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Sensorimotor learning and associated visual perception are intact but unrelated in autism spectrum disorder

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Number of text pages = 21
Number of tables = 2
Number of figures = 3

Abstract

Humans show an astonishing capability to learn sensorimotor behaviours. However, data from sensorimotor learning experiments suggest the integration of efferent sensorimotor commands, afferent sensorimotor information, and visual consequences of a performed action during learning is different in autism, leading to atypical representation of internal action models. Here, we investigated the generalisation of a sensorimotor internal action model formed during sensorimotor learning to a different, but associated, visual perception task. Although motor timing was generally less accurate in adults with autism, following practice with feedback both autistic adults, and controls, significantly improved performance of the movement sequence timing task by reducing timing error. In a subsequent perception task, both groups demonstrated similar temporal-discrimination accuracy (autism = 75%; control = 76%). Significant correlations between motor timing error, and temporal-discrimination during a perception task, was found for controls. No significant correlations were found for autistic adults. Our findings indicate that autistic adults demonstrated adaptation by reducing motor timing error through sensorimotor learning. However, the finding of significant correlations between motor timing error and temporal-discrimination accuracy in the control group only suggests sensorimotor processes underpinning internal action model formation operate differently in autism. **Lay Summary:** We showed autistic adults learned a new motor skill, and visually judged moving objects, to a similar level of accuracy as a control group. Unlike the control group, there was no relationship between how well autistic adults learned the motor skill, and how well they judged objects. The lack of a relationship might be one of the reasons autistic adults interact differently in the social world.

Key words: sensorimotor learning; internal action model; temporal-discrimination; autism

Introduction

Humans show an astonishing capability to learn a variety of sensorimotor behaviours ranging from using chopsticks, to cycling a mountain bike. The acquisition of such behaviours is based on learning to represent internal action models through the integration of self-generated efferent sensorimotor commands, afferent sensorimotor information, visual consequences of a performed action (Elliott et al., 2010; Shadmehr & Mussa-Ivaldi, 1994; Wolpert, Diedrichsen, & Flanagan, 2011), and terminal feedback regarding the movement outcome (Salmoni, Schmidt, & Walter, 1984). Following learning, acquired sensorimotor information is used during planning (efferent commands; e.g., specification of forces) to select appropriate internal action models required to execute goal-directed movements (Elliott et al., 2010). Internal action models also control (via efferent copy) ongoing movements by comparing what was predicted/expected, against online motor and sensory information. They also generalise to other contexts to support decision-making (Wolpert & Landy, 2012), where perception of movement related information performed by a person, or an object, is processed and compared against an internal action model (Aglioti, Cesari, Romani, & Urgesi, 2008; Blakemore & Decety, 2001) so that an appropriate sensorimotor response is selected.

Although these processes are operational in most of the population from a young age, individuals with autism spectrum disorder (henceforth autism) show wide-spread disturbances in sensorimotor behaviour (Cook, Blakemore, & Press, 2013; Gowen & Hamilton, 2013; Haswell, Izawa, Dowell, Mostofsky, & Shadmehr, 2009; Leary & Hill, 1996; Rinehart & McGinley, 2010; Teitelbaum, Teitelbaum, Nye, Fryman, & Maurer, 1998; Thompson et al., 2016). During motor planning, there is a deficit in predicting/anticipating the correct sensorimotor consequences of an executed motor action leading to execution atypicalities (Cattaneo et al., 2007; Fabbri-Destro, Cattaneo, Boria, & Rizzolatti, 2009; Hughes, 1996; Rinehart et al., 2006; Rinehart, Bradshaw, Brereton, & Tonge, 2001).

Executed movements are generally slower, and have greater spatial variability at peak velocity and peak acceleration (Glazebrook, Gonzalez, Hansen, & Elliott, 2009), which is a consequence of difficulties with integrating online visual feedback from the environment, with the efferent and reafferent motor information from the limb (Glazebrook et al., 2009; Mari, Castiello, Marks, Marraffa, & Prior, 2003). Increased variability during movement has also been found in the kinematic variable jerk, and because a greater magnitude of jerk is positively correlated with a greater atypical visual perception of biological motion, suggests autistic individuals might develop a specific sensorimotor system (via experience and learning) that influences how the underlying perception-action processes generalise to different contexts (Cook et al., 2013).

The aforementioned planning, variability and generalisation difficulties are reported from tasks examining motor control, and online motor execution, rather than sensorimotor learning. What is known from adaptation studies is the representation of internal action models following sensorimotor learning is intact in autism (Gidley Larson, Bastian, Donchin, Shadmehr, & Mostofsky, 2008). However, the generalisation of developed sensorimotor information seems to show atypical neural and behavioural specificity (Ament et al., 2015; Haswell et al., 2009; Marko et al., 2015; Nebel et al., 2015; Sharer et al., 2015). For example, autistic people showed superior performance when physically transferring acquired sensorimotor information based on intrinsic motor coordinates, rather than extrinsic visual coordinates (Haswell et al., 2009). The implication is that altered sensorimotor integration during learning leads to a prioritisation on proprioceptive feedback (Izawa et al., 2012), rather than the typical combination of proprioceptive and visual feedback. In the current work, we were interested in understanding whether generalisation is also compromised when an acquired action model forms the basis of making perceptual judgements towards objects that require the processing of information (e.g., timing) similar to that acquired during learning.

This is an important question as there is a bi-directional link between perception and action (Prinz, 1997) so altered sensorimotor integration during learning could lead to altered visual action recognition.

To this end, autistic adults and control adults performed a sensorimotor learning protocol where they practised a movement sequence timing task with knowledge-of-results provided as feedback. Following practice, feedback was removed in a retention test to examine sensorimotor learning. To examine our principal question, we correlated data from the sensorimotor learning task with findings from a perception task that required participants to observe and discriminate movements that displayed the same movement structure, but different absolute temporal parameters. We expected both groups to improve performance by reducing motor timing error across practice and thereby demonstrate sensorimotor learning in a retention test (Gidley Larson et al., 2008; Müller, Cauich, Rubio, Mizuno, & Courchesne, 2004). For temporal-discrimination during perception, which utilises learned sensorimotor internal action models to process and compare incoming visual information (Blakemore & Decety, 2001; Wolpert & Landy, 2012), we expected the control group to show a significant negative relationship with motor timing error (Casile & Giese, 2006; Hecht, Vogt, & Prinz, 2001). For the autism group, we expected a different or absent relationship between motor timing error and temporal-discrimination if atypical functioning of the sensorimotor process underpins sensorimotor learning and visual action recognition.

