Children with Autism Spectrum Disorder use inefficient goal-directed whole body movements compared to typical development.

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ABSTRACT

Children with Autism Spectrum Disorder (ASD) have differences in their movements which impact their functional performance. Virtual-reality enables researchers to study movement in safe, engaging environments. We used motion-capture to measure how 7-13-year-old children with ASD and typically-developing (TD) children make whole-body movements in a virtual-reality task. Although children were successful, we observed differences in their movements. Children with ASD were less efficient moving to the target. Children with ASD appeared to lack a movement strategy. While TD children were more likely to overshoot near targets and undershoot far targets, children with ASD did not modulate their strategy. Using kinematic data from tasks in virtual-reality, we can begin to understand the pattern of movement challenges experienced by children with ASD.

INTRODUCTION

Autism spectrum disorder (ASD) is diagnosed based on two core symptom domains–differences in social communication and restricted, repetitive patterns of behavior, interests, or activities–but differences in movements such as odd gait and clumsiness are also associated (American Psychiatric Association, 2013). Movement differences in ASD have long been a subject of interest, beginning with the earliest descriptions of ASD (Asperger, 1991). Despite this early recognition of movement differences in ASD, there has been relatively little work in this domain compared to the vast literature on core symptoms. To begin shedding light on movement differences in children with ASD, we examined how children with ASD perform goal-directed, whole-body movements.

As many as 79-97% of children with ASD are at risk of or have motor impairment compared to general population norms (Bhat, 2020; Green et al., 2009; Hilton, Miller, et al., 2021; Zhang, Whilte, Klohr, & Constantino, 2012). These differences begin early in development and persist throughout childhood (Bhat, Landa, & Galloway, 2011; Fournier, Hass, Naik, Lodha, & Cauraugh, 2010; Lloyd, MacDonald, & Lord, 2013; Van Waelvelde, Oostra, Dewitte, Van Den Broeck, & Jongmans, 2010). In particular, individuals with ASD often have gross motor differences, beginning with delays in meeting motor milestones (Davidovitch, Stein, Koren, & Friedman, 2018; Fulceri et al., 2019), continuing through the school years with differences in performance on standardized motor assessments (Fisher et al., 2018; Green et al., 2009; Jansiewicz et al., 2006; Liu & Breslin, 2013; Miller et al., 2021; Purpura, Fulceri, Puglisi, Masoni, & Contaldo, 2020), and persisting into adulthood as evidenced by decreased postural control and stability (Doumas, McKenna, & Murphy, 2016; Lim, Partridge, Girdler, & Morris, 2017). These motor differences are often related to the functional outcomes of people with ASD (Licari et al., 2019; Travers et al., 2017). Although these studies have documented the presence of motor problems in ASD using motor milestone checklists, standardized assessments of motor ability, and measures of postural stability, there has been little attention paid to how movements of children with ASD may differ from those of typically-developing (TD) children in terms of their effiency and variability.

Mastery of early motor skills is necessary to access many early developmental opportunities (Adolph, 2008), and motor skills are foundational to the development of skills in many other domains (e.g. affect, perception, social behavior, tool-use, additional motor skills; Adolph & Robinson, 2013). In ASD, motor difficulties may impede children's abilities to engage in many activities of daily living (ADLs; Fisher et al., 2018; Licari et al., 2019). Delayed sitting and crawling in infants at high-risk for ASD have been linked to delays in the development of communication skills (LeBarton & Iverson, 2016). The development of self-care behaviors (e.g, eating, bathing, toileting, and dressing) in children with ASD is related to locomotion, grasping, and visuomotor integration (Jasmin et al., 2009). While many children with ASD eventually learn to perform most of these activities at some level of competency, underlying motor control differences likely limit their efficiency, accuracy, or level of independence.

Researchers have begun to examine how movements made by individuals with ASD may differ from TD individuals. Individuals with ASD exhibit differences during a wide array of movement types including quiet standing (for review, see Lim et al., 2017), leaning (Miller, Caçola, Sherrod, Patterson, & Bugnariu, 2019; Wang et al., 2016), stepping (Bojanek, Wang, White, & Mosconi, 2020), reaching (Glazebrook, Elliott, & Lyons, 2006; Rodgers, Travers, & Mason, 2019), grasping (Carment et al., 2020; Mosconi et al., 2015), catching (Chen et al., 2019), tool-use (Mostofsky et al., 2006), and handwriting (Grace, Enticott, Johnson, & Rinehart, 2017). Across this range of movements, individuals with ASD consistently demonstrate less stable posture, less efficient movements, and reduced accuracy in their movements. To date, postural control (e.g., standing, leaning, stepping) and upper extremity movements (e.g., reaching, grasping, catching, tool-use, handwriting) have been the primary focus of many studies. However, these studies have not provided information about how individuals with ASD make whole-body movements to accomplish a task.

