research question was not if participants with and without CP move differently, but instead, does the presence of sound impact movement performance differentially.

A 2 Group (with CP, without CP) × 2 Condition (ΔSB, ΔSD) design with one between-subject measure (group) and one within-subject measure (condition) was used to assess for any change in movement performance that occurred with the inclusion of the auditory stimuli. Dependent variables included RT (stimulus onset to beginning of movement), MT (movement onset to offset/movement end), constant error (mean endpoint bias), variable error (*SD* of position endpoint), as well as the ratio of ttPV to MT (the relative amount of time available for online control; ttPV/MT). Significant interactions were further analyzed using Tukey's Honestly Significant Difference post hoc test, $p < .05$. Eta squares were used for effect sizes and were interpreted as minimum (.04), moderate (.25), and strong (.64) (Ferguson, 2009).

Results

Reaction Time

The main effect of condition was significant, $F(1, 18) = 37.04$, $p = .000$; for both groups, RT was longer in the ΔSD condition and shorter in the ΔSB condition with an effect size between moderate and strong ($\eta^2 = .35$). No significant differences were found between groups, $F(1, 18) = 1.36$, $p = .258$, $\eta^2 = .045$. While significance was not reached in the Group × Condition interaction, $F(1, 18) = 3.54$, $p = .076$ (see Figure 3a), visual assessment of the amount of change between conditions was observed to be greater for the group with CP, however with minimum effect ($\eta^2 = .06$).

Variability of RT

A statistically significant main effect for condition was found, $F(1, 18) = 15.50$, $p = .0009$. The ΔSD condition led to greater variability of RT while the ΔSB condition led to less variability of RT with a moderate to strong effect ($\eta^2 = .42$). In contrast, analysis indicated no significant difference in the variability of RT between groups, $F(1, 18) = 0.452$, $p = .509$, $\eta^2 = .02$. Although significance was not reached for the Group × Condition interaction, $F(1, 18) = 3.41$, $p = .081$, a pattern was observed where the group with CP showed a larger difference in variability of RT between the SB and SD conditions, as compared to the group without CP, with a minimum to moderate effect ($\eta^2 = .09$).

Movement Time

A significant main effect for condition was found, $F(1, 18) = 90.95$, $p = .0001$; where the least change occurred in the ΔSB condition and the greatest change occurred in the ΔSD condition with a moderate to strong effect ($\eta^2 = .46$). The main effect of group for MT was also statistically significant, $F(1, 18) = 45.874$, $p = .000$, with a moderate to strong effect ($\eta^2 = .37$). The Condition × Group interaction was significant, $F(1, 18) = 88.65$, $p = .000$, $\eta^2 = .45$. Post hoc analysis of the Group × Condition interaction indicated that for the group with CP, there was no significant difference between conditions; however, for the group without CP, a significant difference was found between conditions (see Figure 3b).

Constant Error (*y*-Axis)

The main effect for condition did not reach significance, $F(1, 18) = 1.716$, $p = .20$, $\eta^2 = .08$. The main effect for group also did not reach statistical significance, $F(1, 18) = 3.706$, $p = .070$. Upon observation, a pattern was noted between groups where the group with CP demonstrated a smaller change between conditions and the group without CP had a greater tendency to undershoot the target in the sound conditions (ΔSB, $M = 8$ mm [±28 mm]; ΔSD, $M = 50$ mm [±79 mm]; see Figure 3d) with a minimum to moderate effect ($\eta^2 = .13$). The Condition × Group interaction was not significant, $F(1, 18) = 1.645$, $p = .215$, $\eta^2 = .08$.

Constant Error (*x*-Axis)

The main effect for condition did not reach significance, $F(1, 18) = 1.093$, $p = .30$, $\eta^2 = .05$. The main effect for group also did not reach statistical significance, $F(1, 18) = 1.867$, $p = .19$, $\eta^2 = .08$. The Condition × Group interaction approached statistical significance, $F(1, 18) = 4.230$, $p = .054$. Although significance was not reached, visual inspection suggests a larger pattern of change in the *x*-axis in the ΔSD condition for the group with CP and less change occurring in the group without CP, with a minimum to moderate effect ($\eta^2 = .18$).

