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A Kinematic Analysis of How Young Adults With and Without Autism Plan and Control Goal-Directed Movements

Cheryl M. Glazebrook, Digby Elliott, and James Lyons

We examined the planning and control of goal-directed aiming movements in young adults with autism. Participants performed rapid manual aiming movements to one of two targets. We manipulated the difficulty of the planning and control process by varying both target size and amplitude of the movements. Consistent with previous research, participants with autism took longer to prepare and execute movements, particularly when the index of difficulty was high. Although there were no group differences for accuracy, participants with autism exhibited more temporal and spatial variability over the initial phase of the movement even though mean peak accelerations and velocities were lower than for control participants. Our results suggest that although persons with autism have difficulty specifying muscular force, they compensate for this initial variability during limb deceleration. Perhaps persons with autism have learned to keep initial impulses low to minimize the spatial variability that needs to be corrected for during the online control phase of the movement.

Key Words: autism spectrum disorder, movement control, motor, manual aiming

The primary focus of most research related to autism has been on the perceptual and social differences these individuals exhibit relative to typically developing persons. Although persons with autism sometimes exhibit superior visuospatial and auditory abilities, there is no question that extreme difficulties with social understanding and interaction are among the most apparent and debilitating symptoms in autism. One area that has been largely overlooked is the impact of early motor problems on later social interaction. A number of years ago Leary and Hill (1996) made the case that early disturbances in motor control could lead to drastic differences in social interactions similar to those observed in individuals with autism. Specifically, if an individual has problems organizing, initiating, and executing goal-directed movements it becomes very difficult for that person to interact efficiently in the environment. This could have a profound impact on the development of higher order cognitive and social behaviors.

A number of studies have demonstrated differences in how individuals with autism perform reaching movements and achieve postural stability (Mari, Castiello,

The authors are with the Dept of Kinesiology, McMaster University, Hamilton, ON L8S 4K1.

Marraffa, & Prior, 2003; Minshew, Sung, Jones, & Furman, 2004; Molloy, Dietrich, & Bhattacharya, 2003; Schmitz, Martineau, Barthelemy, & Assaiante, 2003). Masterton and Biederman (1983) were one of the first to examine how individuals with autism perform goal-directed reaching movements. Their participants were trained to place wooden blocks onto targets while viewing the target apparatus through a prism lens that displaced vision of their environment. Normally when an individual learns to adapt an aiming movement while wearing a prism lens, and vision of their limb is available during training, this adaptation does not transfer to the other hand. One interpretation is that the unattended modality (proprioception) is recalibrated. For the adaptation to transfer hands, the participants need to focus on proprioception in order for the visual environment in general to recalibrate (Elliott & Roy, 1981). In Masterton and Biederman's study the participants with autism successfully transferred the adaptation from one hand to the other, however, both the chronologically age matched participants and the participants with mental retardation did not exhibit transfer to their other hand. This difference suggests the participants with autism had focused on proprioceptive information instead of online visual feedback to execute their movements during the adaptation phase.

In contrast to the finding that persons with autism focus on proprioceptive feedback, Molloy et al. (2003) manipulated the somatosensory and visual feedback that was available while participants maintained a stable upright posture by removing vision and/or changing the surface participants were standing on (adding a piece of foam). They demonstrated that persons with autism rely heavily on visual control to maintain postural stability. Although the interpretations of the results of these two studies are contradictory, one common thread is that *how* individuals with autism use various types of information for motor performance may be different from the general population, even if the outcome of their performance is similar.

A number of other studies have found both qualitative and quantitative differences in the performance of motor tasks by individuals with autism. Schmitz et al. (2003) asked persons with autism to perform an unloading task to investigate the timing of their muscular responses. Compared to a group without autism, the children with autism were slower to initiate a compensatory response to a reduction in the load they were holding. This suggests that the children with autism were not engaged in feedforward control. In other words, they reacted to the change in force using visual and/or proprioceptive feedback. Another recent study (Martineau, Schmitz, Assaiante, Blanc, & Barthélémy, 2004) reported differences in cortical activity between a group of children with autism and a control group of children without autism when performing a voluntary load-lifting task. Specifically, the children with autism did not exhibit the expected event related desynchronization prior to movement initiation that was present in the children without autism. Together, these studies suggest there are differences at the neurophysiological and behavioral levels of control in children with autism.

Differences in motor control may also be evident from an early age, and in some cases before a firm diagnosis of autism is given. Miyahara et al. (1997) and Teitelbaum et al. (1998) reported that individuals with an autism spectrum disorder show significant delays reaching conventional motor milestones (Miyahara et al., 1997; Teitelbaum et al., 1998). Hallett et al. (1993) also reported gross motor differences in adults with autism. In a retrospective study Teitelbaum and colleagues (1998) noted asymmetrical arm and leg movements when the infants with autism learned to crawl and walk. More recently, Zwaigenbaum and colleagues (2005) reported findings from an ongoing prospective study of infants whose older sibling is diagnosed with autism. The infants who later went on to be diagnosed with autism already exhibited different behaviors as early as 6 months old. At this age the infants were not as vocal as one would expect and somewhat passive. Interestingly, they did not exhibit more traditional signs of autism, however, delays in motor development (e.g., low muscle tone) were present (Zwaigenbaum, 2005).

Although not traditionally associated with autistic behavior, there is growing evidence that a significant proportion of individuals with autism are delayed reaching the motor milestones and/or exhibit aberrant motor control. However, very few studies have gone beyond gross measures of general delays and differences in timing to explore what exactly is different about movements performed by individuals with autism. One exception is a recent study by Mari and colleagues (2003) where children with autism were asked to reach and grasp two different sized cubes placed at two different distances. The authors explored specific kinematic differences in how the movements were executed (e.g., time to reach peak velocity, peak velocity, deceleration time) as well as the coordination of the reach and grasp component movements. Overall the children with autism performed the reach and grasp movements quite well. They adjusted the timing of the peak grip aperture and velocity of the reach and grasp components to the size and distance of the object. For example, the participants reached higher peak velocities *later* in the movement when reaching towards cubes that were further away and scaled the peak aperture appropriately to the size of the object. In spite of this, depending on IQ, the children with autism executed the movements either slower or faster than the children in the control group. Specifically, the children with autism who had low IQs performed the movements more slowly compared to the children without autism and the children with autism who had an IQ in the average or high range. Conversely, the children with autism who had average/high IQs executed the reach and grasp movements more quickly than either of the other two groups of children. The children with low IQs also demonstrated a delay in the onset of the grasp component relative to the reach component of the movement, which the authors suggest may be indicative of problems with parallel processing. Overall the results from this study suggest that children with autism have different movement profiles depending on their level of functioning. The subgroup of children with autism who had low IQ scores performed their movements more slowly and had difficulty coordinating the multiple components of the movements. In contrast, the subgroup of children with average or high IQ scores were able to coordinate the component movements but performed the movements faster than the children without autism. This strategy may be indicative of a problem using online feedback. In other words, the children attempted to execute the movements before they "forget" what the goal was (Mari et al., 2003). In summary, regardless of the level of functioning, children with autism appear to perform everyday reach and grasp movements differently from typically developing children.