New developments in the fields of virtual reality and gaming have provided a wide range of opportunities for researchers to design highly-controlled, safe, and engaging tasks for children with ASD (Malihi et al., 2020). Prior work with children with ASD has focused primarily on the use of virtual reality for the assessment and teaching of social skills (for review, see Miller & Bugnariu, 2016). Conversely, work with TD and other atypical populations (e.g., developmental coordination disorder, cerebral palsy, Parkinson's disease) have used virtual reality for the assessment of movements (Canning et al., 2020; Gonsalves, Campbell, Jensen, & Straker, 2015; Levac et al., 2010) and training of motor skills (Li, Lam-Damji, Chau, & Fehlings, 2009; Prasertsakul, Kaimuk, Chinjenpradit, Limroongreungrat, & Charoensuk, 2018; Ravi, Kumar, & Singhi, 2017). In related work, researchers have begun using video games to distinguish between children with ASD and TD children by examining body movement (Ardalan, Assadi, Surgent, & Travers, 2019) and imitation (Tunçgenç et al., 2020) but virtual reality has not been widely utilized in this way, with a few notable exceptions (e.g., Greffou et al., 2012; Miller et al., 2019). We have extended the use of virtual reality technology in children with ASD by integrating it with motion capture, which has enabled us to precisely quantify and characterize differences in how children with ASD make goal-directed, whole-body movements during virtual reality tasks (Miller, Bugnariu, Patterson, Wijayasinghe, & Popa, 2017). Using this innovative approach to measuring movement differences between children with ASD and TD children, we can begin to understand the unique pattern of movement challenges experienced by children with ASD.

Current Study

Goal-directed, whole-body movements are critical for many activities of daily living. In ASD, there has been work on general gross motor skills and static postural control, but there is less work on dynamic, goal-directed, whole-body movements. In this study, we examined spatial efficiency and variability of whole-body movements to a static target in children with ASD and TD children using immersive virtual reality and motion-capture technology. We examined how successfully children with ASD completed whole-body movements to a static target compared to TD children. We also examined the amount of time used to complete the task, and how children adjusted their movements to the target based on the distance from their starting position to the target location. Finally, we assessed how efficient children were in completing these movements by quantifying the length of the paths they took to the target and the variability of these path lengths.

METHOD

Participants

We tested 16 children with ASD (Male = 14, Female = 2, M_{age} = 10.6 years , SD_{age} = 1.82, $Range_{\text{age}}$ = 7-13) and 12 TD children (Male = 7, Female = 5, M_{age} = 9.25 years, SD_{age} = 1.91, $Range_{\text{age}}$ = 7-13). For the ASD group, the participant's guardian confirmed that their child had a prior diagnosis of ASD or Asperger's syndrome from an educational or healthcare professional according to DSM-IV or DSM-V criteria. This community diagnosis was confirmed by the research team using the ADOS-2 (Lord et al., 2012) and ADI-R (Rutter, Le Couteur, & Lord, 2003) prior to experimental testing.

Potential participants with a current or prior diagnosis of a genetic or neurological disorder (not including ASD), brain injury, meningitis, structural brain abnormality, motion sickness, neurofibromatosis, seizure disorder, head injury or concussion with loss of consciousness, psychiatric diagnosis (not including anxiety or depression), movement disorder (e.g., cerebral palsy), or oculomotor disorder were excluded from participation, as well as those who were currently taking benzodiazepines or antipsychotics. Participants who scored < 70 in the nonverbal domain of the WASI-II (Wechsler, 2011) were also excluded. TD individuals that met any of the exclusion criteria for the ASD group, had a score of > 7 on the Social Communication Questionnaire (Rutter, Bailey, & Lord, 2003), or had any first-degree relatives with a diagnosis of ASD, Asperger's Syndrome, or related developmental disorder were excluded from participation. This study was approved by the North Texas Regional Institutional Review Board in accordance with U.S. Federal Policy for the Protection of Human Subjects. Prior to participation, all guardians gave informed consent, and all minor participants gave assent.

Safe Zone Task

The Safe Zone task is an immersive virtual reality task that requires a participant to move their user-controlled object (a blue ball, 29.21 cm in diameter, controlled by a marker placed on the participant's 7th cervical vertebrae) in the mediolateral direction to a safe zone (a green rectangle, 31.75 cm across) within 3 s for 16 trials (Figure 1, for more details on the apparatus see Miller et al., 2017). Each trial began with a fixation cross at the center of the screen for 600ms. Following the cross, the trial began when the user-controlled ball and the safe zone appeared simultaneously on the screen (Figure 1A). Participants were instructed to move their body to get their ball into the safe zone. The participant could lean and/or step to move their ball to the safe zone. Their movements were amplified 3.65 times that of the screen distance (e.g., a participant moving from the center of the screen to the safe zone at 97.85 cm would need to move their body 26.8 cm to overlap the safe zone). The safe zone appeared on the left or right side of the screen at either 48.93 cm (requiring the participant to move 13.4 cm from center) or 97.85 cm (requiring the participant to move 26.8 cm) from the center of screen in a random order. Although the safe zones always appeared at a specific distance from the center of the screen, the participants did not always start exactly at the center of the screen creating variable distances from the participants' starting positions and the locations of the safe zone. To ensure that movements on trials were comparable, only trials where the participant started a minimum of 6.7 cm and a maximum of 35cm from the safe zone location were used for analysis.

