

Isolating Visual and Proprioceptive Components of Motor Sequence Learning in ASD

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In addition to defining impairments in social communication skills, individuals with autism spectrum disorder (ASD) also show impairments in more basic sensory and motor skills. Development of new skills involves integrating information from multiple sensory modalities. This input is then used to form internal models of action that can be accessed when both performing skilled movements, as well as understanding those actions performed by others. Learning skilled gestures is particularly reliant on integration of visual and proprioceptive input. We used a modified serial reaction time task (SRTT) to decompose proprioceptive and visual components and examine whether patterns of implicit motor skill learning differ in ASD participants as compared with healthy controls. While both groups learned the implicit motor sequence during training, healthy controls showed robust generalization whereas ASD participants demonstrated little generalization when visual input was constant. In contrast, no group differences in generalization were observed when proprioceptive input was constant, with both groups showing limited degrees of generalization. The findings suggest, when learning a motor sequence, individuals with ASD tend to rely less on visual feedback than do healthy controls. Visuomotor representations are considered to underlie imitative learning and action understanding and are thereby crucial to social skill and cognitive development. Thus, anomalous patterns of implicit motor learning, with a tendency to discount visual feedback, may be an important contributor in core social communication deficits that characterize ASD. *Autism Res* 2015,0:000–000. © 2015 International Society for Autism Research, Wiley Periodicals, Inc.

Keywords: serial reaction time task; ASD; motor learning; proprioception

Introduction

Generation of internal models of action, or sensorimotor representations, is critical to social, communicative, and motor skill acquisition. Recently, our understanding of altered motor development in autism spectrum disorder (ASD) and its relationship to anomalous sensorimotor representations and the core deficit of social communication [APA, 2013] has substantially increased.

Motor function difficulties in ASD are evident in infancy [Teitelbaum et al., 1998; Landa, 2008], persist into adulthood [Dziuk et al., 2007; Jansiewicz et al., 2006; Suter et al., 2007], and effectively distinguish children with ASD from healthy controls (HC) and children with other developmental disabilities [Ament et al., 2015; MacNeil & Mostofsky, 2012; Whyatt & Craig, 2012]. Furthermore, children with ASD struggle identifying representations of gestures accurately [Dowell, Mahone, & Mostofsky, 2009]. Sensorimotor repre-

sentation when learning novel movements may play a causative role with motor function and social communication deficits.

Sensorimotor representations form during basic motor skill development. Procedural learning is implicit skill acquisition through repeated exposure and practice in which an individual's motor command is associated with sensory feedback [Squire, 1986; Willingham, Nissen, & Bullemer, 1989]. This association produces a sensorimotor representation, during action observation, enabling interpretation of meaning from another's actions through self-other mapping [Klin, Jones, Schultz, & Volkmar et al., 2003; Mattar & Gribble, 2005; Rizzolatti, Fogassi, & Gallese, 2002]. Procedural learning underlies social, communicative, and motor skill acquisition. Atypical motor skill development may lead to atypical sensorimotor representations [Gidley-Larson & Mostofsky, 2008; Klinger & Dawson, 2001; Walenski, Mostofsky, Gidley-Larson, & Ullman, 2008].

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Table 1. Participant Characteristics

Subject	Diagnosis	Age	Gender	FSIQ	VIQ	PIQ
A1	PDD-NOS	33	M	117	117	114
A2	AS	18	M	73	67	83
A3	AS	25	F	128	132	118
A4	AS	42	M	124	131	111
A5	AS	54	F	128	121	129
A6	PDD-NOS	64	M	117	111	119
A7	PDD-NOS	56	M	94	75	119
A8	AS	50	M	124	121	119
A9	AS	62	M	134	131	129
A10	AS	64	M	140 ^a		
A11	AS	19	M	127	121	126
A12	AS	20	M	96	103	89
A13	PDD-NOS	21	M	120	109	128
A14	Autism	17	M	81	82	84
A15	AS	62	M	123	118	121
A16	AS	24	M	123	113	127
A17	AS	22	M	110	119	117
A18	AS	44	M	102	83	91
C1		53	F			
C2		47	M			
C3		26	F			
C4		32	M			
C5		19	M			
C6		39	M			
C7		61	M			
C8		19	M			
C9		21	F			
C10		19	F			
C11		64	F			

^a FSIQ was acquired from clinical report that did not contain subscales

Models formed from an atypical system have far reaching consequences in this framework.