Given the increasing evidence that delays and deficits in motor functioning impact the lives of individuals with autism we sought to develop a better understanding of *what* is different about their movements from typically developing persons. Given the discrepant conclusions in the literature, we were particularly interested in determining whether limb control differences in persons with autism reflect movement planning and feedforward control problems or processes more related to feedback-based online control. We chose to examine simple manual aiming movements. For these movements, it is easy to vary the task difficulty by manipulating the size of the target and the amplitude of the movement (i.e., Fitts, 1954; Fitts & Peterson, 1964). In addition, there is a rich literature of kinematic studies involving manual aiming movements. Most theoretical explanations of speed-accuracy relations in goal-directed aiming involve a dual process of limb control. Specifically, the early characteristics of the movement trajectory are thought to be determined by an initial movement plan that propels the limb in the general direction of the target. Feedback-based processing, later in the movement, adjusts the limb trajectory as necessary so the movement terminates within the target boundaries. Thus movement preparation time (i.e., reaction time) plus the magnitude and variability associated with early kinematic markers (e.g., peak acceleration, peak velocity) give us insight into movement preparation, and late kinematic events/variables (e.g., time after peak velocity) help us understand the efficiency of online control processes.

Unlike many of the previous experiments (cf., Minshew et al., 2004) the participants in the present experiment were young adults with autism. This choice of age group allows us to look at how well individuals with autism are able to control movements beyond the years where considerable motor development is normally taking place. Thus, we can begin to address whether persons with autism are delayed in their motor functioning, or if deficits persist throughout their lifespan. Finally, in addition to the standard kinematic analysis Mari et al. (2003) conducted, we investigated the variability of a number of timing and spatial variables. Normally when individuals perform repeated movements they execute each movement in a similar fashion, which is indicative of a well-formed and easily retrievable movement plan. Knowledge of how consistent individuals with autism are when executing repeated movements will provide insight into how "noisy" the motor system is and how consistent their movements are across repeated aiming attempts.

Method

Participants

Nine participants with autism (eight male) and nine participants without autism, matched for chronological age, completed the experiment. Depending on chronological age the participants with autism were diagnosed previously by a qualified clinician according to the criteria in the DSM-III, DSM-III(R), or DSM-IV (Diagnostic and Statistical Manual of Mental Disorders). Two participants in each group were left-handed and all participants had normal or corrected-to-normal vision. The average chronological age of the participants with autism was 26.9 years ($SD = 6.8$) and 25.1 years ($SD = 5.1$) for the participants without autism. The participants with autism also completed the Peabody Picture Vocabulary Test-Revised (PPVT-R) as a measure of receptive language ability, and Raven's Progressive Matrices (RPM) as a measure of non-verbal ability. The PPVT-R requires participants to identify the item associated with a spoken word in a series of pictures. The RPM uses a series of matrices to measure an individual's ability to deduce visual patterns. The verbal mental age of the nine participants with autism ranged from 5.83 to 33.67 years with a mean of 16.5 years (*SD* = 9.5). Performance on RPM ranged from 11 to 58/60 with an average of 43/60 (*SD* = 15.8) correct decisions. The IQ equivalent of the raw RPM scores ranged from 65 to 119 with a mean of 92 (*SD* = 21). Any medications the participants with autism reported taking are listed in Table 1 in conjunction with age, sex, and verbal/nonverbal ability information. All participants, and their legal guardian (where appropriate), gave informed consent before participating in the study. All procedures were approved by the McMaster Research Ethics Board and participants were compensated for their time.

Table 1 Group Characteristics for Participants with Autism (1-9) and Chronologically Age-Matched Peers (10-18)

Participant	Sex	Handedness	CA	VA	NVA	Medications
1	M	L	27	5 (11)	65	Carbamazepine; Citalopram; Lipitor
2	M	R	36	17 (7)	90	Risperal; Sertaline
3	M	R	20	5 (10)	69	None
4	M	R	28	8 (0)	107	None
5	M	R	18	33 (8)	119	Seroquel; Paroxetine
6	M	L	20	18 (6)	102	Dexedrine; Resperadal; Celexa
7	M	R	25	27 (6)	84	Divalproex; Fluoxetine; Risperdal; Anafranil
8	M	R	36	17 (10)	119	Synthroid; Prozac (not consistently)
9	F	R	32	14 (1)	72	None
10	M	R	26	n/a	n/a	n/a
11	M	R	23	n/a	n/a	n/a
12	M	R	29	n/a	n/a	n/a
13	M	R	18	n/a	n/a	n/a
14	M	L	23	n/a	n/a	n/a
15	M	R	30	n/a	n/a	n/a
16	M	R	23	n/a	n/a	n/a
17	M	R	34	n/a	n/a	n/a
18	F	L	20	n/a	n/a	n/a

Note. Verbal ability (VA) is based on results of PPVT-R and reported in years (months). Non-verbal ability (NVA) is reported as the IQ equivalent of each participant's performance on RPM.

Apparatus

An Epson PowerLite projector suspended 103 cm above a 75 cm high table was used to project the target image onto a piece of black Bristol board (see Figure 1). The target images were two yellow circles (1 or 2 cm) connected by a 16 or 32 cm horizontal line. All possible combinations of left target size, right target size, and line length were used. A 3 mm red portion of the line that connected the two circles indicated the start location for each trial. If both circles were the same size, the start location was always the midpoint between the two circles. However, if one circle was large (2 cm) and one was small (1 cm) the start location was either at the midpoint between the two circles or at the point where the two possible movements had an equal index of difficulty (according to Fitts' Law: ID = $\log_2(2A/W)$, where A = amplitude of movement, W = width of target). Therefore, as illustrated in Figure 2, there were five possible IDs (3, 3.41, 4, 4.41, 5), and two combinations of target size and length led to the three middle IDs. This was done to allow us to investigate the relative importance of target size and movement amplitude. For the present analysis we included only conditions where the ID to the left and right targets was equal.