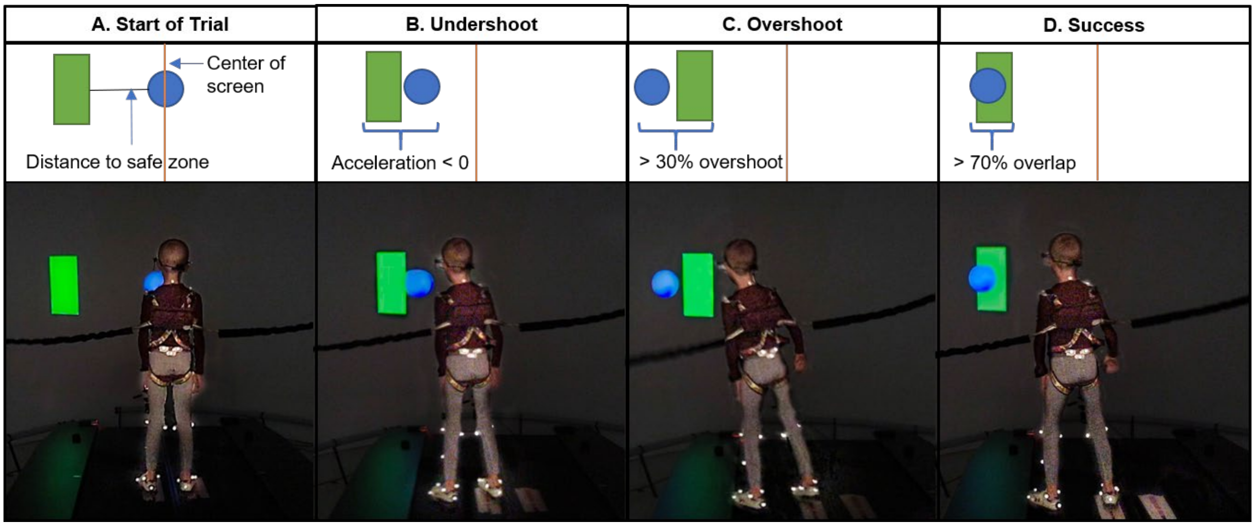

Figure 1. Participant moving their user-controlled blue ball into the safe zone (green rectangle). A. The participant starts in the center of the screen and distance is calculated as the distance

from the participant's location to the center of the safe zone. B. An undershoot is counted when a participant begins moving and their acceleration drops below 0 before reaching the safe zone. C. An overshoot is counted if the participant passes the safe zone by more than 30% of the blue ball diameter. D. Success is counted if the participant moves 70% of their blue ball into safe zone for 200ms within 3 seconds.

Variables of Interest

To successfully complete the task, or score a "hit", participants needed to move at least 70% of their ball into the safe zone for 200 ms continuously (Figure 1D). If participants did not reach the safe zone or were unable to keep their ball in the safe zone for 200 ms continuously within 3 s, the safe zone disappeared, and the trial was scored as unsuccessful.

Trial duration was calculated as the duration of time between when the safe zone appeared to the time that the participant scored a hit. Trial duration was only calculated for successful trials with a possible range of 0.2 to 2.9 s because failed trials were fixed at 3 s. Trials were coded as overshoots when a participant moved their ball through the safe zone with more than 30% of the ball extended beyond the opposite side of the safe zone (Figure 1C; e.g., moving from the left side, passing through the safe zone, and continuing to the right). Overshoots indicate an overestimate of the amount of movement necessary to reach the safe zone.

Trials were coded as undershoots when a participant's movement acceleration dropped below 0 and then increased above 0 again prior to reaching the safe zone (Figure 1B). Undershoots indicate an underestimate of the amount of movement necessary to reach the safe zone. Undershoots that resulted from the change in direction required to come back to the safe zone following an overshoot were excluded from analysis.

Path efficiency is the ratio of the actual path length to the optimal path length. Actual path length was calculated by summing the Euclidean distance between the position of the marker on the 7th cervical vertebrae (C7 marker) at each consecutive frame within a single trial. Optimal path length was calculated by measuring the nearest distance between the position of the participant's C7 marker at the start of the trial and the center of the safe zone (Figure 1A). Smaller ratios are indicative of better path efficiency. Path efficiency indicates the overall spatial efficiency of the movement during the task.

Path variability is the ratio of the standard deviation of each participant's path length to near and far safe zones (determined via median split) to the mean path length distance of each participant’s movements to near and far safe zones multiplied by 100. Path variability is a standardized measure of variation of path length distances.

Data Analyses

Generalized linear and linear mixed effects models were used to regress success, trial duration, overshoots, undershoots, path efficiency, and path variability on group (ASD, TD), age (continuous), distance from the safe zone (continuous), screen side (left, right), and/or trial number (1-16) with a random intercept of participant. For a trial to be included in the analysis, the participant’s starting position needed to be more than 6.7 cm (24.5 cm on the screen) away from the safe zone, less than 35 cm (127.8 cm on the screen) away from the safe zone, and moving less than 50% of their maximum velocity. Of the 448 possible trials, 318 trials (70.98%) met the inclusion criteria (ASD: 63.7%, TD: 80.7%). For analyses of trial duration, overshoots, undershoots, path efficiency, and path variability, only trials that ended in a successful hit were included (282 trials, 62.95% of all possible trials). Estimated marginal means were reported in response scale, β weights were reported in their link scale, if applicable.