Method

Volunteers

Forty (20 autistic; 20 control) male adults volunteered for the study. Volunteers with autism were recruited from an autistic society in North West England, and host University. The volunteers were provided with a participant information sheet and selected if they

consented. The control participants were recruited from the host University. Participants had normal or corrected-to-normal vision and were screened via self-report for the following exclusion criteria: dyspraxia, dyslexia, epilepsy and other neurological or psychiatric conditions. Participants with autism had a diagnosis of autism, Asperger's syndrome or autism spectrum disorder by an independent clinician. Diagnosis was confirmed by a researcher trained (with research-reliability status) in the administration of module 4 of the Autism Diagnostic Observation Schedule 2 (ADOS-2) (Lord et al., 2000). Participants with autism met the threshold for autism spectrum disorder on the ADOS-2 total classification score, and on the communication and reciprocal social interaction subscales. Groups were equated for age, and using the Wechsler Abbreviated Scale of Intelligence (WASI-II) (Wechsler, 1999) matched for full-scale IQ, and the verbal and performance subscales. Sample characteristics are presented in Table 1. The experiment was designed in accordance with the 1964 Declaration of Helsinki and approved by the local research ethics committee.

Apparatus

Participants sat at a table at a viewing distance of approximately 555 mm from a 21-inch CRT monitor (Iiyama Vision Master 505) that operated at a resolution of 1280 x 1024 pixels and refresh rate of 85 Hz. The monitor was driven by a desktop PC (Dell Optiplex GX280), which was connected to graphics tablet (Wacom Intuos Pro XL) with a hand-held stylus (Figure 1a). Experimental stimuli were generated on the desktop PC using the COGENT toolbox (developed by John Romaya at the Laboratory of Neurobiology at the Wellcome Department of Imaging Neuroscience) implemented in MATLAB (Mathworks Inc.).

Sensorimotor Learning Task

All participants performed a familiarisation period, a practice-phase, a retention test, and a perception task. On entering a testing room, a participant was met by an investigator and asked to sit on a chair, in front of a table, where a computer monitor and graphics tablet were positioned. The participant received verbal information indicating the familiarisation period allowed the participant time to get used to the equipment and task. The participant was informed they could ask as many questions as they liked. The investigator showed the participant the task set-up containing the monitor, tablet and hand-held stylus. We did not measure handedness as this was not a primary manipulation in the study, but we did ask all participants to use their right-hand so that similar musculature was recruited across participants when making left-to-right movements on the tablet. Note, all 40 participants verbally indicated their hand preference was the right-hand. After receiving the hand-held stylus, the participant was provided with an opportunity to move the stylus on the tablet in a horizontal sinusoidal action so that a white cursor on the monitor moved in a corresponding direction. During this time, the experimenter highlighted to the participant the sensorimotor relationship between the white cursor presented on the monitor and the hand movement made with the stylus on the tablet. Once familiarised with the equipment, the participant was verbally informed they would complete three familiarisation trials in order to understand the nature of the to-be-learned movement sequence timing task. The participant was informed that a trial would begin with three red target circles being presented horizontally across the midline of the monitor (Figure 1a). To physically start a trial, the participant was informed that they should move the stylus so that the white cursor was positioned within the left-hand start target. Once positioned, the three targets turned green, and a trial could be commenced. The sequence was to move the cursor to hit the centre target (segment 1), followed by a reversal movement back to the start target (segment 2), and finally a reversal so that the

cursor moved back through the centre target in order to stop in the end target on the right-hand side of the display (segment 3) in order to exactly attain the timing goal of 1700 ms. All participants confirmed they understood the unit of time in milliseconds. The participant was informed the movement sequence timing task should be completed using the same sequence on every trial. To ensure a participant engaged in sensorimotor learning, he/she was informed that knowledge-of-results would be displayed on the monitor after each trial attempt (e.g., Too Fast or Too Slow by 98 ms; see Figure 1). All participants were verbally trained to process the feedback so that a movement response on trial n+1 was modified using the magnitude and direction of knowledge-of-results received on trial n (e.g., go slower by 98 ms). Finally, to ensure participants performed the correct spatial dimensions of the movement sequence timing task, an error message appeared on the monitor if the cursor did not pass through each target in the correct order (NB. all participants successfully performed the three familiarisation trials).

After the familiarisation period, participants performed the practice-phase by practising the movement sequence timing task for thirty trials. A trial commenced with the timing goal being displayed (i.e., Timing Goal = 1700 ms) at the centre of monitor for 2000 ms, after which it was replaced by the three red target circles. The trial followed the exact same procedure as the familiarisation period. Knowledge-of-results was provided after every trial. Fifteen minutes later, a retention test was conducted in order to measure sensorimotor learning. Participants completed six trials of the movement sequence timing task but without knowledge-of-results (NB. zero error trials were recorded during the practice phase or retention test).

Insert Figure 1 here.

Perception Task

Following the retention test, a perception task was carried out that involved all participants observing different pre-recorded models (e.g., model *n*) on the monitor. The models were generated by an experimenter and thus displayed human biological motion. The model was presented as a white cursor that followed the same movement path as that required to complete the motor sequence timing task performed during sensorimotor learning but with duration of +/- 200, 400, or 600 ms from the 1700 ms movement time goal. Accordingly, there were six models with duration of 1100, 1300, 1500, 1900, 2100 or 2300 ms. The perception task comprised a continuous sequence of 36 model demonstrations. Following the first observation of model *n* (Trial *n*; Figure 1b), a participant observed model *n*+1 (Trial *n*+1; Figure 1b) and was asked to make a temporal-discrimination (Answer; Figure 1b) as to whether the movement time (e.g., 1900 ms) was 'faster', 'slower', or the 'same' as model *n*. There was no requirement to estimate the duration of the absolute difference in milliseconds. Following the first pair (model *n* and model *n*+1), model *n*+1 became model *n*, and the procedure continued resulting in a total of thirty-five temporal-discrimination trials. The sequence of thirty-six models was structured into six blocks, which contained the six different movement time options, and these were fully randomised to control for order effects.