Participants wore a banjo pick on the index finger of their dominant hand with an infra-red emitting diode (IRED) attached to the top. Movements were always performed with the dominant hand and three-dimensional displacement data of the participants' start position and aiming movement were collected for 1.5 s at

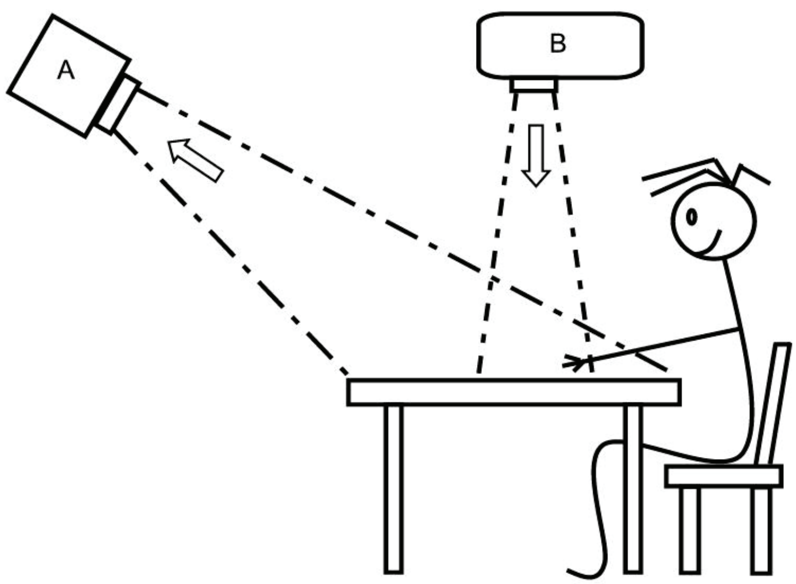

Figure 1—Diagram of experimental set-up. A: OPTOTRAK, B: projector

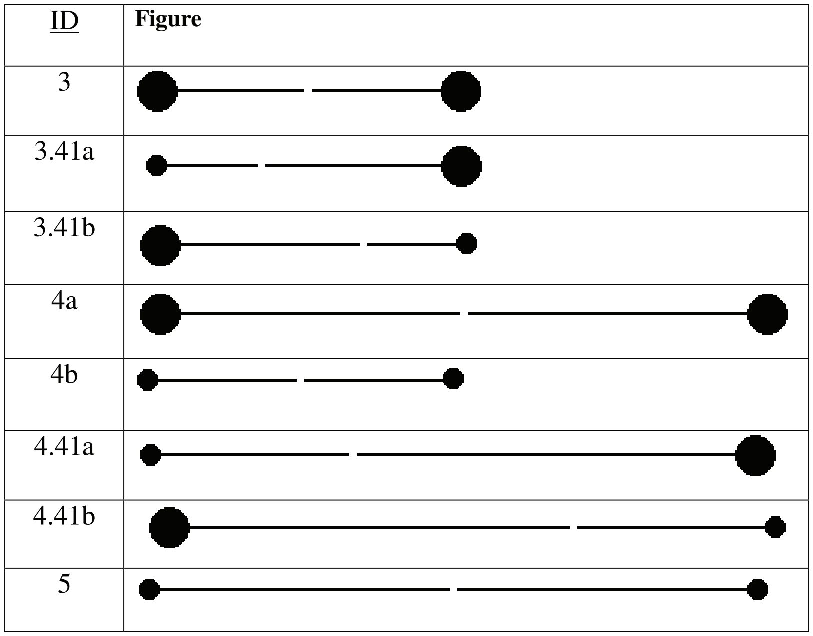

Figure 2—Diagram of the eight possible indices of difficulty (ID) and the corresponding figure (assuming movements are executed to the right circle). Small circles had a diameter of 1 cm, large circles had a diameter of 2 cm. The longer distance between the two targets was 32 cm, and the shorter distance was 16 cm.

500 Hz using an OPTOTRAK-3020 (Northern Digital Inc., Waterloo, ON). Custom software designed with E-Prime (version 1.0; Psychology Software Tools Inc., Pittsburgh, PA) was used to coordinate the presentation of the images and initiation of the OPTOTRAK. The 24 possible trial types included factorial combination of 2 contralateral potential target (1, 2 cm) × 2 ipsilateral potential target (1, 2 cm) × 2 length (8, 16 cm) × 2 actual target side (ipsilateral, contralateral). All 16 of these conditions were conducted with the starting location at the midpoint between the two targets. In addition, there were 8 conditions with different target sizes with the starting location positioned such that the ID between the two targets was equal. The 24 possible trial types were presented in a pseudorandom order (i.e., the 24 trial types were randomized 10 times).

Procedure

The task was clearly explained to each participant prior to the experimental trials. A small number of practice trials (< 10) were also completed to familiarize participants with the task. The experimental phase began once the experimenter was satisfied the participant understood the instructions and was comfortable with the task. Each trial began when one of the eight possible images was projected onto the tabletop. Participants were instructed to place their index finger/banjo pick on the start location, after which the experimenter initiated a random foreperiod of 2000–2550 ms. Next, either the right or left circle turned red and the program initiated an OPTOTRAK recording. The red circle was also the signal for participants to move their index finger as quickly and accurately as they could to the target circle. Once the target image disappeared the participants relaxed and the next trial was initiated when he or she was ready, for a total of 240 trials. Breaks could be taken after any trial, and were encouraged after approximately 80 trials if the individual did not indicate they would like a break before that point.

Data Analysis

First, the OPTOTRAK data in the primary axis of the movement (X) were filtered using a dual-pass Butterworth filter with a cut off frequency of 10 Hz. Next, the filtered displacement data were differentiated once to obtain velocity and a second time to obtain acceleration. Custom software (Chua & Elliott, 1993) was used to identify movement initiation, termination, and various kinematic markers. The start and end of each movement was defined as the frame where the velocity rose above or fell below 30 mm/s and remained there for more than 70 ms. The data were organized according to group (with autism, without autism), target side (contralateral, ipsilateral), and ID (3, 3.41a, 3.41b, 4a, 4b, 4.41a, 4.41b, 5) (see Figure 2). We removed any trials where the signed error for an individual trial was more than 2.5 *SD* units from the center of the target, or the RT fell outside ± 2.5 *SD* of the mean for that participant to eliminate trials where the target was not successfully acquired. Less than 6% of the trials were removed for the participants with autism and less than 5% were removed for the participants without autism.