RESULTS

Success

As expected, both participants with ASD and TD participants were capable of performing the task, successfully scoring hits on most valid trials (ASD: 89.96% success rate, TD: 88.39% success rate). Differences in success were due to more difficulty at increased distance and participants learning to move to the safe zone more successfully in later trials. A generalized linear mixed effects model using a binomial distribution with a logit link was used to regress success onto fixed factors of group, age, distance, screen side, and trial number with a random intercept by participant. This analysis showed main effects of distance to the safe zone (Wald $\chi^2_1 = 7.13$, $p = .008$, $\beta = -0.08$, Figure 2) and trial number (Wald $\chi^2_1 = 12.98$, $p < .001$, $\beta = 0.17$, Figure 3). Participants were less successful as the distance to the safe zone increased. Participants were more successful as the trial number increased (i.e., later trials compared to earlier trials). There were no group differences in success ($p > .05$).

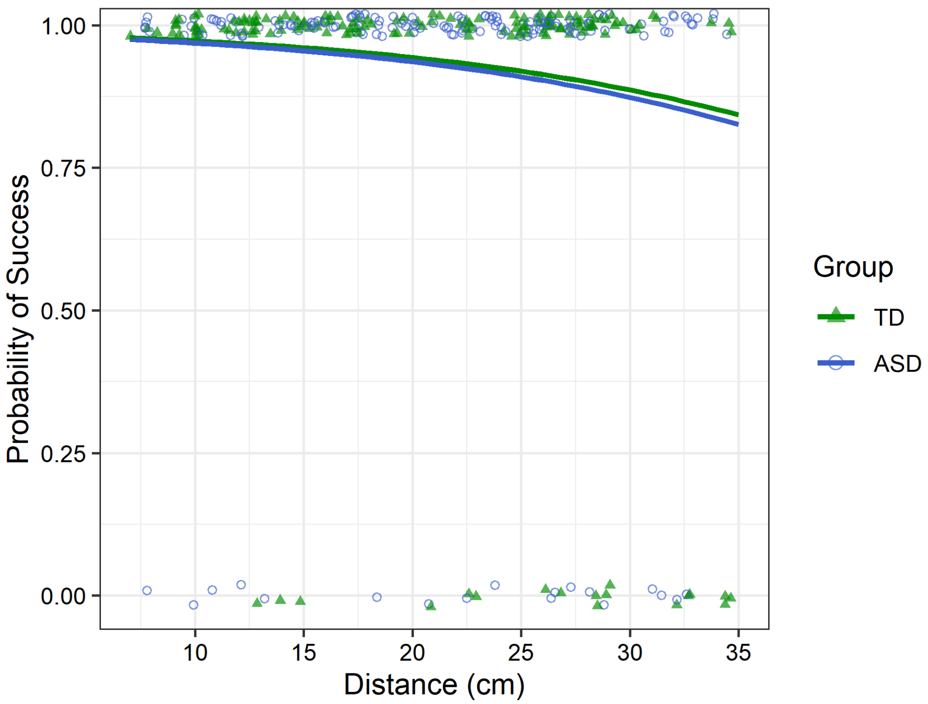

Figure 2. Children's probability of success decreased as the distance to the safe zone increased.

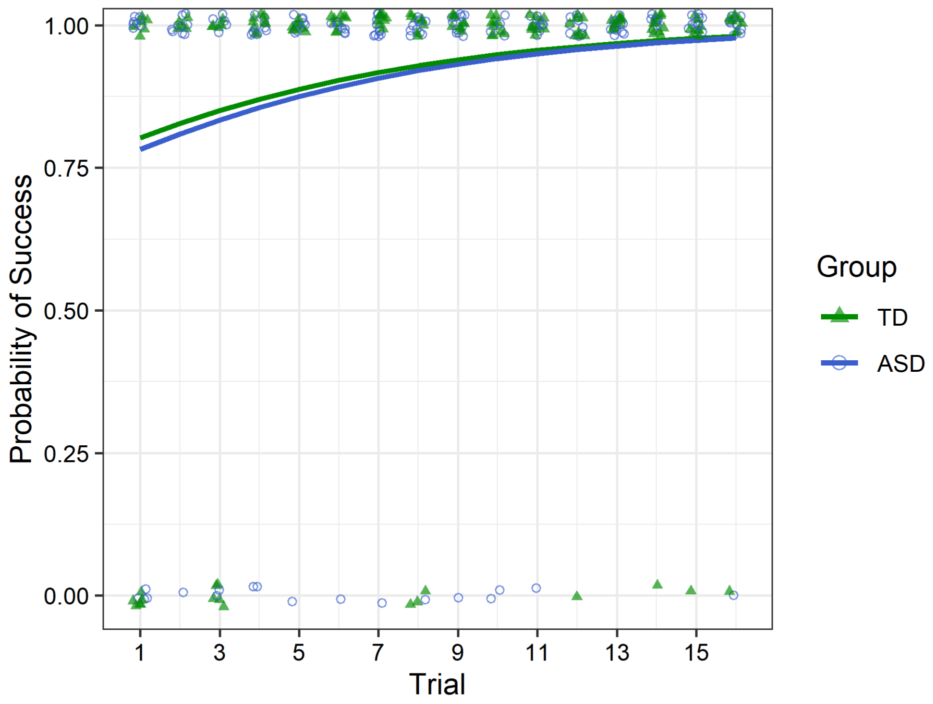

Figure 3. Children's probability of success increased as trial number increased.