Data Reduction and Analysis

We quantified *total error* (E) to measure performance and learning (Badets, Blandin, & Shea, 2006) because this dependent variable best characterises overall accuracy at attaining the 1700 ms timing goal (Schmidt & Lee, 2011). The equation for E is: $E = \sqrt{(CE^2 + VE^2)}$, where CE is a measure of response bias (plus or minus the timing goal), computed as the average of the signed differences between actual total movement time and the timing goal, and VE is a measure of response variability, computed as the standard deviation of the signed

errors. We then calculated intra-participant means from the first six trials to represent the early phase of practice, and the last six trials to represent the late phase of practice. Individual-participant means were submitted to 2 Group (autism; control) x 2 Phase (early; late) repeated measures ANOVA. Significant main and/or interaction effects were decomposed using Tukey HSD post-hoc procedure. To examine learning effects, a mean calculated from the six retention test trials was analysed using a two-tailed independent-samples t-test. Alpha was set at $p < 0.05$. Partial eta squared (η_p^2) and Cohen's *d* expressed the size of the effect. Percentage change score [(*new* mean – *original* mean)/*original* mean) x 100] quantified the relative change in performance.

Temporal-discrimination performance during the perception task was quantified by totalling the number of correct responses for each participant. Groups were then compared using an independent samples t-test. Pearson's correlation coefficient was calculated to determine the relationship between timing error in the early, late and retention test phases of the sensorimotor learning task, and temporal-discrimination accuracy during the perception task.

Results

Sensorimotor Learning Task

The analyses conducted on total error revealed no group x phase interaction [$F(1, 38) = 1.53$, $p = 0.224$, $\eta_p^2 = 0.04$], but significant main effects were observed for phase [$F(1, 38) = 67.44$, $p = 0.001$, $\eta_p^2 = 0.64$] and group [$F(1, 38) = 7.89$, $p = 0.008$, $\eta_p^2 = 0.17$]. For the phase effect, total error reduced by 1173 ms (65%) leading to a significant improvement in timing performance between early and late phases (Figure 2). As illustrated in Table 2, the movement time data indicates that both groups were reasonably close to achieving the 1700

ms criterion timing goal in the Late phase. While the improvement was similar for both groups (control = 70%; autism = 62%), the significant group effect indicated that total error score was 362 ms lower in the control, than the autism, group. The significant difference between the groups remained [$t(38) = 3.89$, $p = 0.001$, $d = 1.12$] when knowledge-of-results was removed in the retention test, with the total error score for the control group being 422 ms lower than the autism group.

Insert Figure 2 here.

Perception Task

From a possible 35 correct responses, the autism group made 25 (SD = 3), and the control group made 26 (SD = 2), correct responses. Both groups [$t(28) = -0.52$, $p = 0.608$, $d = 0.39$] were equally successful (autism: M = 75%, SD = 10 %; control: M = 76%, SD = 7 %) at temporal-discrimination.

Relationship between sensorimotor learning and temporal-discrimination

There was no significant correlation between total error in the early phase of sensorimotor learning and temporal-discrimination accuracy for the autism ($r = -0.10$, $p = 0.331$) and control ($r = 0.00$, $p = 0.497$) groups (Figure 3a and b). Importantly, there was a significant negative correlation for the control group (Figure 3d and f) between total error in the late phase ($r = -0.49$, $p = 0.014$) and retention test ($r = -0.52$, $p = 0.009$) and temporal-discrimination accuracy. Control adults who demonstrated the lowest total error were the most accurate at temporal-discrimination during the perception task. For autistic adults, there was no significant correlation between total error and temporal-discrimination in the late phase ($r = 0.12$, $p = 0.322$) and retention test ($r = 0.11$, $p = 0.328$) (Figures 3c and e).

Insert Figure 3 here.

Discussion

The autism group significantly reduced total error across the practice phase, with a magnitude of change similar to the control group. This effect confirmed the development of an internal action model is intact in autism (Gidley Larson et al., 2008; Müller, Kleinhans, Kemmotsu, Pierce, & Courchesne, 2003). However, total error in the autism group was generally higher than the control group during practice, and remained so in retention when knowledge-of-results was removed (Fournier, Hass, Naik, Lodha, & Cauraugh, 2010; Ghaziuddin & Butler, 1998). Together, these findings indicate the functionality of the internal action model in autism was less effective than the control group. Indeed, it has been suggested that motor planning is compromised in autism (Hughes, 1996), with adults incorrectly specifying sensorimotor commands (Rinehart et al., 2006) leading to increased sensorimotor variability during motor execution (Glazebrook, Elliott, & Lyons, 2006; Glazebrook et al., 2009).

The general difference we observed in sensorimotor motor timing error during practice and retention for the autism group is likely to be underpinned by altered neural activity that occurs during sensorimotor sequence learning in autism (Müller et al., 2004). Compared to controls that showed reduced premotor activity consistent with neural adaptation across learning (Jenkins, Brooks, Nixon, Frackowiak, & Passingham, 1994), autistic adults showed enhanced activation. The differential recruitment was associated with scattered activation patterns that led to functional differences in learning processes in the autistic visuomotor system (Müller et al., 2004; Müller et al., 2003). Moreover, altered resting state synchrony in neural activation between visual (lateral occipital cortex) and motor

(pre- and post-central gyrus) regions (Nebel et al., 2015) is suggested to influence the integration of visuomotor information during sensorimotor learning (Ament et al., 2015; Haswell et al., 2009; Marko et al., 2015; Nebel et al., 2015; Sharer et al., 2015). This underpins the development of autism specific (Cook, 2016; Cook et al., 2013) internal action models that function differently when generalised to alternative sensorimotor contexts such as imitation (Haswell et al., 2009; Izawa et al., 2012).