Reaction time (RT) was defined as the time from the onset of the movement imperative (i.e., circle turning red) until movement initiation and movement time (MT) was the elapsed time from movement initiation to movement termination. The various kinematic markers (e.g., peak acceleration, peak velocity) were identified using custom software (Chua & Elliott, 1993). RT and MT are measures of how much time participants require for movement preparation and execution, respectively, whereas the kinematic measures provide insight into how the movement outcome was achieved. Peak acceleration, velocity, the time to achieve these kinematic events, as well as trial to trial variability provide information about the timing and magnitude of the initial impulse required to propel the limb toward the target. The symmetry of the velocity profile as well as spatial variability at different points in the movement provide information both about the initial impulse and online processes that may be involved in the reduction of movement error via feedback-based control. Pearson Product Moment (PPM) correlations between the PPVT-R score (verbal age) and participant's average RT and MT were calculated to explore if the verbal age of the participants with autism influenced the performance measures. The PPM correlations were repeated using the IQ equivalent scores from the RPM and the average RT and MT to determine if nonverbal ability affected the performance of the individuals with autism. The performance and kinematic measures were analyzed using a 2 Group × 2 Target Side (contralateral, ipsilateral) × 8 ID mixed analysis of variance (ANOVA). All significant effects involving more than two means were further analyzed using Tukey's Honestly Significant Difference (HSD, $p < .05$).

Results

Performance Measures

Error. An initial analysis revealed the participants with autism landed in the target on 97.6% of the trials while the participants without autism landed in the target on 97.4% of the trials (that were included in the data analyses). Thus, both groups of participants were following the instructions and landing in the target on the majority of trials.

Reaction Time. There were main effects for group [$F(1, 16) = 6.85$, $p < .02$], target side [$F(1, 16) = 5.47$, $p < .04$], and ID [$F(7, 112) = 24.5$, $p < .0001$], as well as a group by ID interaction, $F(7, 112) = 2.16$, $p < .05$. Overall, the group with autism required more time to prepare their movements (autism = 479 ms, *SD* = 77; without autism = 392 ms, *SD* = 62) and both groups of participants spent more time preparing movements to the contralateral side (C = 445 ms, *SD* = 94; I = 426 ms, *SD* = 70). The Group by ID interaction is depicted in Figure 3. Although both groups showed an increase in RT with ID, participants with autism appeared to be more affected by the amplitude of the movement than the target size. Specifically post hoc analyses (Tukey's HSD, $p < .05$) indicated a significant difference in RT between the two targets with an ID of 4 (1 cm-16 cm versus 2 cm-32 cm) for the participants with autism, but not for the participants without autism.

The IQ equivalent scores from Raven's Progressive Matrices (RPM) were significantly correlated with the participants' RT on this task (C = –0.73, I = –0.69; $p < .05$), as well as the correlation coefficients between RT and verbal age (PPVT-R). Specifically, the participants with autism who performed better on the PPVT-R reacted faster to targets on both the ipsilateral ($r = –0.71$, $p < .05$) and contralateral ($r = –0.73$; $p < .05$) side.

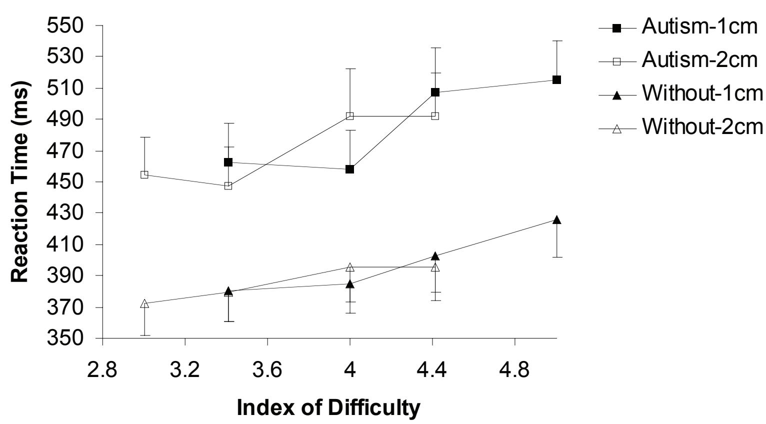

Figure 3—Mean reaction time (ms) and standard error bars as a function of group and index of difficulty (ID). Means have been organized according to group and target size for each ID (e.g., Autism-1cm).

Movement Time. The main effects for group [$F(1, 16) = 8.5$, $p < .01$], target side $F(1, 16) = 7.24$, $p < .02$], and ID [$F(7, 112) = 113.9$, $p < .001$], were statistically significant. As expected, the participants with autism required more time to execute their movements (357 ms, $SD = 76$) than participants without autism (266 ms, $SD = 54$) and participants in both groups took more time to execute movements to the contralateral target (320 ms, $SD = 85$; I = 303 ms, $SD = 74$). Consistent with the RT data, the group by ID interaction was also significant, $F(7, 112) = 4.21$, $p < .001$. As illustrated in Figure 4, both groups of participants were more influenced by the amplitude of the movement than the size of the target. That is, the distance traveled contributed more to the overall MT than the index of difficulty. However, the impact of increasing the length of the movements was even more dramatic for the participants with autism.

Unlike the RT correlations, participants' IQ equivalent score on RPMs was unrelated to MT performance for this task (C = –0.16, I = –0.22, $p > .10$). However, verbal age (PPVT-R) was negatively correlated with MT. Specifically, the participants with autism with higher scores performed their movements more quickly to both the contralateral ($r = –0.73$, $p < .05$) and ipsilateral ($r = –0.71$, $p < .05$) targets.