Trial Duration

Participants with ASD took longer to complete the task on successful trials. A linear mixed effects model was used to regress trial duration of successful trials onto group, age, and distance to the safe zone with a random intercept by participant. This analysis showed main effects of group (Wald $\chi^2_1 = 6.98$, $p = .008$, $\beta = 0.24$, Figure 3), age (Wald $\chi^2_1 = 10.31$, $p = .001$, $\beta = -0.08$), and distance to the safe zone (Wald $\chi^2_1 = 59.75$, $p < .001$, $\beta = 0.03$, Figure 4). Participants with ASD (*M* = 1.94, *SE* = 0.06) used more time to get to the safe zone compared to TD participants (*M* = 1.70, *SE* = 0.07). Both participants with ASD and TD used more time to get to the safe zone as the distance to the safe zone increased. Older participants used less time to get to the safe zones than younger participants.

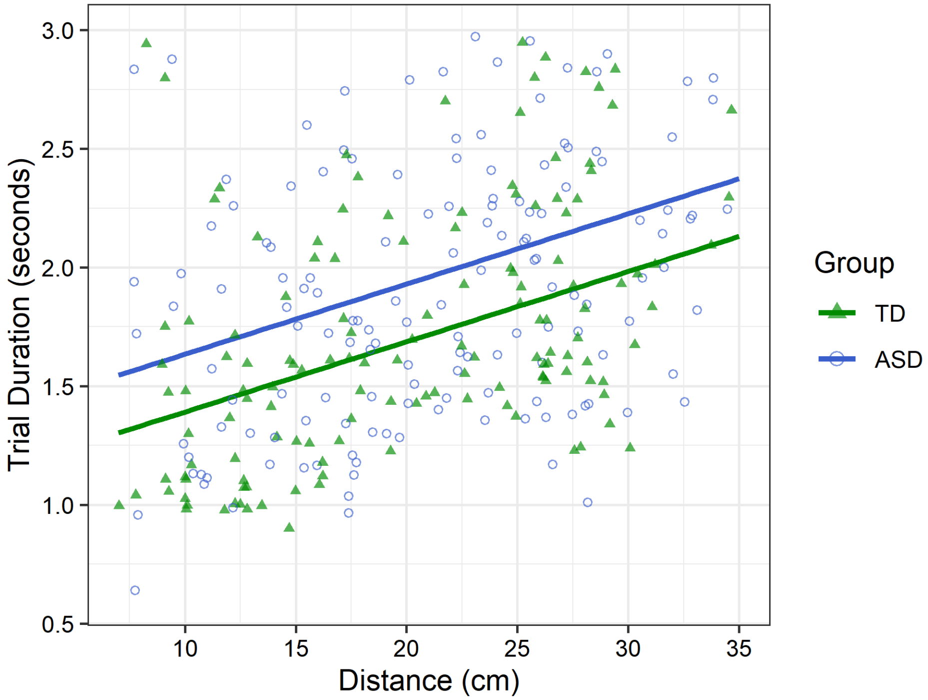

Figure 4. Children with ASD used more time to move to the safe zone than TD children. In both groups, children used more time to move to the safe zone as distance increased.

Overshoots

TD participants made fewer overshoots to safe zones that were further away than participants with ASD. A generalized linear mixed effects model using a Poisson distribution with a log link was used to regress number of overshoots on successful trials onto fixed factors of group, age and distance with a random intercept by participant. This analysis showed main effects of group (Wald $\chi^2_1 = 6.71$, $p = .010$, $\beta = 0.65$) and distance to the safe zone (Wald $\chi^2_1 = 16.47$, $p < .001$, $\beta = -0.06$). These main effects were qualified by a Group X Distance interaction (Wald $\chi^2_1 = 7.23$, $p = .007$, $\beta = 0.08$, Figure 5). TD participants made fewer overshoots than participants with ASD as distance increased.

