

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

1 **Introduction**

2 Humans show an astonishing capability to learn a variety of sensorimotor behaviours ranging
3 from using chopsticks, to cycling a mountain bike. The acquisition of such behaviours is
4 based on learning to represent internal action models through the integration of self-generated
5 efferent sensorimotor commands, afferent sensorimotor information, visual consequences of
6 a performed action (Elliott et al., 2010; Shadmehr & Mussa-Ivaldi, 1994; Wolpert,
7 Diedrichsen, & Flanagan, 2011), and terminal feedback regarding the movement outcome
8 (Salmoni, Schmidt, & Walter, 1984). Following learning, acquired sensorimotor information
9 is used during planning (efferent commands; e.g., specification of forces) to select
10 appropriate internal action models required to execute goal-directed movements (Elliott et al.,
11 2010). Internal action models also control (via efferent copy) ongoing movements by
12 comparing what was predicted/expected, against online motor and sensory information. They
13 also generalise to other contexts to support decision-making (Wolpert & Landy, 2012), where
14 perception of movement related information performed by a person, or an object, is processed
15 and compared against an internal action model (Aglioti, Cesari, Romani, & Urgesi, 2008;
16 Blakemore & Decety, 2001) so that an appropriate sensorimotor response is selected.

17 Although these processes are operational in most of the population from a young age,
18 individuals with autism spectrum disorder (henceforth autism) show wide-spread
19 disturbances in sensorimotor behaviour (Cook, Blakemore, & Press, 2013; Gowen &
20 Hamilton, 2013; Haswell, Izawa, Dowell, Mostofsky, & Shadmehr, 2009; Leary & Hill,
21 1996; Rinehart & McGinley, 2010; Teitelbaum, Teitelbaum, Nye, Fryman, & Maurer, 1998;
22 Thompson et al., 2016). During motor planning, there is a deficit in predicting/anticipating
23 the correct sensorimotor consequences of an executed motor action leading to execution
24 atypicalities (Cattaneo et al., 2007; Fabbri-Destro, Cattaneo, Boria, & Rizzolatti, 2009;
25 Hughes, 1996; Rinehart et al., 2006; Rinehart, Bradshaw, Brereton, & Tonge, 2001).

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

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

1 *Sensorimotor Learning Task*

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

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

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

23
24 Insert Figure 1 here.
25

1 *Perception Task*

2 Following the retention test, a perception task was carried out that involved all
3 participants observing different pre-recorded models (e.g., model n) on the monitor. The
4 models were generated by an experimenter and thus displayed human biological motion. The
5 model was presented as a white cursor that followed the same movement path as that required
6 to complete the motor sequence timing task performed during sensorimotor learning but with
7 duration of +/- 200, 400, or 600 ms from the 1700 ms movement time goal. Accordingly,
8 there were six models with duration of 1100, 1300, 1500, 1900, 2100 or 2300 ms. The
9 perception task comprised a continuous sequence of 36 model demonstrations. Following the
10 first observation of model n (Trial n ; Figure 1b), a participant observed model $n+1$ (Trial
11 $n+1$; Figure 1b) and was asked to make a temporal-discrimination (Answer; Figure 1b) as to
12 whether the movement time (e.g., 1900 ms) was ‘faster’, ‘slower’, or the ‘same’ as model n .
13 There was no requirement to estimate the duration of the absolute difference in milliseconds.
14 Following the first pair (model n and model $n+1$), model $n+1$ became model n , and the
15 procedure continued resulting in a total of thirty-five temporal-discrimination trials. The
16 sequence of thirty-six models was structured into six blocks, which contained the six different
17 movement time options, and these were fully randomised to control for order effects.

18 19 *Data Reduction and Analysis*

20 We quantified *total error* (E) to measure performance and learning (Badets, Blandin,
21 & Shea, 2006) because this dependent variable best characterises overall accuracy at attaining
22 the 1700 ms timing goal (Schmidt & Lee, 2011). The equation for E is: $E = \sqrt{(CE^2 + VE^2)}$,
23 where CE is a measure of response bias (plus or minus the timing goal), computed as the
24 average of the signed differences between actual total movement time and the timing goal,
25 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 $[(new\ mean - original\ mean)/original\ mean] \times 100$ 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, Kleinhan, 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

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

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

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Tables

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

	Autism (N = 20)		Control (N = 20)		<i>p</i> value
	Mean (SD)	Range	Mean (SD)	Range	
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	Late	Retention
	Mean (SD)	Mean (SD)	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.