Having confirmed the development of internal action models in autism and controls, we examined generalisation to an associated, rather than alternative (Izawa et al., 2012), context. Correlation analysis between total error and temporal-discrimination indicated no relationship in the early phase (r = 0.02) of practice for the control group. Importantly, there were significant negative correlations between total error and temporal-discrimination in the late phase (r = -0.49) and retention test (r = -0.52). Although these correlation data do not provide evidence of causality, where improved sensorimotor performance and learning led to enhanced temporal-discrimination accuracy, the significant relationships are consistent with data (Casile & Giese, 2006; Hecht et al., 2001; Press, Heyes, & Kilner, 2011) showing a bi-directional link between motor and sensory systems leading to superior perceptual judgements following sensorimotor learning. For example, during a perception task, the internal action model developed during sensorimotor learning might act as a forward model, with accuracy resulting from a mechanism (Kilner, Vargas, Duval, Blakemore, & Sirigu, 2004) that predicts the observed trajectory effect based on experience of the trajectory (Kilner, Friston, & Frith, 2007).

There were no significant correlations between total error and temporal-discrimination across the early phase (r = -0.10), late phase (r = 0.12) and retention test (r = 0.11) for the autism group. Therefore, despite exhibiting adaptation across sensorimotor learning, the resulting internal action model did not facilitate temporal-discrimination

accuracy. The finding of low magnitude positive correlations in the late phase and retention test suggests the action-perception mechanism underpinning sensorimotor learning functions differently in autism. Although our correlation analyses do not infer causality, the lack of a relation between the two variables is consistent with work showing a different relationship between the behavioural and neuropsychological effects of sensorimotor learning, and action-observation in autism (Dziuk et al., 2007; Haswell et al., 2009; Nebel et al., 2015). Specifically, although autistic children showed functional sensorimotor adaption, the generalisation of these effects to an associated motor transfer test was different to controls, and indicated a bias to processing proprioceptive information. Atypical generalisation to an action-observation context was also demonstrated such that greater deficits in motor generalisation correlated with greater deficits in social functioning and imitation (Haswell et al., 2009; Izawa et al., 2012).

Here it is important to recognise the autism group (75%) performed to a similar level of accuracy as the control group (76%) when discriminating temporal differences between two consecutive visual targets displaying biological trajectories with temporal durations ranging from 1100ms to 2300ms. The range of temporal durations examined here is similar to that found to be judged accurately by adults with autism during psychophysiological assessments of timing (Allman, DeLeon, & Wearden, 2011). Our findings from the discrimination task are therefore unlikely to be a simple consequence of the temporal duration of our task. This is supported by the previous finding that autistic adults can accurately discriminate the temporal difference (i.e., 50 ms) between a pair of auditory tones, but are significantly less accurate than controls when learning a sensorimotor sequence task (Mostofsky, Goldberg, Landa, & Denckla, 2000). A reasonable explanation of differential effects for sensorimotor learning and temporal perception in autism and controls is that internal action models may form only a part of a mechanism that links action to perception

and underpins recognition (Blakemore & Decety, 2001). Processes underlying weak central coherence (Frith & Happe, 1994; Happe & Frith, 2006) or superior visual search (O'Riordan, Plaisted, Driver, & Baron-Cohen, 2001; Plaisted, O'Riordan, & Baron-Cohen, 1998a, 1998b) might be engaged as a complementary mechanism(s) in autism. These mechanisms operate at a perceptual-cognitive level and underpin processes that enhance the ability to discriminate local motion perception (Happé & Vital, 2009), and/or superiority in detail-focused (Baron-Cohen, Ashwin, Ashwin, Tavassoli, & Chakrabarti, 2009) processing between stimulus.

In sum, our findings demonstrate motor timing performance was significantly adapted in autistic adults through trial and error processing of sensorimotor information and knowledge-of-results. Although this indicates intact sensorimotor adaptation, there was evidence the resulting sensorimotor learning effects were different to the control group. This was confirmed by the finding of a significant correlation between motor timing error and temporal-discrimination accuracy in the control group only. Sensorimotor processes underpinning internal action model formation would appear to operate differently in autism.

References

Aglioti, S. M., Cesari, P., Romani, M., & Urgesi, C. (2008). Action anticipation and motor resonance in elite basketball players. *Nature Neuroscience, 11*(9), 1109-1116. doi:nature.com/neuro/journal/v11/n9/suppinfo/nn.2182_S1.html

Allman, M. J., DeLeon, I. G., & Wearden, J. H. (2011). Psychophysical Assessment of Timing in Individuals With Autism. *American Journal on Intellectual and Developmental Disabilities, 116*(2), 165-178. doi:doi:10.1352/1944-7558-116.2.165

Ament, K., Mejia, A., Buhlman, R., Erklin, S., Caffo, B., Mostofsky, S. H., & Wodka, E. (2015). Evidence for specificity of motor impairments in catching and balance in children with autism. *Journal of Autism and Developmental Disorders, 45*, 742-751.

Badets, A., Blandin, Y., & Shea, C. H. (2006). Intention in motor learning through observation. *Quarterly Journal of Experimental Psychology, 59*(2), 377-386. doi:10.1080/02724980443000773

Baron-Cohen, S., Ashwin, E., Ashwin, C., Tavassoli, T., & Chakrabarti, B. (2009). Talent in autism: hyper-systemizing, hyper-attention to detail and sensory hypersensitivity. *Philosophical Transactions of the Royal Society B: Biological Sciences, 364*(1522), 1377-1383. doi:10.1098/rstb.2008.0337

Blakemore, S. J., & Decety, J. (2001). From the perception of action to the understanding of intention. *Nature Reviews Neuroscience, 2*(8), 561-567.