Variable Error (*y*-Axis)

The main effect of condition was significant, $F(1, 18) = 7.246$, $p = .0149$; where variability in variable error-*y* decreased in the ΔSB condition and increased in the ΔSD condition with a moderate effect ($\eta^2 = .26$). The main effect for group was also significant, $F(1, 18) = 7.26$, $p = .0148$. Here, the group with CP showed a decrease in the variability, while the group without CP showed an increase in variability with a moderate effect ($\eta^2 = .29$). The Group × Condition interaction was not significant, $F(1, 18) = 2.199$, $p = .155$, $\eta^2 = .08$.

Variable Error (*x*-Axis) and Movement Peaks in *z*-Axis

None of the main effects or interactions reached statistical significance (see Table 1).

Ratio of Time to Peak Velocity by MT

The main effect of condition was not significant, $F(1, 18) = 1.767$, $p = .20$, $\eta^2 = .07$, nor was the main effect of group, $F(1, 18) = .762$, $p = .394$, $\eta^2 = .03$. However, the Group × Condition interaction was significant, $F(1, 18) = 5.948$, $p = .025$. In the group without CP, the smallest change in the ratio of ttPV/MT occurred in the ΔSB condition and for the group with CP the smallest change occurred in the ΔSD condition with a moderate effect ($\eta^2 = .23$). Post hoc analysis of this interaction indicated that in the ΔSB condition no difference was found between groups. However, in the ΔSD condition, a significant difference was found between groups. Within the two groups, no differences were found between conditions in the group with CP in mean change in the ratio of ttPV/MT, while there was a significant difference between conditions for the group without CP (see Figure 3c).

Control Experiment

A control experiment was executed to address whether (a) performance in the SD condition improved for participants without CP if the metronome pace was a faster pace, and (b) if performance improved if participants did not always have prior experience in the NS condition as an initial baseline. The apparatus was identical to that of the main experiment, with a singular IRED attached to the distal phalanx of the index finger of both hands using Blenderm (3M) surgical tape. The procedure was identical to the main experiment and auditory stimuli were presented in the following manner: a 575 Hz tone for 200 ms (followed by a 900 ms pause), a 575 Hz tone for 200 ms (followed by a 900 ms pause), and finally a 600 Hz tone for 300 ms.

Control Experiment Results

Reaction Time. Consistent with the main experiment, there was a significant main effect for condition, $F(2, 26) = 22.7$, $p < .001$, $\eta^2 = .63$. Post hoc analysis

Table 1 The *F* and *p* Values for Each Category of Main Effects for Nonsignificant Variables

Variable	Effect	$F(1, 18)$	$p < .05$	η^2
VE-*x*	Group	1.40	.253	.07
	Condition	0.03	.860	.002
	Condition × Group	0.40	.533	.022
MP-*z*	Group	0.66	.426	.035
	Condition	1.62	.218	.08
	Condition × Group	0.41	.530	.02

Note. VE-*x* = variable error *x*-axis; MP-*z* = movement peaks *z*-axis.

revealed that RT was significantly longer in the SD condition (357 ms) as compared to the NS condition (315 ms), which was significantly longer than the SB condition (249 ms). There was no significant main effect for hand and no interaction between hand and condition. A significant difference was also found in the variability of RT across conditions, $F(2, 26) = 33.4$, $p < .001$, $\eta^2 = .72$. Post hoc analysis revealed that the RT variability was larger for the SD condition ($M = 95.2$) compared with both the NS ($M = 64.6$) and SB ($M = 48.7$) condition.

Constant Error (x-Axis). There was a significant main effect for hand, $F(1, 13) = 7.26$, $p < .02$, $\eta^2 = .34$. There was no significant main effect for condition, $F(2, 26) = 0.12$, $p < .87$, $\eta^2 = .008$, and no interaction between hand and condition, $F(2, 26) = 2.84$, $p < .08$, $\eta^2 = .07$.

Discussion

The present study examined the effect of a RAS on the movement planning and execution phases of a goal-directed reaching task in adults who have CP. It was predicted that if the addition of RAS benefitted movement planning, then more efficient and smoother movement profiles would be observed when the RAS was presented during movement preparation. In contrast, if any improvement with RAS impacted the movement execution phase, then any benefit would be observed in the sound during condition. It was also predicted that the benefits of the RAS would be seen in both groups, but would be greater in the group with CP.