Converging evidence suggests visual and proprioceptive sensory processing systems leveraged in manual gesture procedural learning are utilized to varying degrees in ASD. ASD adults perform worse at object identification than controls when the task requires visual-temporal integration [Nakano, Ota, Kato, & Kitazawa, 2010] and perform better when similar tasks require somatomotor (haptic) integration [Nakano, Kato, & Kitazawa, 2012]. Furthermore, studies examining visual and proprioceptive contributions to motor adaptation in controls, ASD, and ADHD children consistently reveal anomalous patterns of motor learning, with increased reliance on proprioceptive input and decreased reliance on visual input in ASD children [Haswell, Izawa, Dowell, Mostofsky, & Shadmehr, 2009; Izawa et al., 2012; Marko et al., 2015]. These biases are strongly associated with motor and social deficits in ASD [Haswell et al., 2009; Izawa et al., 2012]. Divergent motor learning biases may put complex skills necessary for adaptive social-communicative behavior at a developmental disadvantage.

Consistent with past motor adaptation studies, we hypothesize that individuals with ASD will show anomalous motor sequence learning using a modified version of Nissen and Bullemer's [1987] serial reaction time task (SRTT). Previous SRTT studies demonstrate ASD participants have impaired implicit motor sequence learning [Gidley-Larson & Mostofsky, 2008; Mostofsky, Goldberg, Landa, & Denckla, 2000], although findings are not consistent throughout the field [Gordon & Stark, 2007; Travers, Klinger, Mussey, & Klinger, 2010]. Discrepancies across studies may reflect differences in *how* ASD participants perform the task, such as sensory biases, rather than overall ability, for acquiring motor sequences. We used a modified SRTT to examine generalization of learned sequences across hemispheres in visual versus proprioceptive coordinates [Cohen, Pascual-Leone, Press, & Robertson, 2005], and hypothesized the ASD group would demonstrate differences in learning patterns reflecting enhanced generalization from proprioceptive input and impaired generalization from visual input.

Methods

Participants

Thirty-five adults participated in this study. Three participants were excluded for left-hand dominance and an additional three for having incomplete task data. Data were analyzed from the remaining 18 ASD participants (16 male, 38.72 ± 18.362 years SD) and 11 controls (6 male, 36.36 ± 17.42 years SD). Diagnosis was determined by an independent clinician using DSM-IV criteria. Handedness was defined using the Edinburgh Handedness Inventory [Oldfield, 1971]. IQ in the ASD cohort was assessed using the WASI [Wechsler, 1999] (See samples characteristics in Table 1). Participants were recruited through approved advertisements on community bulletin boards and a local ASD organization's site: The Asperger/Autism Network.

Paradigm

A modified SRTT assessed visual and proprioceptive motor generalization components in procedural learning. Tasks were introduced to participants as reaction time (RT) tests. Certain task sections contained a repeating sequence to be implicitly learned. Throughout the task, a circular stimulus (diameter 20 mm) would appear in one of four positions on a Dell Latitude D831 laptop with a 15.3 in display, corresponding to one of four buttons on a Cedrus RB-410 response pad. Participants situated 800 mm away from the screen were instructed to respond by pressing the appropriate button when stimuli appeared. Following a correct response, a 400 ms interval passed before the next

stimulus presentation. Stimuli remained on screen until a correct response appeared. The task was coded, performed, and recorded using SuperLab 2 [Cedrus Corporation, 2010]. Motor sequence learning was assessed by comparing RTs during the last sequence and random blocks. Only correct responses were included in analyses. Participants were trained using their dominant right hand and tested using their untrained hand, similar to Cohen et al. [2005]. Generalization of learning from trained to untrained hand was used as a probe of reliance on visual and proprioceptive input [Cohen et al., 2005; Masterton & Biederman, 1983; Willingham, 1998].

The experiment was divided into two sessions with a break in between. Each session had two right-hand training periods, one short and one long. A test period followed during which participants used the left hand to perform the same task with the original sequence in one session and the mirror of the original sequence in the other. Visual-based generalization using external coordinates was assessed using the original sequence during the test period. Thus, the visual goal remained constant from the training phase but required a different motor pattern when performed by the left rather than the right hand. Proprioceptive-based generalization using internal coordinates was assessed using the mirrored sequence during the test period. This configuration maintained the same motor pattern as the trained hand while changing the visual input (see Fig. 1 for experimental setup). Session order was randomized within groups. For each participant, two unique sequences were randomly assigned to either the visual or proprioceptive SRTT sessions to avoid sequence-learning effects across sessions.