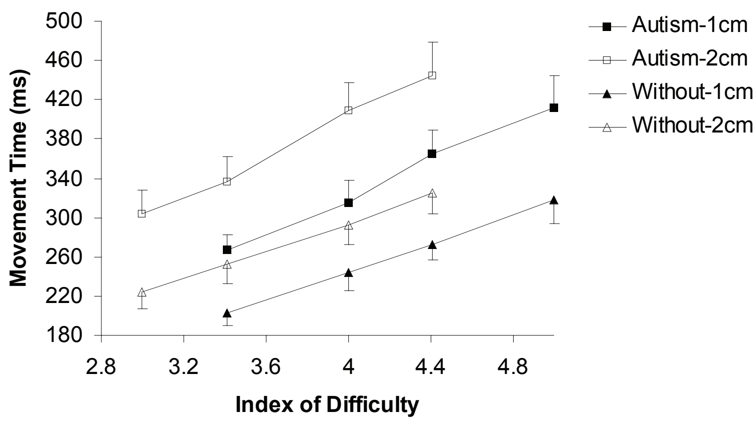

Figure 4—Mean movement time (ms) and standard error bars as a function of group and index of difficulty (ID). Means have been organized according to group and target size for each ID (e.g., Autism-1cm).

Kinematic Measures

Peak Acceleration. The main effects for group [$F(1, 16) = 7.99$, $p < .02$], and ID [$F(7, 112) = 51.9$, $p < .0001$] were significant. Overall, the participants with autism reached a much lower peak acceleration (8,893 mm/s^2, $SD = 5{,}418$), compared to the participants without autism (15,583 mm/s^2, $SD = 5{,}948$). Further analysis of the main effect for ID revealed that participants in both groups reached a higher PA when movements were executed to targets further away. In addition, the group by ID [$F(7, 112) = 12.17$, $p < .0001$] and target side by ID [$F(7, 112) = 7.31$, $p < .0001$]

interactions were also significant. Further analysis of the group by ID interaction revealed that the participants with autism increased the PA for longer movements, however, not to the same degree as the participants without autism (see Figure 5). Further analysis of the target side by ID interaction revealed a significant difference between the contralateral and ipsilateral side in only three cases. Participants reached higher PAs when performing movements to the ipsilateral target when the ID of the movement was 3.41 or 4.41 and the target was small. However, this pattern was reversed when the ID of the movement was 4.41 and the target was large (Table 2).

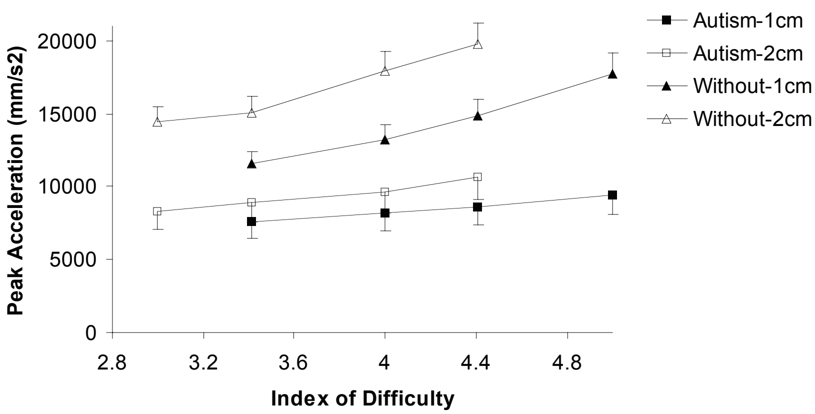

Figure 5—Mean peak acceleration (mm/s^2) and standard error bars as a function of group and index of difficulty (ID). Means have been organized according to group and target size for each ID (e.g., Autism-1cm).

Table 2 Mean Peak Acceleration (mm/s^2) and Standard Deviation (in brackets), Collapsed Across Group, As a Function of Index of Difficulty, Target Size, and Target Side

	3	3.41	4	4.41	5
Target: 1cm					
Contralateral		8,907	10,507	10,480	13,655
		(4,507)	(5,392)	(5,017)	(6,938)
Ipsilateral		10,180	10,860	12,894	13,484
		(4,001)	(4,777)	(5,165)	(5,366)
Target: 2cm					
Contralateral	11,082	12,113	13,474	16,020	
	(5,465)	(5,731)	(6,723)	(7,549)	
Ipsilateral	11,713	11,897	14,082	14,455	
	(4,688)	(5,076)	(5,221)	(5,742)	

Peak Velocity. The main effects for group [$F(1, 16) = 8.29$, $p < .01$], target side [$F(1, 16) = 11.27$, $p < .01$], and ID [$F(7, 112) = 12.88$, $p < .001$] were all significant. The participants with autism achieved a lower peak velocity (699 mm/s, $SD = 313$) compared to the participants without autism (1,002 mm/s, $SD = 242$). Participants in both groups reached lower peak velocities when executing movements to the contralateral (803 mm/s, $SD = 257$) versus the ipsilateral (898 mm/s, $SD = 253$) side. Finally, as illustrated in Figure 5, participants reached a higher PV when performing movements to targets that were further away.

In addition, the group by ID interaction was also significant [$F(7, 112) = 12.88$, $p < .0001$] (Figure 6). Similar to PA, the participants with autism did not increase their PV to the same degree as the participants without autism as the distance to be traveled increased.

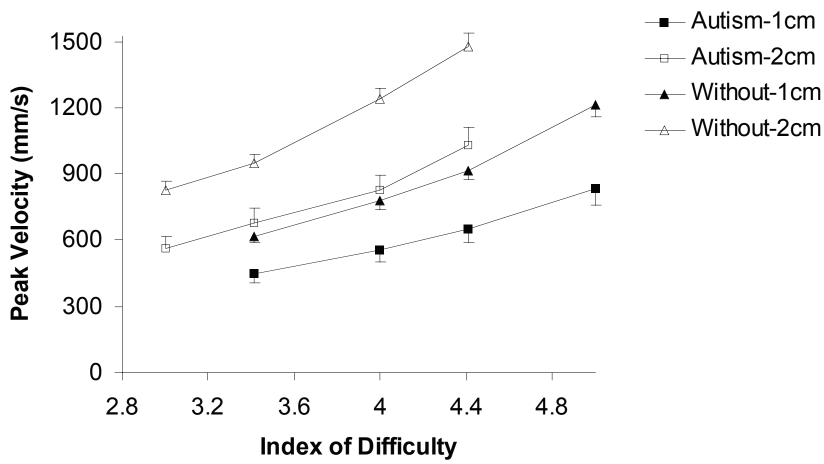

Figure 6—Mean peak velocity (mm/s) and standard error bars as a function of group and index of difficulty (ID). Means have been organized according to group and target size for each ID (e.g., Autism-1cm).