Overall, the presence of sound before reach initiation led to improvements in both temporal and spatial movement characteristics for both groups. For the group with CP, when sound was presented before movement onset, more direct and accurate reaching was facilitated. By comparison, when sound was presented during the reaching movement, both groups demonstrated a delay in response time and decreased spatial accuracy. The SD condition challenged participants to navigate both spatial and temporal accuracy during the reaching task. The above results provide evidence that when sound was incorporated into the planning phase of the movement, the temporal characteristics (RT and MT) of the reaches became more consistent and may have supplemented reach performance. The temporal consistency gained during movement planning appears to have resulted in improved endpoint accuracy.

Movement Planning

One suggestion for how auditory feedback improves movement execution is that it reduces the uncertainty related to target acquisition and frees up attentional resources for planning the subsequent movement (Hatfield et al., 2010). The incorporation of RAS has also been proposed to ready the motor system by entraining the neural firing of the motor system in preparation for movement initiation (Thaut, 2013). Consistent with the above predictions, the use of RAS was found to supplement RT in a goal-directed reaching task performed by neurotypical individuals, where RTs improved with sound presented before movement onset (Peters & Glazebrook, 2020). Here, the predictions were supported as movement planning improved (i.e., RT decreased) when sound was presented before movement initiation. The incorporation of RAS in the planning phase effectively modulated movement planning and initiation, resulting in shorter RTs. In the control study, this finding also held when the RAS engaged a more natural (faster) pace. It is of particular interest that RTs in the group with CP were brought considerably closer to the RTs of the group without CP in the SB condition. Given this disproportionate improvement, we suggest that the added auditory RAS during movement planning may regulate and facilitate action preparation for the group with CP.

The RAS have been proposed to prepare the motor system for movement performance by engaging auditory neurons which then entrain motor neurons (Thaut, 2013). In the present study, RTs improved when the RAS were present before movement onset, and the temporal differences of the groups were clear as there were differences in RT variability between the two groups. The observed pattern of RT variability in the group with CP was similar to the group without CP, where the amount of change in variability when sound was present during planning decreased. This contrasts with the increased variability of RT in the SD condition for the group with CP. Overall, a relationship in both groups was observed where the stable timing pattern established by the RAS led to a reduction in timing uncertainty and improved movement planning.

Elliott et al. (2010) and Elliott, Hansen, Mendoza, and Tremblay (2004) have proposed that individuals tend to undershoot a target because less energy is required to initiate a correction in the same direction of motion. It has been suggested that because the incorporation of RAS during movement planning has temporal benefits to movement performance, this benefit may also facilitate improved spatial accuracy (Peters & Glazebrook, 2020). In the present study, when the RAS was heard before movement onset, the group without CP overshot the target an average of 8 mm (see Figure 3d) in the SB condition. Thus, endpoint accuracy improved with the RAS in the planning phase of reaching (SB). For the group with CP, the RAS also appeared to elicit movement control strategies that promoted online limb control by shifting the relative time to PV earlier such that there was more available time for online limb control. The group with CP also demonstrated a decrease in the amount of endpoint variability (constant error-*y*) in the SB condition, indicating that when the RAS was heard before initiating reaching, movement accuracy was facilitated.

Current RAS and reaching literature suggest that when RAS is presented before movement initiation, sound may function as an external focus of attention (Peters & Glazebrook, 2020). External, as opposed to internal or body centered, attentional focus has been repeatedly shown to foster automaticity of, and result in faster, movement control processing in neurotypical groups (Wulf, Lewthwaite, Cardozo, & Chiviacowsky, 2018; Wulf, McNevin, & Shea, 2001), as well as those with intellectual disability (Chiviacowsky, Wulf, & Ávila, 2013). When individuals with intellectual disability performed a throwing task with instructions that elicited an external focus of attention, their skill performance improved (Chiviacowsky et al., 2013). Instructions facilitating this focus may supplement learning by releasing the attentional demand of the task (Chiviacowsky et al., 2013). Further to this, RAS has been found to prime the motor system in movement planning and regulate spatial characteristics of muscle activation patterns and movement control (Thaut, Kenyon, Schauer, & McIntosh, 1999; Thaut, 2013;