Casile, A., & Giese, M. A. (2006). Nonvisual Motor Training Influences Biological Motion Perception. *Current Biology, 16*(1), 69-74. doi:doi.org/10.1016/j.cub.2005.10.071

Cattaneo, L., Fabbri-Destro, M., Boria, S., Pieraccini, C., Monti, A., Cossu, G., & Rizzolatti, G. (2007). Impairment of actions chains in autism and its possible role in intention understanding. *Proceedings of the National Academy of Sciences, 104*(45), 17825-17830. doi:10.1073/pnas.0706273104

Cook, J. (2016). From movement kinematics to social cognition: the case of autism. *Philosophical Transactions of the Royal Society of London B: Biological Sciences, 371*(1693). doi:10.1098/rstb.2015.0372

Cook, J., Blakemore, S.-J., & Press, C. (2013). Atypical basic movement kinematics in autism spectrum conditions. *Brain, 136*(9), 2816-2824. doi:10.1093/brain/awt208

Dziuk, M. A., Gidley Larson, J. C., Apostu, A., Mahone, E. M., Denckla, M. B., & Mostofsky, S. H. (2007). Dyspraxia in autism: association with motor, social, and communicative deficits. *Developmental Medicine & Child Neurology, 49*(10), 734-739. doi:10.1111/j.1469-8749.2007.00734.x

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

Fabbri-Destro, M., Cattaneo, L., Boria, S., & Rizzolatti, G. (2009). Planning actions in autism. *Experimental Brain Research, 192*(3), 521-525. doi:10.1007/s00221-008-1578-3

Fournier, K., Hass, C., Naik, S., Lodha, N., & Cauraugh, J. (2010). Motor Coordination in Autism Spectrum Disorders: A Synthesis and Meta-Analysis. *Journal of Autism and Developmental Disorders, 40*(10), 1227-1240. doi:10.1007/s10803-010-0981-3

Frith, U., & Happe, F. (1994). Autism: beyond "theory of mind". *Cognition, 50*(1-3), 115-132.

Ghaziuddin, M., & Butler, E. (1998). Clumsiness in autism and Asperger syndrome: a further report. *Journal of Intellectual Disability Research, 42*(1), 43-48. doi:10.1046/j.1365-2788.1998.00065.x

Gidley Larson, J. C., Bastian, A. J., Donchin, O., Shadmehr, R., & Mostofsky, S. H. (2008). Acquisition of internal models of motor tasks in children with autism. *Brain, 131*(11), 2894-2903. doi:10.1093/brain/awn226

Glazebrook, C. M., Elliott, D., & Lyons, J. (2006). A kinematic analysis of how young adults with and without autism plan and control goal-directed movements. *Motor control, 10*(3), 244-264.

Glazebrook, C. M., Gonzalez, D., Hansen, S., & Elliott, D. (2009). The role of vision for online control of manual aiming movements in persons with autism spectrum disorders. *Autism, 13*(4), 411-433. doi:Doi 10.1177/1362361309105659

Gowen, E., & Hamilton, A. F. d. C. (2013). Motor Abilities in Autism: A Review Using a Computational Context. *Journal of Autism and Developmental Disorders, 43*(2), 323-344. doi:10.1007/s10803-012-1574-0

Happe, F., & Frith, U. (2006). The Weak Coherence Account: Detail-focused Cognitive Style in Autism Spectrum Disorders. *Journal of Autism and Developmental Disorders, 36*(1), 5-25. doi:10.1007/s10803-005-0039-0

Happé, F., & Vital, P. (2009). What aspects of autism predispose to talent? *Philosophical Transactions of the Royal Society B: Biological Sciences, 364*(1522), 1369-1375. doi:10.1098/rstb.2008.0332

Haswell, C. C., Izawa, J., Dowell, L. R., Mostofsky, S. H., & Shadmehr, R. (2009). Representation of internal models of action in the autistic brain. *Nature Neuroscience, 12*(8), 970-972. doi:nature.com/neuro/journal/v12/n8/suppinfo/nn.235

Hecht, H., Vogt, S., & Prinz, W. (2001). Motor learning enhances perceptual judgment: a case for action-perception transfer. *Psychological Research, 65*(1), 3-14. doi:10.1007/s004260000043

Hughes, C. (1996). Brief report: Planning problems in autism at the level of motor control. *Journal of Autism and Developmental Disorders, 26*(1), 99-107. doi:10.1007/BF02276237

Izawa, J., Pekny, S. E., Marko, M. K., Haswell, C. C., Shadmehr, R., & Mostofsky, S. H. (2012). Motor Learning Relies on Integrated Sensory Inputs in ADHD, but Over-Selectively on Proprioception in Autism Spectrum Conditions. *Autism Research, 5*(2), 124-136. doi:10.1002/aur.1222

Jenkins, I., Brooks, D., Nixon, P., Frackowiak, R., & Passingham, R. (1994). Motor sequence learning: a study with positron emission tomography. *The Journal of Neuroscience, 14*(6), 3775-3790.

Kilner, J. M., Friston, K. J., & Frith, C. D. (2007). The mirror-neuron system: a Bayesian perspective. *Neuroreport, 18*(6), 619-623.

Kilner, J. M., Vargas, C., Duval, S., Blakemore, S.-J., & Sirigu, A. (2004). Motor activation prior to observation of a predicted movement. *Nature Neuroscience, 7*(12), 1299-1301. doi:nature.com/neuro/journal/v7/n12/suppinfo/nn1355_S1.html

Leary, M. R., & Hill, D. A. (1996). Moving on: autism and movement disturbance. *Mental Tetardation, 34*(1), 39-53.

Lord, C., Risi, S., Lambrecht, L., Cook, E., Jr., Leventhal, B., DiLavore, P., . . . Rutter, M. (2000). The Autism Diagnostic Observation Schedule—Generic: A Standard Measure of Social and Communication Deficits Associated with the Spectrum of Autism. *Journal of Autism and Developmental Disorders, 30*(3), 205-223. doi:10.1023/A:1005592401947

Mari, M., Castiello, U., Marks, D., Marraffa, C., & Prior, M. (2003). The reach–to–grasp movement in children with autism spectrum disorder. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, 358*(1430), 393-403. doi:10.1098/rstb.2002.1205

Marko, M. K., Crocetti, D., Hulst, T., Donchin, O., Shadmehr, R., & Mostofsky, S. H. (2015). Behavioural and neural basis of anomalous motor learning in children with autism. *Brain, 138*(3), 784-797. doi:10.1093/brain/awu394