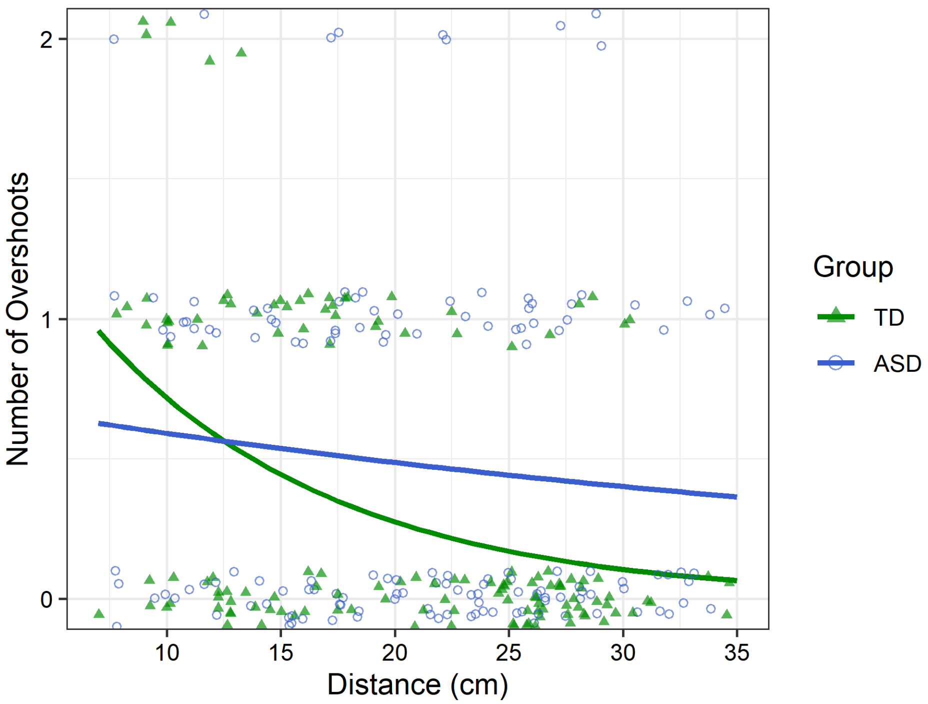

Figure 5. TD children made fewer overshoots compared to children with ASD as the distance to the safe zone increased.

Undershoots

TD participants made more undershoots to safe zones compared to participants with ASD. A generalized linear mixed effects model using a Poisson distribution with a log link was used to regress number of undershoots on successful trials onto fixed factors of group, age, and distance with a random intercept by participant. This analysis showed a main effect of distance to the safe zone (Wald $\chi^2_1 = 26.11$, $p < .001$, $\beta = 0.06$), which was qualified by a Group X Distance interaction (Wald $\chi^2_1 = 6.57$, $p = .010$, $\beta = -0.06$, Figure 6). TD participants made more undershoots as distance increased compared to participants with ASD.

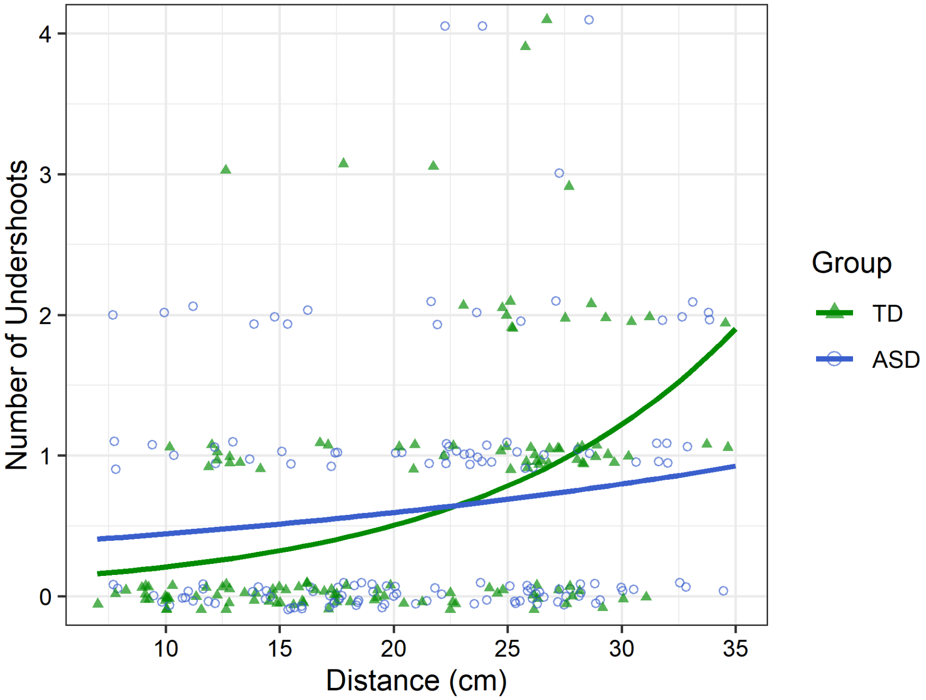

Figure 6. TD children made more undershoots compared to ASD children as the distance to the safe zone increased.

Path efficiency

Participants with ASD made less efficient movements compared to TD participants. Additionally, participants in both groups made more efficient movements to the safe zone as distance increased. A generalized linear mixed effects model using a Gamma distribution with a log link was used to regress the path efficiency of successful trials onto fixed factors of group, age, and distance with a random intercept by participant. This analysis showed a main effect of group (Wald $\chi^2_1 = 3.89$, $p = .048$, $\beta = 0.23$), such that participants with ASD ($M = 1.79$, $SE = 0.13$) used less efficient paths than TD participants ($M = 1.42$, $SE = 0.13$) as indicated by higher path efficiency scores. There was also a main effect of distance to the safe zone (Wald $\chi^2_1 = 86.64$, $p < .001$, $\beta = -0.02$, Figure 7), such that both groups took more efficient paths to the safe zone as the distance to the safe zone increased as indicated by lower path efficiency scores.