Time to Peak Velocity. The main effects for both group [$F(1, 16) = 14.7$, $p <.01$] and ID [$F(7, 112) = 91.4$, $p < .001$] were significant for the mean time to peak velocity. Consistent with the MT results, it took the participants with autism longer to reach peak velocity (with autism = 152 ms, $SD = 47$; without autism = 104 ms, $SD = 25$). Further analysis of the main effect for ID revealed that participants took longer to reach peak velocity as the ID increased. However, within each level of ID, participants took longer to reach peak velocity as the distance to travel increased. The group by ID [$F(7, 112) = 6.08$, $p < .0001$] and target side by ID [$F(7, 112) = 5.16$, $p < .0001$] interactions were both significant as well as the group by target side by ID interaction [$F(7, 112) = 2.68$, $p < .02$]. Further analysis of the 3-way interaction revealed that except for the 4.41 ID large target, the participants without autism were not influenced by target side. However, the participants with autism took longer to reach peak velocity when moving to targets on their ipsilateral side, but only for longer movements with an ID of 4 to 5. In one situation (when

ID = 4.41 and the target was small), the participants with autism demonstrated the reverse pattern (i.e., took *less* time to reach PV when moving to targets on their ipsilateral side) (Figure 7.).

When the within participant standard deviation of the time to peak velocity was analyzed the main effect for group was the only significant finding [$F(1, 16) = 8.37$, $p < .02$]. The participants with autism were almost twice as variable in the time to peak velocity (31 ms) compared to the participants without autism (16 ms).

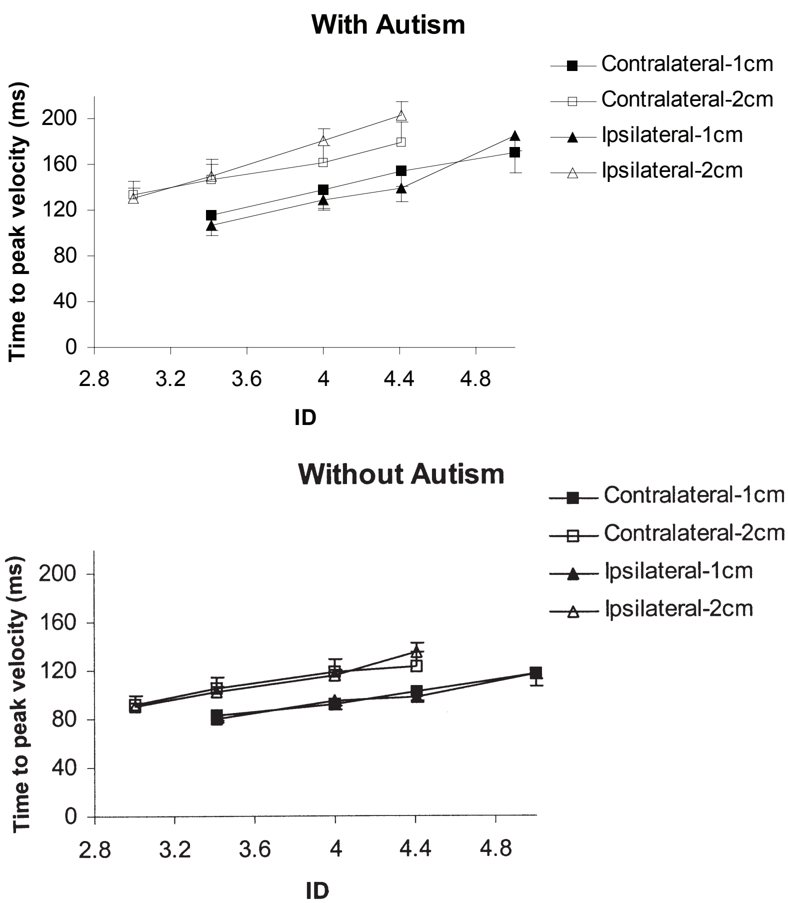

Figure 7—Mean time to peak velocity (ms) and standard error bars as a function of group, target side, and ID.

Proportional Time After Peak Velocity. The only significant main effect for proportional time after peak velocity (i.e., time after peak velocity/MT) was ID [$F(7, 112) = 3.79$, $p < .01$]. As illustrated in Table 3, overall as the movements became longer and the ID became higher participants spent more proportional time after PV. The target side by ID interaction was also significant [$F(7, 112)$

Table 3 Mean Proportional Time After Peak Velocity (Time After Peak Velocity/MT) and Standard Deviation (in brackets), Collapsed Across Group, As a Function of Index of Difficulty, Target Size, and Target Side

	3	3.41	4	4.41	5
Target: 1cm					
Contralateral		0.58	0.59	0.59	0.61
		(0.09)	(0.08)	(0.06)	(0.05)
Ipsilateral		0.55	0.56	0.59	0.56
		(0.09)	(0.08)	(0.08)	(0.07)
Target: 2cm					
Contralateral	0.57	0.56	0.60	0.61	
	(0.07)	(0.07)	(0.06)	(0.06)	
Ipsilateral	0.55	0.54	0.54	0.53	
	(0.08)	(0.09)	(0.07)	(0.07)	

= 3.22, $p < .01$]. Participants spent more proportional time after peak velocity when executing movements to the contralateral side compared to the ipsilateral side, however, the difference between the contralateral and ipsilateral sides was only significant for longer movements [ID = 4a (large target), 4.41a (large target), 5].

Displacement at Peak Velocity. Both the main effects for target side [$F(1, 16) = 21.72$, $p < .001$] and ID [$F(7, 112) = 1{,}112.997$, $p < .0001$] were significant, as well as the target side by ID interaction [$F(7, 112) = 14.7$, $p < .0001$]. Overall, participants achieved a greater displacement at peak velocity when executing movements to the ipsilateral (63 mm, $SD = 28$) versus the contralateral (55 mm, $SD = 22$) side. Not surprisingly, further analysis of the main effect for ID suggested that participants also reached a greater displacement at peak velocity when the distance to be traveled was greater. The target side by ID interaction resulted from a significantly greater increase in the displacement at peak velocity for longer movements on the contralateral side.