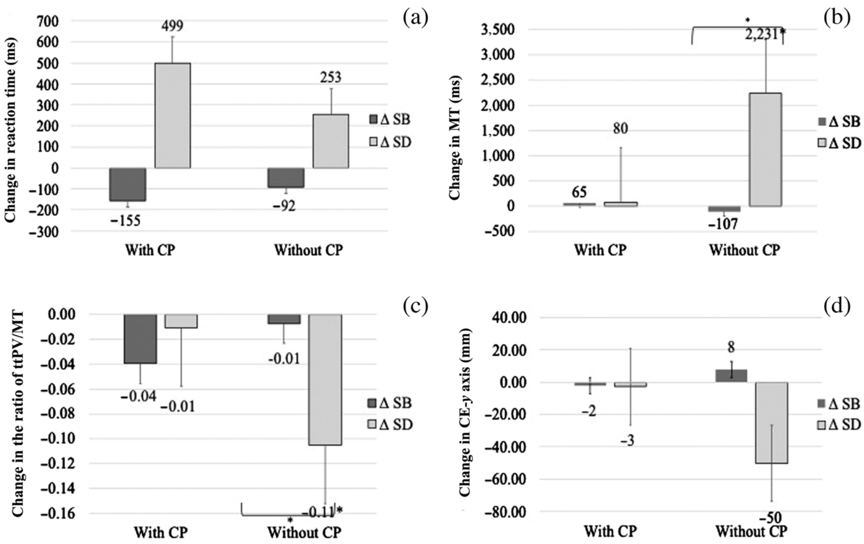

Figure 3 — Graphical representations of RT, MT, ttPV/MT, and CE-*y*. *Note.* (a) The amount of change in RT for each auditory condition for both groups (in milliseconds); (b) the amount of change in MT for each auditory condition, for both groups (in milliseconds); (c) the amount of change in the ratio of ttPV/MT for each auditory condition, for both groups; and (d) the amount of change in CE-*y* in each auditory condition, for both groups (in millimeters). CP = cerebral palsy; RT = reaction time; MT = movement time; ttPV = time to peak velocity; CE-*y* = constant error in the *y*-axis; SB = sound before; SD = sound during. *denotes significance ($p < .05$)

Thaut & Kenyon, 2003). Temporal priming may optimize neuromotor mechanisms, resulting in improved response times and movement trajectories. Here, it is suggested that the external temporal parameters defined by the RAS modulated movement planning by reducing the attentional demands of the task, as shown by the improvements in RT, and facilitated online control and stabilization of endpoint variability, for both groups.

Movement Execution

Task instructions can influence movement performance as instructions direct subjects' focus to specific stimuli when auditory and visual stimuli are presented simultaneously (Andersen, Tiippana, & Sams, 2004). The presence of the sound during reaching, in combination with the task instruction to time their reach with the sound, created a complex dual-task condition with longer response times and reduced target accuracy. In other words, participants had to manage both spatial and temporal accuracy while reaching.

Recognizing the potential limitation of the slow pace of the auditory stimuli (6 s) for the participants without CP, a control study used a faster pace (3 s) and replicated the results of the main study. Specifically, when instructed to time movements with a shorter RAS, RT still increased (i.e., slowed). Here, the increase in RT likely relates to the complexity of the task and the timing of movement with the RAS, rather than to the slow pace.

The plegias associated with CP include visual–perceptual impairment and motor impairment, where both vary according to the location of the brain lesion and resulting developmental neural reorganization (Stiers et al., 2002). Previous literature on upper limb function in CP and stroke indicate that when a temporal constraint is added to a reaching task, compensatory actions, such as increased movement of the torso at movement initiation, may be used to reach the target successfully (Ferrari, Tersi, Ferrari, Sghedoni, & Chiari, 2010; Figueiredo et al., 2015; James, Ziviani, Ware, & Boyd, 2015; Ju et al., 2012; Thaut et al., 2002). Consistent with previous literature, participants with CP were inclined to use compensatory actions to complete the task and reduce overall effort. The RAS in the SD condition also increased the sensory processing, making any perceptual issues in the group with CP more apparent. This explanation is consistent with the finding that the group with CP effectively ignored the instruction to time to the RAS; a strategy to manage sensory inputs.