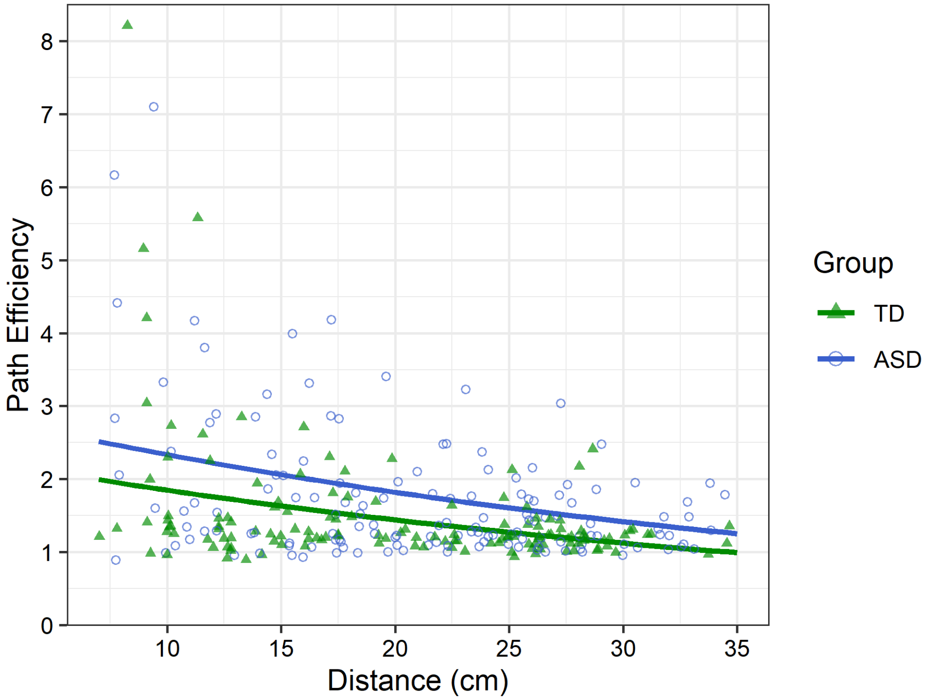

Figure 7. Children with ASD were less efficient than TD children. In both groups, children were more efficient as the distance to the safe zone increased.

Path variability

Both participants with ASD and TD participants made more variable movements to the near safe zones compared to far safe zones. A generalized linear mixed effects model using a Gamma distribution and a log link was used to regress the coefficient of variability of the movement path of successful trials onto fixed factors of group, distance, and age with a random intercept by participant. This analysis showed a main effect of distance to the safe zone (Wald $\chi^2_1 = 18.25$, $p < .001$, $\beta = -0.45$, Figure 8), such that participants in both groups had larger coefficients of variability for the movements to near safe zones ($M = 35.00$, $SE = 3.03$) compared to movements to far safe zones ($M = 22.40$, $SE = 2.17$).

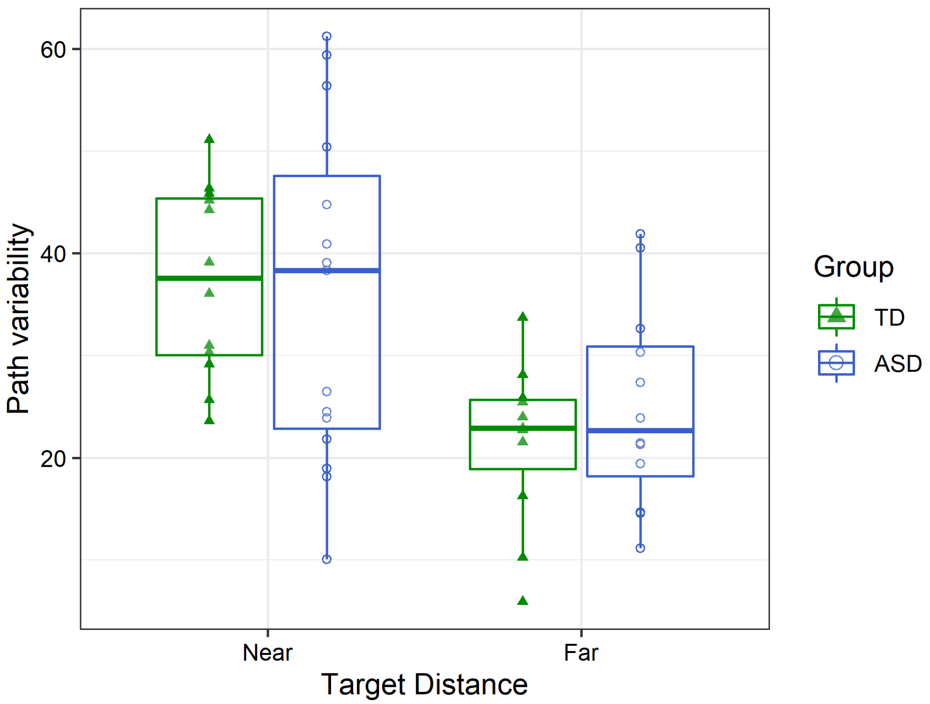

Figure 8. In both groups, children had more variable paths to the safe zone at near distances compared to far distances. Hinges correspond to the first and third quartiles. Whiskers extend to the largest value within 1.5 times the interquartile range.

DISCUSSION

Whole-body movement is required for many activities of daily living. Here, we investigated how children with ASD and TD children made whole-body movements to a static target in an immersive virtual reality task. Children with ASD are capable of completing many motor tasks, but the efficiency with which they complete these tasks may not be optimal. As expected, children in both groups were highly successful on this task, scoring a hit on more than 88% of trials. Although the rate of success indicates that children in both groups were able to complete this task, the more fine-grained data show different levels of movement efficiency between children with ASD and TD children. Specifically, when examining the trial duration, children with ASD used significantly more time than TD children to complete each trial. At first glance, this increase in trial duration of 240 ms for children with ASD may seem negligible, but it represents 10-20% more time required to complete a goal-directed movement compared to TD children. When considered in the context of how quickly a child performs activities of daily living (e.g., dressing, classroom tasks, social interactions), this 10-20% increase in time-to-completion could result in a child with ASD feeling frustrated or self-conscious, or being left behind as their peers move on to the next activity.