Mostofsky, S. H., Goldberg, M. C., Landa, R. J., & Denckla, M. B. (2000). Evidence for a deficit in procedural learning in children and adolescents with autism: Implications for cerebellar contribution. *Journal of the International Neuropsychological Society, 6*(07), 752-759. doi:doi:null

Müller, R.-A., Cauich, C., Rubio, M. A., Mizuno, A., & Courchesne, E. (2004). Abnormal activity patterns in premotor cortex during sequence learning in autistic patients. *Biological Psychiatry, 56*(5), 323-332. doi:doi.org/10.1016/j.biopsych.2004.06.007

Müller, R.-A., Kleinhans, N., Kemmotsu, N., Pierce, K., & Courchesne, E. (2003). Abnormal Variability and Distribution of Functional Maps in Autism: An fMRI Study of

Visuomotor Learning. *American Journal of Psychiatry, 160*(10), 1847-1862. doi:10.1176/appi.ajp.160.10.1847

Nebel, M. B., Eloyan, A., Nettles, C. A., Sweeney, K. L., Ament, K., Ward, R. E., . . . Mostofsky, S. H. (2015). Intrinsic Visual-Motor Synchrony Correlates With Social Deficits in Autism. *Biological Psychiatry*. doi:dx.doi.org/10.1016.

O'Riordan, M. A., Plaisted, K. C., Driver, J., & Baron-Cohen, S. (2001). Superior visual search in autism. *Journal of Experimental Psychology: Human Perception and Performance, 27*(3), 719-730.

Plaisted, K., O'Riordan, M., & Baron-Cohen, S. (1998a). Enhanced Discrimination of Novel, Highly Similar Stimuli by Adults with Autism During a Perceptual Learning Task. *Journal of Child Psychology and Psychiatry, 39*(5), 765-775. doi:10.1111/1469-7610.00375

Plaisted, K., O'Riordan, M., & Baron-Cohen, S. (1998b). Enhanced Visual Search for a Conjunctive Target in Autism: A Research Note. *The Journal of Child Psychology and Psychiatry and Allied Disciplines, 39*(05), 777-783. doi:doi:null

Press, C., Heyes, C., & Kilner, J. M. (2011). Learning to understand others' actions. *Biology Letters, 7*(3), 457-460. doi:10.1098/rsbl.2010.0850

Prinz, W. (1997). Perception and action planning. *European Journal of Cognitive Psychology, 9*(2), 129-154.

Rinehart, N. J., Bellgrove, M. A., Tonge, B. J., Brereton, A. V., Howells-Rankin, D., & Bradshaw, J. L. (2006). An examination of movement kinematics in young people with high-functioning autism and Asperger's disorder: Further evidence for a motor planning deficit. *Journal of Autism and Developmental Disorders, 36*(6), 757-767. doi:DOI 10.1007/s10803-006-0118-x

Rinehart, N. J., Bradshaw, J., Brereton, A., & Tonge, B. (2001). Movement Preparation in High-Functioning Autism and Asperger Disorder: A Serial Choice Reaction Time Task Involving Motor Reprogramming. *Journal of Autism and Developmental Disorders, 31*(1), 79-88. doi:10.1023/A:1005617831035

Rinehart, N. J., & McGinley, J. (2010). Is motor dysfunction core to autism spectrum disorder? *Developmental Medicine & Child Neurology, 52*(8), 697-697.

Salmoni, A. W., Schmidt, R. A., & Walter, C. B. (1984). Knowledge of results and motor learning: a review and critical reappraisal. *Psychological Bulletin, 95*(3), 355-386.

Schmidt, R. A., & Lee, T. D. (2011). *Motor control and learning: A behavioral emphasis* (5th ed.): Human Kinetics, Champaign, IL.

Shadmehr, R., & Mussa-Ivaldi, F. A. (1994). Adaptive representation of dynamics during learning of a motor task. *The Journal of Neuroscience, 14*(5), 3208-3224.

Sharer, E., Crocetti, D., Muschelli, J., Barber, A. D., Nebel, M. B., Caffo, B. S., . . . Mostofsky, S. H. (2015). Neural Correlates of Visuomotor Learning in Autism. *Journal of Child Neurology*. doi:10.1177/0883073815600869

Teitelbaum, P., Teitelbaum, O., Nye, J., Fryman, J., & Maurer, R. G. (1998). Movement analysis in infancy may be useful for early diagnosis of autism. *Proceedings of the National Academy of Sciences, 95*(23), 13982-13987. doi:10.1073/pnas.95.23.13982

Thompson, A., Murphy, D., Dell'Acqua, F., Ecker, C., McAlonan, G., Howells, H., . . . Lombardo, M. V. (2016). Impaired Communication Between the Motor and Somatosensory Homunculus Is Associated With Poor Manual Dexterity in Autism Spectrum Disorder. *Biological Psychiatry, 81*(3), 211-219. doi:10.1016/j.biopsych.2016.06.020

Wechsler, D. (1999). *Wechsler Abbreviated Scales of Intelligence (WASI).* San Antonio, TX: Psychological Corporation.

Wolpert, D. M., Diedrichsen, J., & Flanagan, J. R. (2011). Principles of sensorimotor learning. *Nature Reviews Neuroscience, 12*(12), 739-751. doi:10.1038/nrn3112

Wolpert, D. M., & Landy, M. S. (2012). Motor control is decision-making. *Current Opinion in Neurobiology, 22*(6), 996-1003. doi:DOI 10.1016/j.conb.2012.05.003

Tables

Table 1. Participant characteristics of the autism and control groups.

	Autism (N = 20)		Control (N = 20)		
	Mean (SD)	Range	Mean (SD)	Range	*p* value
Chronological Age	26 (7)	18-44	25 (8)	18-45	0.539
IQ: Full Scale	108 (8)	92-119	109 (7)	94-123	0.556
IQ: Verbal	107 (11)	88-130	110 (8)	98-125	0.277
IQ: Performance	106 (10)	91-128	105 (11)	82-124	0.824
ADOS: Total	9 (2)	7-16			
ADOS: Communication	3 (1)	2-6			
ADOS: Social Interaction	6 (2)	4-10			
Gender	20 M: 0 F		20 M: 0 F		

Table 2. Mean (SD) movement time (ms) data presented as a function of group and phase.