As previously noted, the group without CP demonstrated an increase in participant bias for undershooting the target in the SD condition. The large target undershoot errors were not found in the control study where the RAS had a 3-s duration. Given the reported influence of RAS on the temporal and spatial modulation of movement control, it is likely that the instruction to time their reaches to the RAS over a 6-s duration of time resulted in the group without CP stopping short of the target and waiting for the final tone before finishing their reach (Thaut, 2013; Thaut et al., 1999). In contrast, the group with CP were overall more accurate at target acquisition in the sound during condition. Although not statistically significant, the observed improvement in endpoint accuracy for the group with CP demonstrates that for participants who were able to time their movements to the auditory stimulus, the selected timing of the stimulus was appropriate and potentially helpful.

Limitations

In the absence of published data related to how adults with CP perform reaching movements, an a priori power calculation was not conducted. A post hoc power analysis was conducted (G*Power, Düsseldorf, Germany; Faul, Erdfelder, Lang, & Buchner, 2007); alpha was set at .05 and eta squares from constant error-*y* axis (.13) were used to calculate an achieved power of 0.91. The small effect sizes were likely due to the small sample size and the increased variability of the group with CP (GMFCS 2–4). Due to the relatively small sample size and the range of GMFCS levels, individual GMFCS levels were not taken into consideration in the analysis. To ensure generalizability to the GMFCS levels broadly, future work could consider subgroups of ambulatory (GMFCS 1–2) and less-ambulatory (GMFCS 3–5) individuals with CP.

Future Directions

The observed impact of sound on movement performance for adults with CP warrants further investigation. Future consideration for how alternate forms of rhythm, such as singing, drumming, or rhythmic cues, might affect movement performance is needed. At GMFCS level four individuals may experience acute contractures of the shoulders and arms and may use their feet or head to access tablet devices adapted for communication and participation in adapted PAs. The incorporation of the RAS with a modified reaching and/or Fitts' task using different parts of the body may also be considered to capture the functional movement capabilities of individuals across the GMFCS continuum. Future studies should also specifically take into consideration sex and/or gender.

Conclusion

The present study examined the effect of RAS during the movement planning and execution phases of goal-directed reaches. Based on the results, it is proposed that both groups used the RAS during movement planning to reduce the uncertainty of target acquisition. It is proposed that the use of the rhythm before movement onset had a regulatory effect on movement planning, for both groups. The rhythm may also serve as an external focus of attention that facilitated movement performance. Thus, the rhythm benefited both temporal and spatial parameters of movement performance for adults with CP. It is suggested that the incorporation of a rhythm (i.e., singing, a drumbeat, counting) into rehabilitation modalities and physical activities may be an effective and low-risk/safe strategy that may benefit movement performance for individuals with CP.

Acknowledgments

The authors thank the participants for their time and to CP Manitoba and The Movement Centre, Inc. for their assistance with recruitment. This research was supported by the Natural Sciences and Engineering Research Council of Canada, the Canadian Foundation for Innovation, and Research Manitoba. Author JL was supported by Research Manitoba and the University of Manitoba. The authors have no known conflict of interest to disclose.

References

Andersen, T.S., Tiippana, K., & Sams, M. (2004). Factors influencing audiovisual fission and fusion illusions. *Cognitive Brain Research, 21*(3), 301–308. PubMed ID: 15511646 doi:10.1016/j.cogbrainres.2004.06.004

Chiviacowsky, S., Wulf, G., & Ávila, L.T.G. (2013). An external focus of attention enhances motor learning in children with intellectual disabilities. *Journal of Intellectual Disability Research, 57*(7), 627–634. PubMed ID: 22563795 doi:10.1111/j.1365-2788.2012.01569.x

Cremer, N., Hurvitz, E.A., & Peterson, M.D. (2017). Multimorbidity in middle-aged adults with cerebral palsy. *The American Journal of Medicine, 130,* 744.e9–744.e15. PubMed ID: 28065772 doi:10.1016/j.amjmed.2016.11.044

Damiano, D.L. (2006). Activity, activity, activity: Rethinking our physical therapy approach to cerebral palsy. *Physical Therapy, 86*(11), 1534–1540. PubMed ID: 17094192 doi:10.2522/ptj.20050397

Elias, L.J., Bryden, M.P., & Bulman-Fleming, M.B. (1998). Footedness is a better predictor than is handedness of emotional lateralization. *Neuropsychologia, 36*(1), 37–43. PubMed ID: 9533385 doi:10.1016/S0028-3932(97)00107-3