Children with ASD may have been less efficient in their whole-body movements compared to TD children due to strategies they used to reach the safe zone. Examining the number of overshoots and undershoots that children with ASD and TD used to reach the safe zone, a distinct pattern emerged. TD children made more undershoots to further safe zone distances and more overshoots to nearer safe zones distances. Conversely, children with ASD made similar numbers of overshoots and undershoots to safe zones at all distances. This modulation of strategy seen in TD children may reflect a prioritization of postural control for the purpose of maintaining balance. Overshooting safe zones at far distances would potentially place the body's center of mass outside of the limits of postural stability, meaning an undershoot of the safe zones at further distances is a safer strategy. There is no potential for a negative postural stability consequence for overshooting a safe zone at a near distance as the body's center of mass is still well within the limits of stability. The lack of consistent modulation observed in children with ASD may indicate either an inability to accurately estimate limits of their postural stability or an inability to change strategy based on perceived challenge to their postural stability. These findings are aligned with work by Mosconi and colleagues, in which individuals with ASD did not effectively use feedforward information when executing and modulating grip force, making less accurate initial movements and often overshooting targets (Mosconi et al., 2015; Wang et al., 2015).

Children with ASD also exhibited differences in the path efficiency of their movements compared to TD children. Children with ASD moved toward the safe zone via paths that diverged more from the optimal path (i.e., a straight line) compared to TD children. Combined with increased trial durations, children with ASD not only took longer to reach the safe zone, but also moved more to reach the same location compared to TD children. In terms of activities of daily living, this suggests that children with ASD may not only take longer to complete individual tasks, but may also expend additional energy in doing so. This may, in turn, lead to a higher level of exertion and fatigue for children with ASD than their TD peers when completing the same tasks. Higher levels of exertion and fatigue could discourage children with ASD from trying similar activities in the future.

We also examined the path variability in children's movements to near and far safe zone locations. Interestingly, there were not significant differences in the path variability of movements between children with ASD and TD children. This indicates that the inefficiencies in children's movements to a safe zone are not due entirely to inconsistencies from movement to movement, but also differences that occur within each movement. There were, however, differences in path variability for near and far safe zone distances. Children's movements to safe zones at near distances were significantly more variable than their movements to safe zones at far distances. Although children with ASD did not show significant differences in their path variability, they had a higher rate of excluded trials compared to TD children, likely due to difficulty getting their bodies back to the center of the screen before the next trial began. This indicates that children with ASD are not only less efficient within a single trial, but also across a series of trials. In other words, performing consecutive tasks without sufficient time between them may also be difficult for children with ASD compared to TD children.

Finally, the current study adds to the growing literature indicating that immersive virtual reality can be used effectively for research with children with ASD (Malihi et al., 2020; Miller & Bugnariu, 2016). Further, the precise measurements of movements in immersive virtual reality environments can be leveraged to not only determine whether the motor skills of children with ASD are different from those of TD children, but how their individual movements are different. This opens the door for a wide array of potential questions that can be answered regarding how differences in the movements of children with ASD impact their daily life in varying contexts.

CONCLUSION

Overall, children with ASD used more time to complete a goal-directed whole-body movement and were less efficient when making these movements compared to TD children. The increased time and energy necessary to complete goal-directed whole body movements may have a negative impact on the functional abilities of children with ASD. Considering our results in conjunction with prior findings of upper-extremity motor inefficiencies (Glazebrook et al., 2006), it is possible that complex ADLs requiring both whole-body and upper-extremity movements (e.g., many self-care tasks) may be even more taxing for individuals with ASD. The additive impact of these inefficiencies across a self-care routine that includes dressing, eating, brushing teeth, and gathering personal items would be substantial in terms of both time and energy.

Given these differences, it is imperative that children with ASD receive adequate therapeutic intervention to improve their motor skills. Unfortunately, few people with ASD receive intervention that would improve whole-body motor skills, with only 5% of individuals with ASD receiving physical therapy and only 37.5% receiving occupational therapy (Zablotsky et al., 2015). Further, many of these services are limited in scope. In the case of physical therapy, the focus is often on simply meeting early motor milestones (e.g., crawling, standing, walking). In the case of occupational therapy, goals are typically focused on sensory processing or handwriting. To help improve functional outcomes and quality of life for children with ASD, policy-makers need to substantially increase access to physical and occupational therapy for individuals with ASD, and researchers and clinicians need to develop interventions tailored specifically to the unique movement challenges experienced by this population.

Contributions

Contributed to conception and design: HLM, RMP, NLB
Contributed to acquisition of data: HLM, GMS
Contributed to analysis and interpretation of data: NEF, HLM, TNT
Drafted and/or revised the article: NEF, HLM
Approved the submitted version for publication: NEF, HLM, TNT, GMS, RMP, NLB

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Data and Supplementary Material Accessibility

The data and code for this paper are currently in the process of being transferred from one university to another. As there are ongoing discussions about the rights and obligations for this data and code, it cannot be shared at this time.

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