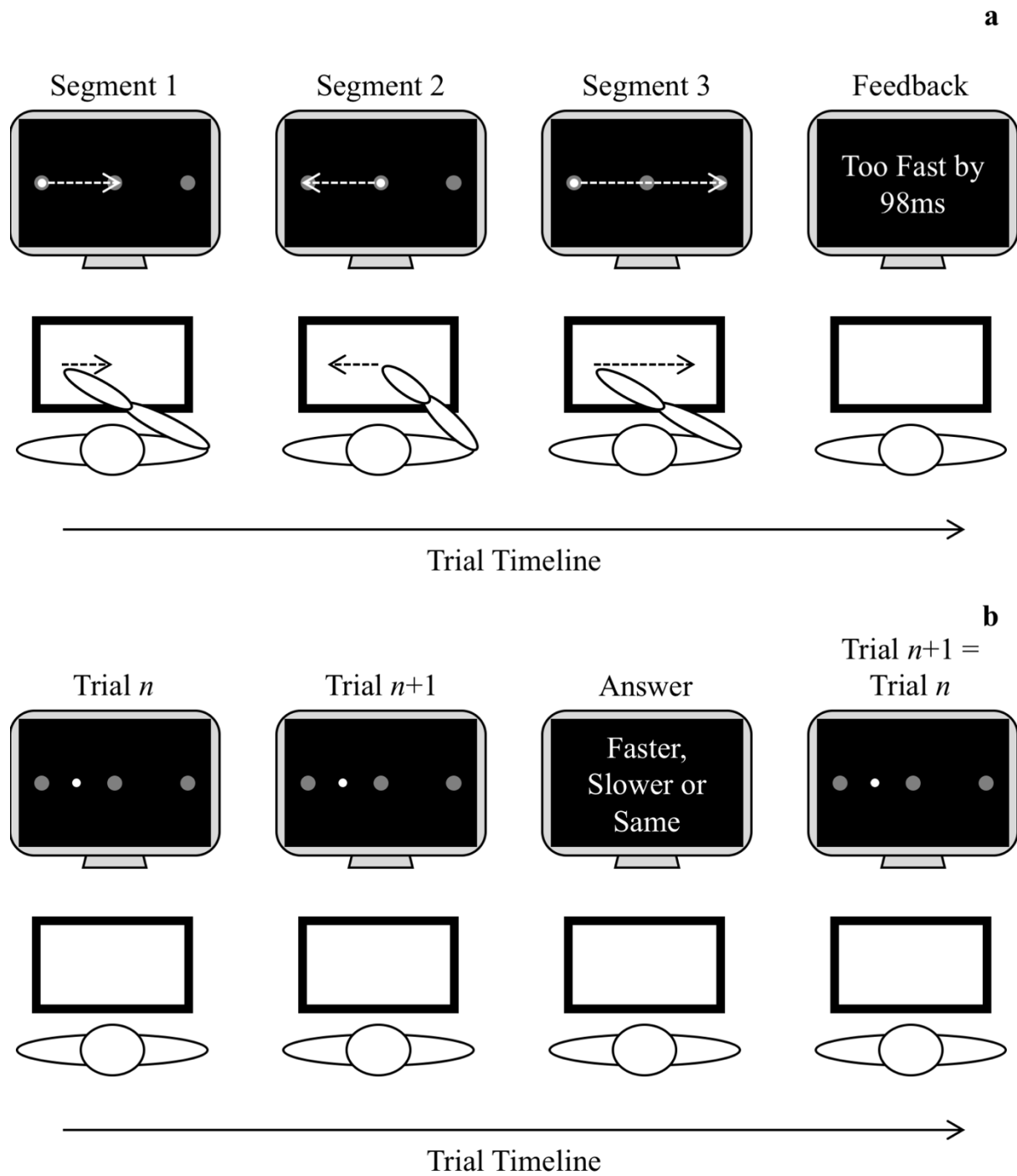


Figure 2.

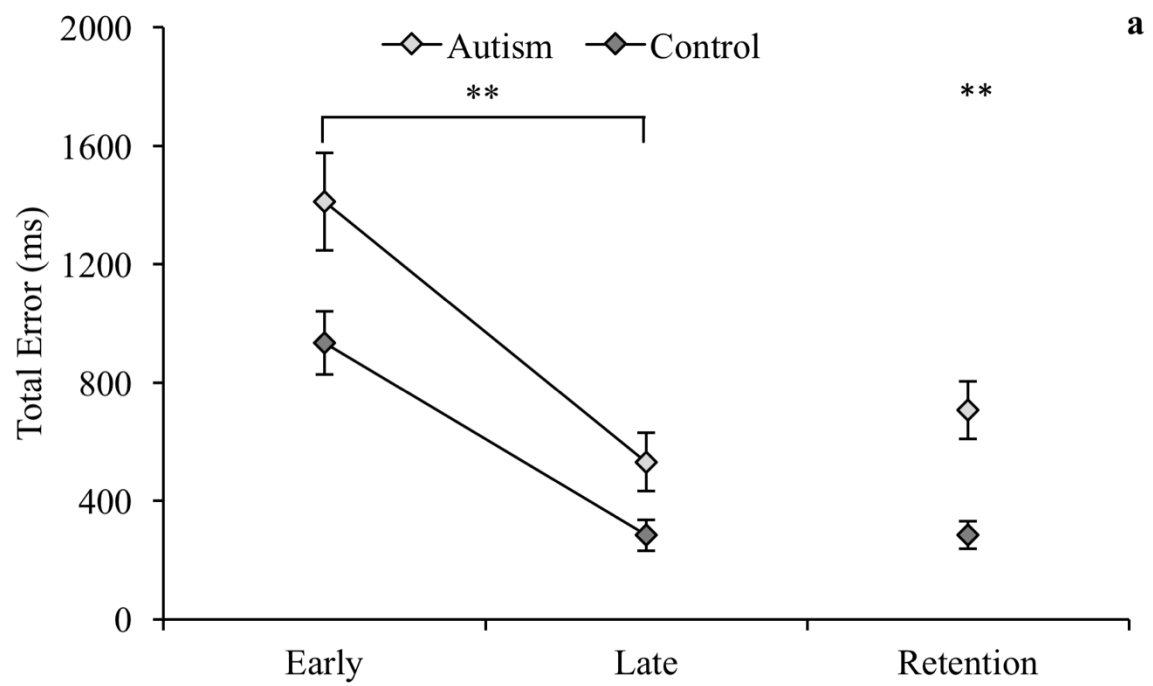


Figure 3.