The short training, long training, and test periods of each session had a 50-trial random block before and after the sequence trial blocks. Random blocks contained pseudo-random sequences with no repeats. The 400-trial long training period sequence block contained 25 repetitions of the 12-trial sequence (300 trials). The 280-trial short training period and test period sequence blocks contained 15 repetitions of the same 12-trial sequence (180 trials).

Data Analysis

Learning occurs when RT decreases in sequenced trials and increases, or rebounds, upon the random sequence reintroduction. Rebound disambiguates sequence specific learning from general task adaptation. Learning scores were calculated by subtracting the average correct RT of the last 50 trials of the sequence block from the average correct RT from the 50 trials of the subsequent random block during the test period. Trials that fell below 200 ms or beyond 2.7 standard deviations

[Cohen et al., 2005; Cohen & Robertson, 2007] of the mean were removed from learning score calculation to eliminate anticipatory errors and attention lapses.

Differences in motor generalization during visual and proprioceptive sessions between groups were assessed using a repeated measures two-way ANOVA on learning scores. Planned simple effect comparisons were used to assess group differences in visual-based and proprioceptive-based skill learning scores.

Results

Groups were matched on age ($t[27] = 0.775$, $P = 0.445$, $d = 0.298$) but not gender ($X^2 = 4.398$, $P = 0.036$, $\phi = 0.389$). Age and performance were not significantly correlated (G: $r = -0.071$, $P = 0.713$; M: $r = 0.060$, $P = 0.758$) across groups or within groups. Error rates were low in both groups (ASD: $M = 6.21\%$, $SD = 4.90\%$; HC: $M = 7.95\%$, $SD = 7.88\%$) with no significant between-group differences ($t[96] = -1.610$, $P = 0.111$, $d = 0.329$). Removed RTs as anticipatory errors or attention lapses only encompassed 1.07% of all data and did not significantly differ across groups ($t[172] = 0.277$, $P = 0.781$, $d = 0.0422$). Baseline RT during the initial random block of each condition did not differ between groups ($t[27] = 0.208$, $P = 0.262$, $d = 0.460$). Both groups demonstrated sequence learning: across training periods the average sequenced trial performance was significantly faster than average random trial performance (ASD: $t[17] = -2.692$, $P = 0.015$; HC: $t[10] = -3.369$, $P = 0.007$).

For both test conditions, overall RT for all blocks did not differ between groups (Visual: $F[1,27] = 1.929$, $P = 0.176$, $\eta_p^2 = 0.067$; Proprioceptive: $F[1,27] = 1.069$, $P = 0.310$, $\eta_p^2 = 0.038$). A repeated measures two-way ANOVA, with motor component (visual, proprioceptive) as the within-subject factor and diagnostic group (controls, ASD) as the between-subject factor, revealed a significant interaction effect between motor component and group membership on learning score ($F[1,27] = 11.06$, $P = 0.003$, $\eta_p^2 = 0.291$). The significant motor component effect on learning scores ($F[1,27] = 5.626$, $P = 0.025$, $\eta_p^2 = 0.172$) is explained by the significant simple effect of motor component ($t[10] = 3.52$, $P = 0.006$, $d = 1.06$) in controls and not ASD participants ($t[17] = -0.787$, $P = 0.442$, $d = -0.186$). There was no main effect of diagnosis on learning score ($F[1,27] = 1.197$, $P = 0.284$, $\eta_p^2 = 0.042$).

Follow-up analyses of skill component learning scores revealed controls showed greater improvement from sequence learning than ASD participants ($t[27] = 2.765$, $P = 0.010$, $d = 1.23$) during the visual component. Single-sample t-tests revealed only controls showed a visual learning score significantly different from zero (HC: $t(10) = 4.650$, $P = 0.001$, $d = 2.941$; ASD: $t(17) = -0.259$,