	Early Mean (SD)	Late Mean (SD)	Retention Mean (SD)
Autism	2967 (744)	2164 (467)	2322 (468)
Control	2457 (428)	1899 (270)	1928 (247)

Figure Captions

Figure 1. (a) A schematic representation of the movement sequence timing task that has a timing goal of 1700 ms. The sequence was presented as three red targets (diameter = 12 mm) and is depicted by the arrows in Segment 1 (start target to centre target), Segment 2 (centre target to start target), and Segment 3 (start target to end target). The target positions had an equidistant extent of 100 mm between the centre of each target. The white circle depicts the cursor (diameter = 6 mm) and represents the motion of the hand-held stylus drawn on the monitor. Feedback on the CRT monitor represents knowledge-of-results provided to the participant in ms. **(b)** A schematic representation of the perception task. The white circle represents the model. The movement sequence is depicted by the three targets. An example trial is outlined by Trial Timeline arrow.

Figure 2. Mean total error presented as a function of group and phase (** $p < 0.001$).

Figure 3. Correlation between total error (y axis) in the early phase **(a, b)**, late phase **(c, d)** and retention test **(e, f)** of sensorimotor learning and number of correct responses (x axis) during temporal-discrimination.

Figure 1.

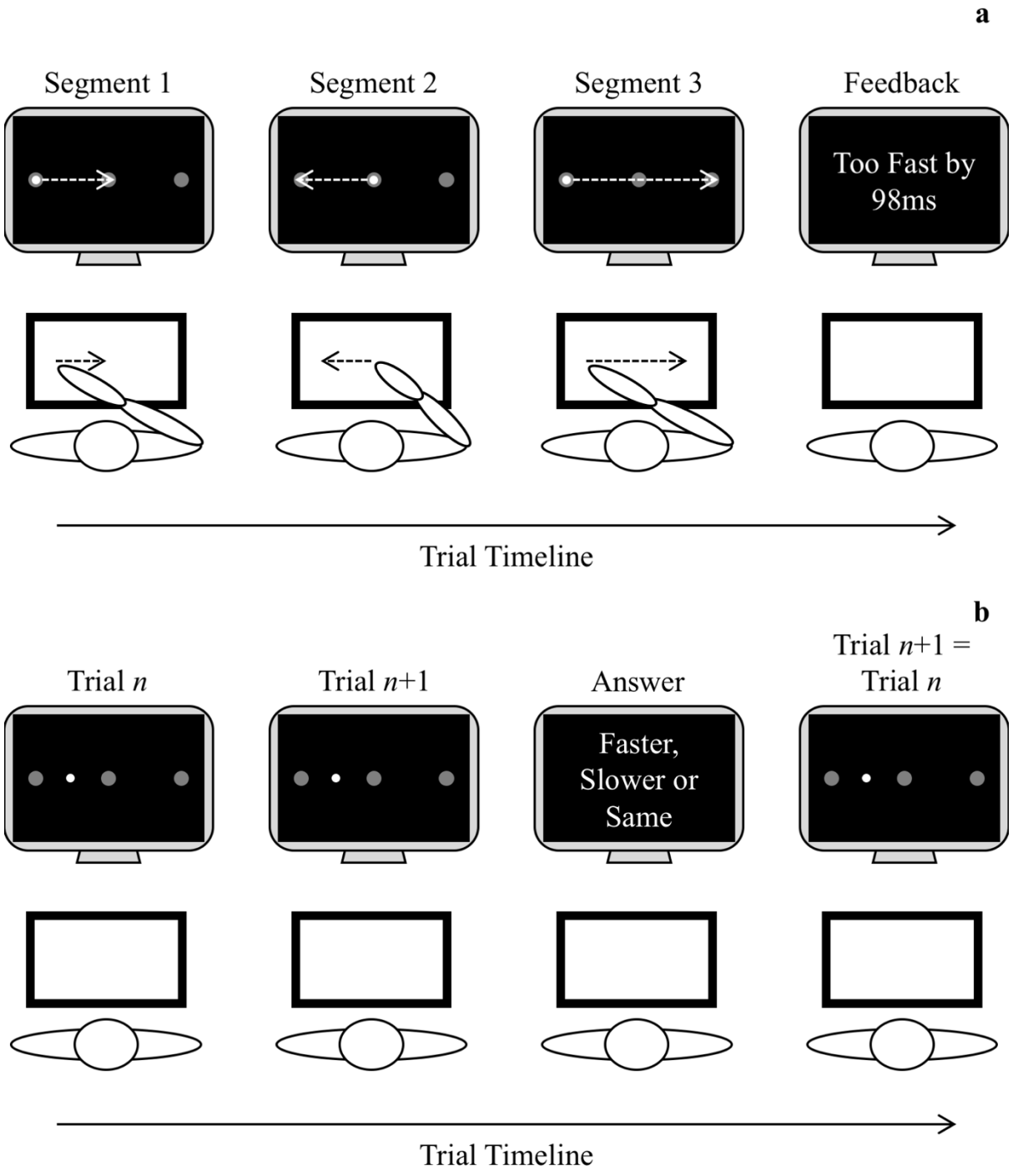

a
Segment 1
Segment 2
Segment 3
Feedback
Too Fast by 98ms
Trial Timeline
b
Trial n
Trial n+1
Answer
Trial n+1 = Trial n
Faster, Slower or Same
Trial Timeline

Figure 2.

