RESEARCH ARTICLE

Seeing a Page in a Flipbook: Shorter Visual Temporal Integration Windows in 2-Year-Old Toddlers with Autism Spectrum Disorder

Julie Freschl, David Melcher, Alice Carter, Zsuzsa Kaldy, and Erik Blaser

Individuals with autism spectrum disorder (ASD) experience differences in visual temporal processing, the part of vision responsible for parsing continuous input into discrete objects and events. Here we investigated temporal processing in 2-year-old toddlers diagnosed with ASD and age-matched typically developing (TD) toddlers. We used a visual search task where the visibility of the target was determined by the pace of a display sequence. On *integration* trials, each display viewed alone had no visible target, but if integrated over time, the target became visible. On *segmentation* trials, the target became visible only when displays were perceptually segmented. We measured the percent of trials when participants fixated the target as a function of the stimulus onset asynchrony (SOA) between displays. We computed the crossover point of the integration and segmentation performance functions for each group, an estimate of the *temporal integration window* (TIW), the period in which visual input is combined. We found that both groups of toddlers had significantly longer TIWs (125 ms) than adults (65 ms) from previous studies using the same paradigm, and that toddlers with ASD had significantly shorter TIWs (108 ms) than chronologically age-matched TD controls (142 ms). ***Autism Res*** *2020, 00: 1–13*. © 2020 International Society for Autism Research and Wiley Periodicals LLC

Lay Summary: We investigated how young children, with and without autism, organize dynamic visual information across time, using a visual search paradigm. We found that toddlers with autism had higher temporal resolution than typically developing (TD) toddlers of the same age – that is, they are more likely to be able to detect rapid change across time, relative to TD toddlers. These differences in visual temporal processing can impact how one sees, interprets, and interacts with the world.

Keywords: visual temporal processing; toddlers; integration; segmentation; autism; temporal integration window

Introduction

Temporal processing determines how the visual system organizes dynamic perceptual information into meaningful objects, scenes, and events. To accomplish this, it balances two complementary goals: *integration* to construct rich, stable representations and *segmentation* to resolve brief events [Blake & Lee, 2005]. Integration and segmentation occur at many levels throughout the brain, from flicker fusion in the retina [Gorea, 2015; Kalloniatis & Luu, 2007], which reaches adult levels in early infancy [Hartmann & Banks, 1992], to episodic memory in the medial temporal structures [Nyberg, McIntosh, Houle, Nilsson, & Tulving, 1996], which is still maturing into late childhood [Ghetti & Bunge, 2012]. In this study, we target mid-level vision processes involved in parsing input into meaningful patterns and forms [Freschl, Melcher, Kaldy, & Blaser, 2019; Wutz & Melcher, 2014; Wutz, Muschter, van Koningsbruggen, Weisz, & Melcher, 2016]; those processes parse the fractionated, dynamic images of a flipbook into a coherent story.

In typical development, it has been shown that 6- to 15-month-old infants have lower visual temporal resolution (relatively poor segmentation) as compared to adults [Farzin, Rivera, & Whitney, 2011a], with segmentation thresholds around 1000–2000 ms in infants (6- and 15-month-olds, respectively) and 100 ms in adults – suggesting infants are more tuned to integrate visual information across time. Then, by around 5 years of age, temporal processing reaches adult levels, suggesting a finer tuning toward perceiving rapid change across time [Arnett & Di Lollo, 1979; Freschl et al., 2019; Hogben, Rodino, Clark, & Pratt, 1995]. Any differences in temporal processing may perturb perceptual and cognitive processes that rely on well-adapted timing, such as object individuation [Drewes, Zhu, Wutz, & Melcher, 2015; Wutz & Melcher, 2014], multisensory integration [Wallace & Stevenson, 2014], visual working memory [Wutz & Melcher, 2013, 2014], apparent motion [Fairhall, Albi, & Melcher, 2014], motion perception [Milne, Swettenham, & Campbell, 2005], face processing [Evers, Steyaert, Noens, & Wagemans, 2015; Uljarevic & Hamilton, 2013], action sequence perception,

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and action planning [Faivre & Koch, 2014], potentially influencing social skills such as turn-taking in joint tasks or in conversation [Schirmer, Meck, & Penney, 2016; Trevarthen & Daniel, 2005]; differences that could contribute to developmental trajectories in autism spectrum disorder (ASD).

It is important, then, to study these perceptual differences since they may affect ASD etiology and "downstream" social and cognitive processes. Previous work on perceptual processing has focused on differences in visual *spatial* organization in ASD [Mottron, 2019; Robertson & Baron-Cohen, 2017]. These differences have been framed by the Weak Central Coherence (WCC) theory, which highlights a bias toward detail as opposed to global gist [Frith, Happé, 1994; Happé & Frith, 2006], and Enhanced Perceptual Function (EPF), which highlights superior local processing as opposed to an inability to process global information (local processing should be thought of as a default mode, and global organization optional) [Mottron & Burack, 2001; Mottron, Dawson, Soulières, Hubert, & Burack, 2006]. That said, empirical findings have been inconsistent, with some studies finding enhanced local processing at the expense of global processing [Shah & Frith, 1983, 1993], and others finding no difference in processing global information [Caron, Mottron, Berthiaume, & Dawson, 2006; Evers, Van der Hallen, Noens, & Wagemans, 2018; Mottron et al., 2006; Simmons et al., 2009]. Indeed, a recent meta-analysis of 56 studies revealed no significant findings of superior local processing nor impaired global processing in autism overall [Van der Hallen, Evers, Brewaeys, Van den Noortgate, & Wagemans, 2015]. Instead, the authors argued that it may actually be *temporal* factors that underlie apparent spatial processing differences: individuals with autism may take longer to process global information. The current study focuses on the early development of the temporal aspects of perceptual organization and tests whether young children with ASD organize visual information across time differently than their typically developing (TD), age-matched peers.