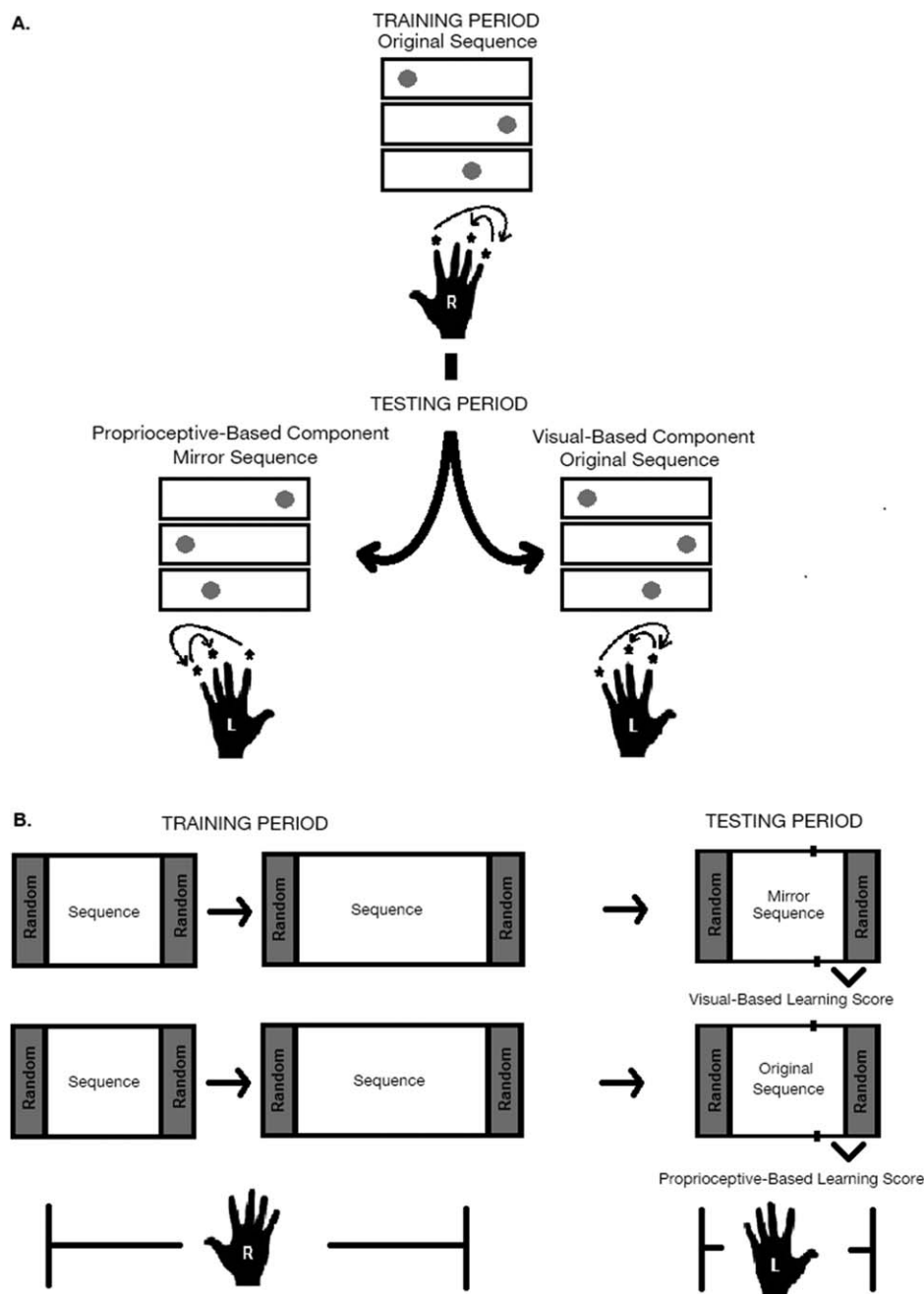


Figure 1. Experimental Design. (A) Design used to isolate motor learning components. Participants implicitly learn a sequence of visual cues (i.e., -1-4-3) and series of finger movements (i.e., -index-pinky-ring) from embedded repeating patterns of stimuli during the training period. The right hand was trained and the learning effects that transferred to the left hand were tested. Visual and proprioceptive configurations of the test period were used to decompose motor learning. Using the left hand while maintaining the visual sequence (i.e., -1-4-3) requires different finger movements (i.e., -pinky-index-middle) and provides a measure of the visual-based component of motor learning. Alternatively, mirroring the visual sequence (i.e., -4-1-2) requires the same finger movements on the new hand (i.e., -index-pinky-ring) and provides a measure of the proprioceptive component of motor learning. (B) Each participant had two configurations of the SRTT. Both had two training periods, short and long, using the right hand and a final test period using the left hand. Within each period random trials (grey blocks) bookended the sequence trials (white blocks). The motor learning score, an assessment of skill transferred to the untrained hand, was calculated using the last 50 random trials and last 50 sequence trials of the test period.