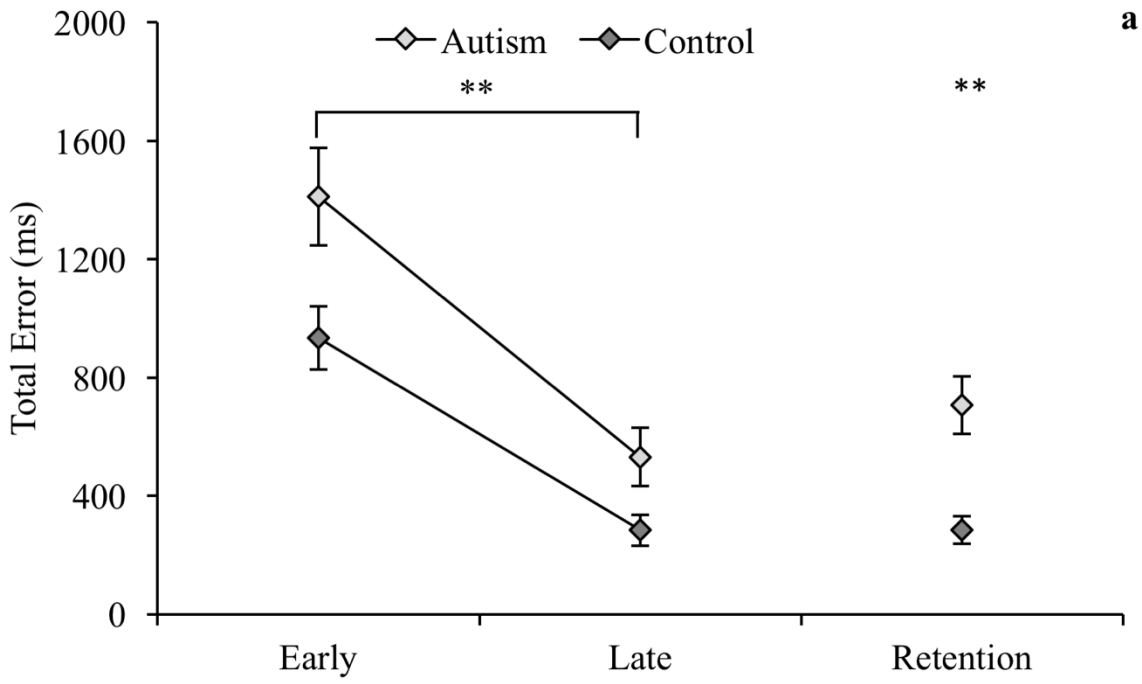
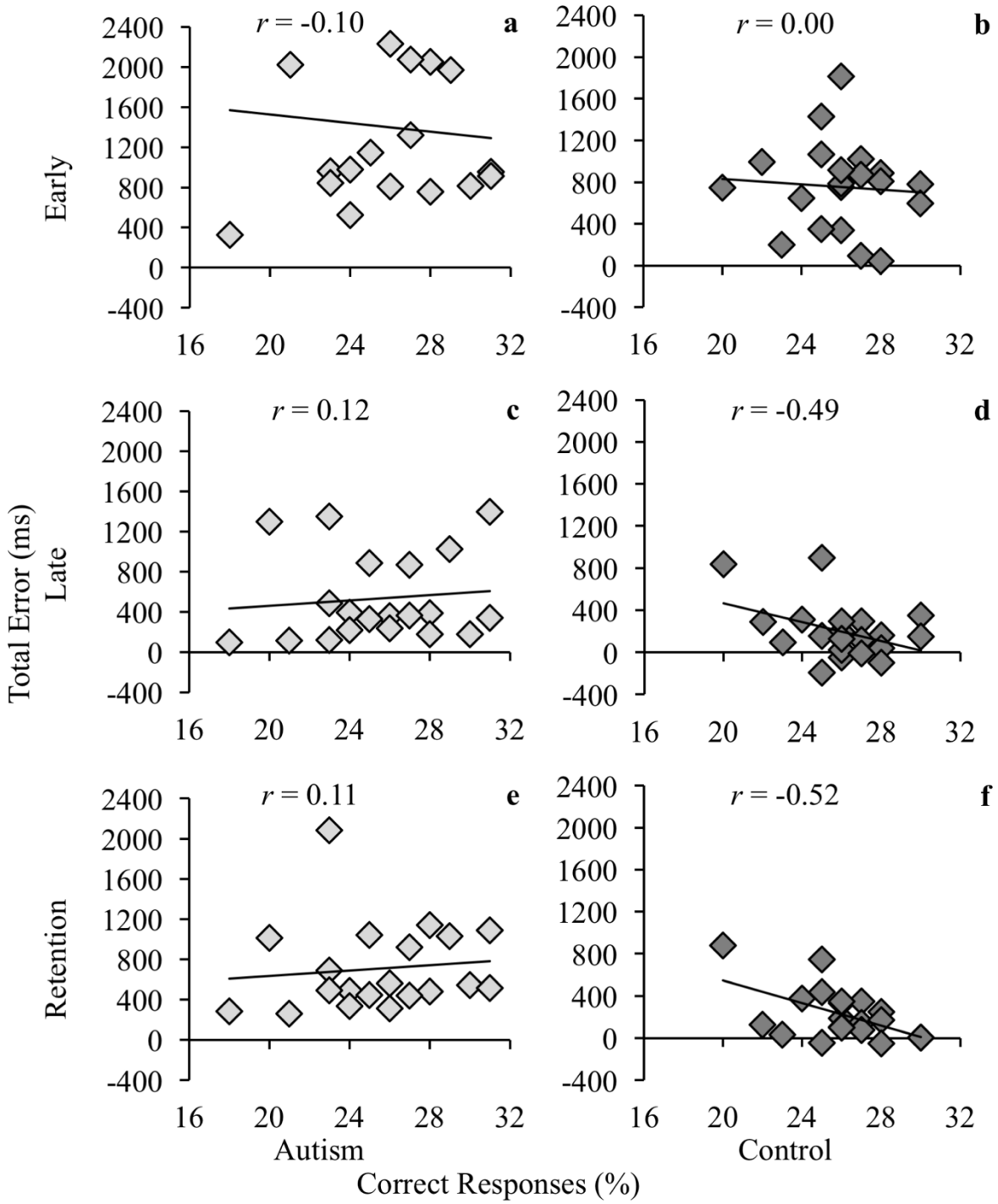

a
Autism
Control
**
**
Total Error (ms)
2000
1600
1200
800
400
0
Early
Late
Retention

Figure 3.


r = -0.10
a
r = 0.00
b
r = 0.12
c
r = -0.49
d
r = 0.11
e
r = -0.52
f
Early
Late
Retention
Total Error (ms)
2400
2000
1600
1200
800
400
0
-400
16
20
24
28
32
Autism
Control
Correct Responses (%)