Spatial Variability. Analysis of spatial variability (2 Group × 4 Kinematic marker × 2 Target side × 8 ID) at four key kinematic markers (peak acceleration, peak velocity, peak deceleration, and endpoint) revealed main effects for kinematic marker [$F(3, 48) = 13.73$, $p < .0001$] and ID [$F(7, 112) = 27.93$, $p < .0001$], as well as significant group by kinematic marker [$F(3, 48) = 5.00$, $p < .01$], kinematic marker by ID [$F(21, 336) = 3.45$, $p < .0001$], and group by kinematic marker by ID [$F(21, 336) = 2.91$, $p < .0001$] interactions. Participants with autism were much more variable in the displacement at peak acceleration (13.9 versus 4.9 mm), somewhat more variable (although not quite statistically so) at peak velocity (10.8 versus 8.5 mm), but no different in the spatial variability at peak deceleration (14.1 versus 14.2 mm) and the endpoint (5.1 versus 5.5 mm). Figure 8 illustrates that the differences in variability of spatial location at peak acceleration and velocity were due primarily to the dramatic increase in variability for movements of longer distances. In addition, for movements of the same distance (1 cm-32 cm versus 2 cm-32 cm) target size also impacted the variability at peak acceleration; that is, the participants with autism were more variable in the displacement at peak acceleration when executing movements to the large versus small target (e.g., ID 4a versus ID 5). The greatest variability occurred when the ID = 4.41a, which is the ID with the longest distance and a large target (2 cm). In other words, both an increase in length and an increase in target area led to more variability in the displacement at peak acceleration.

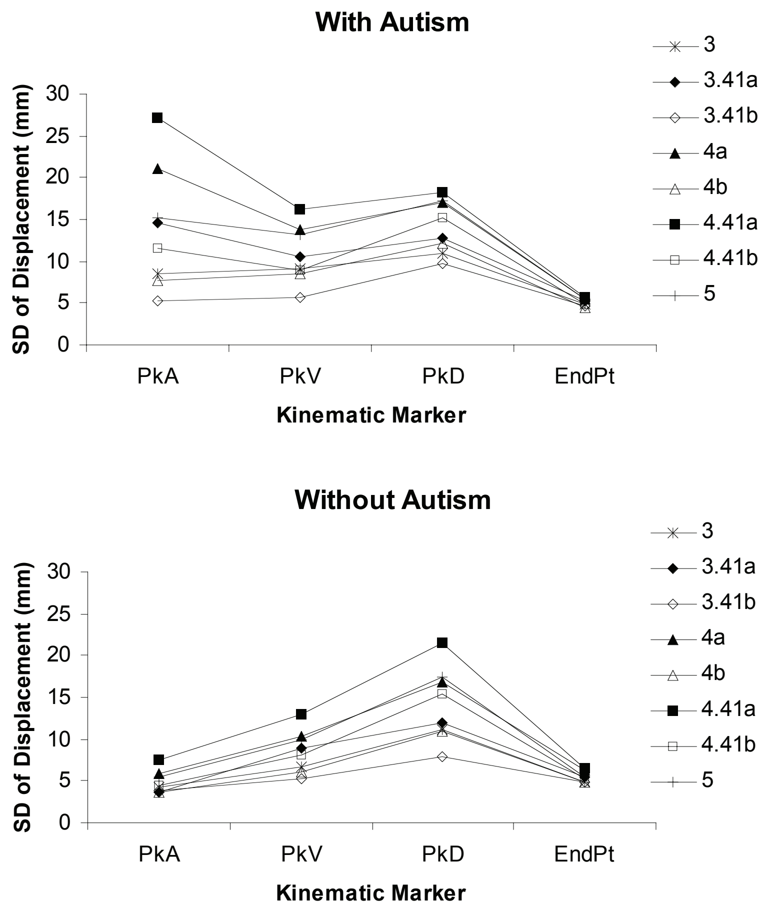

Figure 8—Variability (SD) of displacement at peak acceleration (PkA), peak velocity (PkV), peak deceleration (PkD), and endpoint (EndPt) (mm) as a function of group, kinematic marker, and ID.

Discussion

The main goals of the present study were to gain a better understanding of how individuals with autism perform rapid manual aiming movements, and to explore why overall differences in movement performance occur. To do this, we needed to go beyond gross measures of overall movement performance (e.g., total movement time, or performance batteries) and examine the details of the movement trajectories. We performed detailed analyses of the acceleration, velocity, deceleration, and spatial and temporal variability that together help to clarify how individuals with autism prepare and execute simple rapid aiming movements. Considering the small number of participants and large variability in verbal and non-verbal abilities, the findings of the present experiment should be considered preliminary. However, the current findings are consistent with previous studies (e.g., Mari et al., 2003) and extend those results to young adults with autism. For example, in line with previous work (Mari et al., 2003), the participants with autism required more time to initiate and execute their movements. Despite the small number of participants, there was a significant relationship between verbal ability and reaction time, verbal ability and movement time, as well as non-verbal ability and reaction time. In the present experiment the participants with higher verbal ability both initiated and completed their movements more quickly than the participants with lower verbal abilities. Participants with higher non-verbal ability also initiated their movements more quickly, however, the relationship with movement time was not significant. Once again, the number of participants was relatively low for performing a correlation analysis. However, the present results are similar to Mari et al. (2003) as there was a relationship between verbal ability (or level of functioning) and motor performance. Although the participants with higher verbal abilities perform the movements more quickly, there is still an overall and consistent difference between the participants with and without autism (see also Mari et al., 2003). The kinematic results from the present study begin to paint a picture of why their movements are slower.

Kinematics: Central Tendency

When looking at the movement kinematics, there were many differences between the participants with and without autism. The participants with autism reached about half the acceleration that the participants without autism did. In addition, the participants with autism scaled the acceleration to the length of their movements, (i.e., reached greater accelerations for longer movements), however, not to the same degree as the participants without autism. This same pattern was also evident for peak velocity. Given the differences in peak acceleration, it is not surprising that the participants with autism also reached lower peak velocities. In addition, these lower peak velocities were achieved later in the movement.

Although there were significant differences between the two groups of participants with regards to how long they took to reach peak velocity, there were no differences between the two groups for the displacement at peak velocity. It is encouraging because the time after peak velocity is typically associated with a greater degree of online control than the period before peak velocity (e.g., Elliott et al., 1999). Presumably, the closer the limb is to the target when it begins to decelerate the more effective the corrective process (Beggs & Howarth, 1972). Perhaps the individuals with autism kept their limb acceleration and velocity low to keep the variability in muscular forces low enough to perform accurate movements (i.e., hit the target). The lack of group differences for proportional time after peak velocity and displacement at peak velocity suggests that the overall structure of the movement is intact.