Elliott, D., Hansen, S., Grierson, L.E., Lyons, J., Bennett, S.J., & Hayes, S.J. (2010). Goal-directed aiming: Two components but multiple processes. *Psychological Bulletin, 136*(6), 1023–1044. PubMed ID: 20822209 doi:10.1037/a0020958

Elliott, D., Hansen, S., Mendoza, J., & Tremblay, L. (2004). Learning to optimize speed, accuracy, and energy expenditure: A framework for understanding speed-accuracy relations in goal-directed aiming. *Journal of Motor Behavior, 36*(3), 339–351. PubMed ID: 15262629 doi:10.3200/JMBR.36.3.339-351

Eunson, P. (2012). Aetiology and epidemiology of cerebral palsy. *Paediatrics and Child Health, 22*(9), 361–366. doi:10.1016/j.paed.2012.05.008

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*(2), 175–191. PubMed ID: 17695343 doi:10.3758/BF03193146

Ferguson, C.J. (2009). An effect size primer: A guide for clinicians and researchers. *Professional Psychology: Research and Practice, 40*(5), 542–538. doi:10.1037/a0015808

Ferrari, A., Tersi, L., Ferrari, A., Sghedoni, A., & Chiari, L. (2010). Functional reaching discloses perceptive impairment in diplegic children with cerebral palsy. *Gait & Posture, 32*(2), 253–258. PubMed ID: 20605460 doi:10.1016/j.gaitpost.2010.05.010

Figueiredo, P.R., Silva, P.L., Avelar, B.S., da Fonseca, S.T., Bootsma, R.J., & Mancini, M.C. (2015). Upper limb performance and the structuring of joint movement in teenagers with cerebral palsy: The reciprocal role of task demands and action capabilities. *Experimental Brain Research, 233*(4), 1155–1164. PubMed ID: 25579662 doi:10.1007/s00221-014-4195-3

Hatfield, B.C., Wyatt, W.R., & Shea, J.B. (2010). Effects of auditory feedback on movement time in a fitts task. *Journal of Motor Behavior, 42*(5), 289–293. PubMed ID: 20826421 doi:10.1080/00222895.2010.504759

James, S., Ziviani, J., Ware, R.S., & Boyd, R.N. (2015). Relationships between activities of daily living, upper limb function, and visual perception in children and adolescents with unilateral cerebral palsy. *Devolpmental Medicine & Child Neurology, 57*(9), 852–857. PubMed ID: 25703777 doi:10.1111/dmcn.12715

Johansson, A.M., Domellof, E., & Ronnqvist, L. (2012). Short- and long-term effects of synchronized metronome training in children with hemiplegic cerebral palsy: A two case study. *Developmental Neurorehabilitation, 15*(2), 160–169. PubMed ID: 22296344 doi:10.3109/17518423.2011.635608

Johansson, A.M., Domellof, E., & Ronnqvist, L. (2014). Timing training in three children with diplegic cerebral palsy: Short- and long-term effects on upper-limb movement organization and functioning. *Frontiers in Neurology, 5,* 38. PubMed ID: 24744747 doi:10.3389/fneur.2014.00038

Ju, Y.H., Hwang, I.S., & Cherng, R.J. (2012). Postural adjustment of children with spastic diplegic cerebral palsy during seated hand reaching in different directions. *Archives of Physical Medicine and Rehabilitation, 93*(3), 471–479. PubMed ID: 22265343 doi:10.1016/j.apmr.2011.10.004

Ju, Y.H., You, J.Y., & Cherng, R.J. (2010). Effect of task constraint on reaching performance in children with spastic diplegic cerebral palsy. *Research in Developmental Disabilities, 31*(5), 1076–1082. PubMed ID: 20434308 doi:10.1016/j.ridd.2010.04.001

Liptak, G.S. (2008). Health and well being of adaults with cerebral palsy. *Current Opinion in Neurology, 21,* 136–142. PubMed ID: 18317270 doi:10.1097/WCO.0b013e3282f6a499

Livingston, M.H., Rosenbaum, P.L., Russell, D.J., & Palisano, R.J. (2007). Quality of life among adolescents with cerebral palsy: What does the literature tell us? *Developmental Medicine & Child Neurology, 49*(3), 225–231. PubMed ID: 17355481 doi:10.1111/j.1469-8749.2007.00225.x

Lundy-Ekman, L. (2013). *Neuroscience: Fundamentals for rehabilitation* (4th ed.). St. Louis, MI: Elsevier.