$P = 0.799$, $d = -0.126$). The two groups do not significantly differ during the proprioceptive component [$t(27) = -0.711$, $P = 0.483$, $d = 0.270$], and neither group

had a movement learning score significantly different from zero (HC: $t[10] = -0.486$, $P = 0.637$, $d = -0.310$; ASD: $t[17] = 0.508$, $P = 0.618$, $d = 0.246$) (Fig. 2).

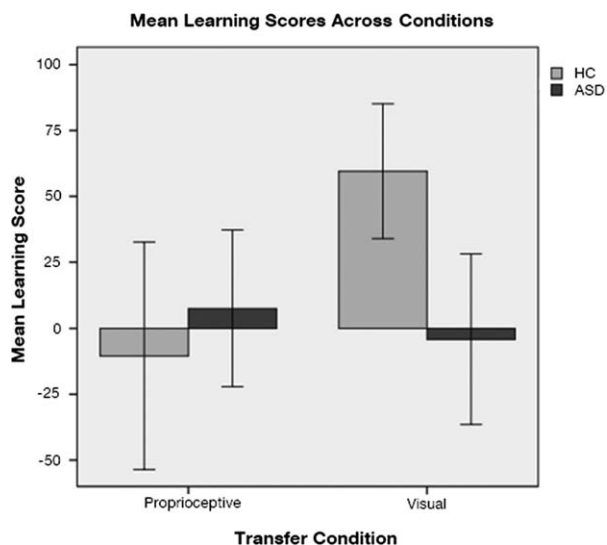


Figure 2. Learning Score Results. Visual and proprioceptive motor learning was tested for each participant. Results showed that the healthy control group demonstrated significantly better generalization of visual motor learning than the ASD group. While only the healthy controls' visual learning scores significantly differed from 0, neither group's demonstrated generalization of proprioceptive motor learning.

Discussion

Results from this study partially confirm our hypotheses. Both groups demonstrated sequence learning during training and were adequately engaged throughout the task. Controls utilized extrinsic-visual aspects from training to generalize the learned sequence to the untrained hand; however, ASD participants did not utilize this component to the same advantage. In contrast, neither group showed an ability to utilize the proprioceptive component for motor sequence generalization to the untrained hand.

Our findings are, in part, consistent with those from motor adaptation studies [Haswell et al., 2009; Izawa et al., 2012; Marko et al., 2015], suggesting ASD participants under-utilize visual input during motor learning. However, ASD participants are not at an advantage for proprioceptive input in this study. This may be due to limitations in sample size, as indicated by the variability within each population and inability to match for gender. Alternatively, our task may fail to capture proprioceptive capability. Our control findings are consistent with Kirsch & Hoffman [2010], who found visual, not proprioceptive, motor learning transfers to the left hand. Training the nondominant left hand and transferring to the right hand improved transfer of proprioceptive motor learning but not the visual component. Thus, a right to left transfer design may have biased the findings in favor of visual component transfer of learning. Lastly, insufficient training may have also reduced

experimental sensitivity to proprioceptive motor learning. Results from previous studies suggest visual and proprioceptive motor skill learning are simultaneously acquired [see Hikosaka, Nakamura, Sakai, & Nakahara, 2002 for review], yet at different rates and using different neural substrates [Bapi, Doya, & Harner, 2000]. The visual component develops faster and is utilized early in learning while the proprioceptive component develops more slowly. Proposed future research include addressing these limitations and including a more detailed behavioral characterization in order to evaluate how these differences may relate to specific behavioral phenotypes.

It should be noted that ASD-associated difficulties with motor sequence learning has also been explored using oculomotor learning tasks. Slower predictive saccade latency for an anticipated stimuli [Goldberg et al., 2002] and slower systemic error correction during adaptation [Mosconi et al., 2013; Johnson et al., 2012] were found and could help explain our impaired visual-motor transfer findings in ASD. However, given that the oculomotor system lacks proprioceptive feedback, relative biases in sensory feedback during motor learning are best explored using limb motor tasks, such as used in this study and prior studies of limb motor adaptation [Haswell et al., 2009; Izawa et al., 2012; Marko et al., 2015].

In summary, consistent with our hypothesis, our findings reveal controls generalized learning in visual external coordinate system to a greater degree than ASD participants. Visuomotor representations are considered to underlie imitative learning and action understanding and are thereby crucial to both social skill and social cognitive development. It follows that anomalous patterns of procedural learning may be an important contributor in the development of core social communication deficits that characterize ASD.

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