Kinematics: Trial-to-Trial Variability

In addition to performing the aiming movements much more slowly than the individuals without autism, the participants with autism were twice as variable in the amount of time taken to reach peak velocity, considerably more variable in the spatial location of peak acceleration, and somewhat more variable in the spatial location of peak velocity. The importance of these findings is that the initial ballistic phase of the movement is not nearly as consistent or repeatable for the individuals with autism as persons without autism, even though they are moving more slowly. This pattern of spatial and temporal variability may be related to the processes associated with the specification and timing of muscular force. This interpretation is consistent with the notion that persons with autism have specific difficulties with feedforward control (Schmitz et al., 2003). Because spatial variability increases with the absolute magnitude of the forces required to accelerate the limb (Meyer, Abrams, Kornblum, Wright, & Smith, 1988; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979), it may be that persons with autism generate less forceful movements to keep the variability associated with the initial phase of the movement under control (i.e., much lower peak acceleration and velocity). Movements to larger targets or of greater length typically require more force, and thus the variability over the initial phase of the movement was more pronounced under these conditions for the participants with autism. Certainly the accuracy results, the spatial variability results, as well as the time after peak velocity findings indicate that participants with autism were able to use visual and other sensory feedback to reduce the variability associated with the initial phase of the movement to hit the target. Thus, although their movements are characteristically slower, and more variable over the initial ballistic phase of movement execution (especially for movements of greater length, or to larger targets), individuals with autism were able to achieve the same endpoint accuracy as their chronologically aged matched peers.

Why Do Differences Exist?

The results suggest participants with autism did not spend any additional time approaching the target. Instead, the largest difference in the kinematics appeared to be in how consistently, and how quickly, the participants with autism reached peak velocity. It is possible that in young adulthood individuals with autism are unable to generate enough force to achieve more typical acceleration and velocity profiles. In conjunction with this, the variability in the time to reach peak velocity (or generate the muscular force) could result from inherent variability in the motor pathways. The fact that the participants with autism did not scale the velocity and acceleration to the length of their movements to the same degree as the participants without autism provides additional support for the view that these individuals have difficulty generating enough muscular force (i.e., movements with greater amplitude require more force).

As mentioned above, another possibility is the participants with autism reduced the speed of their movements to compensate for the initial variability of their movement. As Latash and Anson (1996) proposed, in many cases "abnormal" movements are not inherently different, but are a strategy developed by the nervous system to maximize performance within the given limitations of the system. In this context, individuals with autism may be able to move as quickly as their peers. However, persons with autism have learned to move more slowly to achieve the appropriate accuracy. A similar strategy has been noted in individuals with Down syndrome. The idea is that persons with DS perform their movements much more slowly than typically developing individuals as a conservative strategy to ensure they are able to accomplish the task. Almeida, Corcos, and Latash (1994) have shown that persons with DS are able to improve the acceleration, peak velocity, deceleration, and muscular activity of a simple elbow extension movement over multiple days of practice. This finding suggests that with practice persons with DS are capable of faster movements. As mentioned above, the lower acceleration and velocity profiles exhibited by the individuals with autism may be an attempt to minimize the variability associated with higher limb accelerations and velocities to achieve the required accuracy. It should be noted that the aiming trajectories of young adults in the two groups look very different. Specifically, persons with Down syndrome typically exhibit very asymmetric velocity and acceleration profiles, spending a great deal of the overall movement time after peak velocity. The deceleration phase of the movement is characterized by multiple discontinuities in the trajectory reflecting a strategic approach to the task that is highly feedback dependent (Hansen et al., 2005). In contrast, persons with autism exhibit trajectories that are very similar in space to typically developing persons. The main difference seems related to spatial and temporal variability early in the movement.

An additional interpretation of the slower and more variable ballistic movement is the participants with autism were not as influenced by the visual context of the movement (RT, peak velocity). For example, the size of the target did not impact RT or peak velocity to the same extent as the participants without autism. This finding is consistent with traditional views of autistic behavior. Specifically, persons with autism are thought to be naturally oriented to local attributes and not as influenced by the global context (e.g., Plaisted, Swettenham, & Rees, 1999). Therefore, another possibility for the lack of movement scaling on the part of the participants with autism is simply that the context of the movement did not impact how they performed the task. However, because they did scale their movement (just to a smaller degree), it seems more likely that they attempted to scale the movement appropriately but were not completely successful in doing so.

Summary and Future Directions

Overall, the results of the present study add to the growing evidence that motor skills and performance are atypical in young adults with autism. There is evidence that gross motor movements including walking and postural control are affected, as well as fine motor skills (Hallett et al., 1993; Martineau et al., 2004; Minshew et al., 2004; Miyahara et al., 1997; Molloy et al., 2003). The present results build on Mari et al's (2003) work and begin to address why movements performed by individuals with autism are reported to be clumsy in many situations. A consistent finding seems to be that persons with autism spend considerably more time preparing and executing manual movements. The kinematic analysis from the present study suggests that the slower movement times are primarily due to more time being spent to reach a lower peak velocity. What is not clear from the current results is the reason(s) for these differences.

In the future it will be necessary to encourage the participants with autism to move more quickly to differentiate between these two possibilities for the group differences in time to peak velocity, and overall movement initiation and execution time. By providing feedback about how quickly the movements are and providing incentives for moving faster (but only when the target is successfully acquired; see Elliott, Hansen, Mendoza, & Tremblay, 2004) it will be possible to explore how much voluntary control individuals with autism have over the speed of their movements. In addition, it would be possible to determine what the accuracy cost associated with a reduction in the time to initiate and execute simple aiming movements is for persons with autism.

Finally, mental age appears to be related to motor performance in some situations (Mari et al., 2003). However, more work is needed to determine if it is overall IQ, a specific aspect of IQ, or severity of autistic symptoms that is related to performance. The fact that only verbal ability (and not nonverbal ability) was related to movement time in the present study suggests that it may not be a simple relationship between IQ and motor skills. Further work is needed to clarify the reason(s) for this discrepancy. One possibility is both verbal ability and movement time are related to severity of autistic symptoms while non-verbal ability is related to planning capability. However, without full-scale IQ tests and a greater number of participants the proposed relationships are speculative. Regardless, the results of the present study provide further support for the position that problems with motor skills may be more of an issue for individuals with autism than originally thought. Given the relatively small number of participants, these results should be considered preliminary. However, considering the magnitude of the differences that were evident when performing very straightforward manual movements, it is not difficult to imagine how more complex mouth, eye, and hand movements would present a significant challenge for persons with autism.

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