Malcom, M.P., Massie, C., & Thaut, M.H. (2009). Rhythmic auditory-motor entrainmentimproves hemiparetic arm kinematics during reaching movements: A pilot study. *Top Stroke Rehabilitation, 16*(1), 69–79. PubMed ID: 19443349 doi:10.1310/tsr1601-69

Palisano, R., Rosenbaum, P., Walter, S., Russell, D., Wood, E., & Galuppi, B. (1997). Development and reliability of a system to classify gross motor function in children with cerebral palsy. *Developmental Medicine & Child Neurology, 39*(4), 214–223. PubMed ID: 9183258 doi:10.1111/j.1469-8749.1997.tb07414.x

Peters, C.M., & Glazebrook, C.M. (2020). Rhythmic auditory stimuli heard before and during a reaching movement elicit performance improvements in both temporal and spatial movement parameters. *Acta Psychologica, 207,* 103086. PubMed ID: 32422419 doi:10.1016/j.actpsy.2020.103086

Stiers, P., Vanderkelen, R., Van neste, G., Coene, S., De Rammelaere, M., & Vandenbussche, E. (2002). Visual-perceptual impairment in a random sample of children with cerebral palsy. *Developmental Medicine & Child Neurology, 44,* 370–382. PubMed ID: 12088305 doi:10.1111/j.1469-8749.2002.tb00831.x

Straub, K., & Obrzut, J.E. (2009). Effects of cerebral palsy on neuropsychological function. *Journal of Developmental and Physical Disabilities, 21*(2), 153–167. doi:10.1007/s10882-009-9130-3

Thaut, M.H. (2013). Entrainment and the motor system. *Music Therapy Perspectives, 31*(1), 31–34. doi:10.1093/mtp/31.1.31

Thaut, M.H., & Kenyon, G.P. (2003). Rapid motor adaptations to subliminal frequency shifts during syncopated rhythmic sensorimotor synchronization. *Human Movement Science, 22*(3), 321–338. PubMed ID: 12967761 doi:10.1016/s0167-9457(03)00048-4

Thaut, M.H., Kenyon, G.P., Hurt, C.P., McIntosh, G.C., & Hoemberg, V. (2002). Kinematic optimization of spatiotemporal patterns in paretic arm training with stroke patients. *Neuropsychologia, 40*(7), 1073–1081. PubMed ID: 11900758 doi:10.1016/s0028-3932(01)00141-5. https://www.ncbi.nlm.nih.gov/pubmed/11900758

Thaut, M.H., Kenyon, G.P., Schauer, M., & McIntosh, G. (1999). The connection between rhythmicity and brain function. *IEEE Engineering in Medicine and Biology Magazine, 18*(2), 101–108. PubMed ID: 10101675 doi:10.1109/51.752991

Thorpe, D. (2009). The role of fitness in health and disease: Status of adults with cerebral palsy. *Developmental Medicine & Child Neurology, 51*(Suppl. 4), 52–58. PubMed ID: 19740210 doi:10.1111/j.1469-8749.2009.03433.x

Trevarrow, M.P., Kleinsmith, J., Taylor, B.K., Wilson, T.W., & Kurz, M.J. (2021). The somatosensory cortical activity in individuals with cerebral palsy displays an aberrant developmental trajectory. *The Journal of Physiology, 599*(4), 1281–1289. PubMed ID: 33296078 doi:10.1113/JP280400

Wulf, G., Lewthwaite, R., Cardozo, P., & Chiviacowsky, S. (2018). Triple play: Additive contributions of enhanced expectancies, autonomy support, and external attentional focus to motor learning. *Quarterly Journal of Experimental Psychology, 71*(4), 824–831. PubMed ID: 28056637 doi:10.1080/17470218.2016.1276204

Wulf, G., McNevin, N., & Shea, C. (2001). The automacity of complex motor skill learning as a function of attentional focus. *Quarterly Journal of Experimental Psychology A, 54*(4), 1143–1154. PubMed ID: 11765737 doi:10.1080/713756012