Temporal Processing in Autism

Results on temporal processing of perceptual information in autism so far have been inconclusive. A useful way to characterize temporal processing is in terms of a "Temporal Integration Window" (TIW), the period in which (visual) input is combined into a singular percept [Arnett & Di Lollo, 1979; Freschl et al., 2019; Hogben et al., 1995; Wutz et al., 2016]: if two events fall within the same TIW, they are integrated; if they fall in different temporal windows, they are segmented (shorter TIWs, then, facilitate perceiving rapid change while longer TIWs support information accrual). Across previous work, one can find evidence for longer temporal windows associated with autism, shorter windows, and evidence for no difference. For instance, in a study of multisensory integration [see Wallace and Stevenson, 2014, for a review], Kawakami, Uono, Otsuka, Zhao, and Toichi [2020] found that adults with high autistic traits (as measured by the Autism Quotient score) had more narrow windows that were better able to detect an asynchrony between a visual flash and an auditory beep. However, in that same study, no differences were found in *unisensory* visual (or auditory) asynchrony thresholds, suggesting visual TIWs are not different in adults with high autistic traits (it is important to note that these findings may only be relevant to individuals with high autistic traits without an autism diagnosis). Whereas other studies found atypical multisensory integration for low-level visual information (e.g. flashes and beeps) in individuals with an ASD diagnosis [Bao, Doobay, Mottron, Collignon, & Bertone, 2017; Charbonneau et al., 2020; Collignon et al., 2013; Ostrolenk, Bao, Mottron, Collignon, & Bertone, 2019] – which may be explained by longer temporal windows [Foss-Feig et al., 2010; Kwakye, Foss-Feig, Cascio, Stone, & Wallace, 2011; Stevenson et al., 2014]. Nakano, Ota, Kato, and Kitazawa [2010] measured visual integration in adults with and without ASD (with average-to-high intelligence), using a vertical slit viewing paradigm where targets (familiar objects) moved behind a narrow slit. They found that the ASD group had significantly lower performance (measured by mean rates of correct recognition of each familiar object) than typical controls. This result is consistent with the ASD group having shorter temporal windows. In contrast, Peiker and colleagues [Peiker et al., 2015] used the same vertical slit paradigm and found no significant differences between adults diagnosed with ASD and neurotypical adults. Falter and colleagues [Falter, Elliott, & Bailey, 2012] measured segmentation using a perceptual simultaneity paradigm where subjects judged whether a pair of bars had changed luminance simultaneously or asynchronously, as a function of temporal offset, and found that adults and adolescents with ASD had lower visual simultaneity thresholds (the longest offset at which the bars still appeared to be changing simultaneously), suggesting shorter temporal windows.

The studies discussed so far have focused on adults; there are only a handful of studies that systematically measured visual temporal processing in autism during development. Again here, results vary. *Multisensory* windows were found to be disadvantageously long in children diagnosed with autism, for both simple, non-speech-related flashes and beeps [de Boer-Schellekens, Eussen, & Vroomen, 2013; Kwakye et al., 2011], and complex, speech-related stimuli [Bebko, Weiss, Demark, & Gomez, 2006; Stevenson et al., 2014]. *Unisensory* visual windows, however, when tested within those same studies [Kwakye et al., 2011; Stevenson et al., 2014], were found not to be different. Farzin, Rivera, and Whitney [2011b] measured visual segmentation performance in a task where 2-year-old TD toddlers and toddlers with Fragile X Syndrome (the most common single-gene cause of autism) had to detect a pattern that was flickering out of phase from its neighbors. Temporal segmentation thresholds were higher in 2-year-old toddlers with Fragile X Syndrome, suggesting longer temporal windows. Since the prevalence of autism in Fragile X Syndrome is approximately 30% [Clifford et al., 2007; Rogers, Wehner, & Hagerman, 2001], these findings can only provide some indirect insight into visual temporal processing in early autism. In contrast, Isaksson and colleagues [Isaksson et al., 2018], using a visual simultaneity task, found that older, 8- to 15-year-old children with autism did not differ from TD children at the group level in temporal processing (although individual level analysis revealed greater variance in ASD children). Without testing integration and segmentation skills in the same participant using the same stimuli, some inconsistencies in the literature may be due to differences in general factors such as task understanding, motivation, and response execution. It is also challenging to reconcile results, given the differences in ages and ASD symptom severity across studies.

Current Study

Here we investigate the development of temporal processing in toddlers diagnosed with ASD, and age-matched TD toddlers, at 18–36 months, the youngest age at which an ASD diagnosis can be reliably made, in a paradigm where, importantly, both integration and segmentation skills are measured. Since at this very young age, one of the main concerns that lead families to see a specialist is language and cognitive delays, this means a large portion of our ASD sample will have low mental age (the mean mental age of our sample is a full 2 SD below the mean of the TD group), whereas most autism research is conducted with samples with less substantial intellectual impairment [Brown, Chouinard, & Crewther, 2017; Russell et al., 2019]. Using an eye-tracking task with no verbal instructions, we measured how often a child is able to find a visual target hidden in a cluttered display of other items, as the pace of a sequence of displays was varied to facilitate (or hinder) the visibility of the target. We used a "pop-out" target [Treisman & Gelade, 1980; Wolfe & Horowitz, 2004], and given that this type of target draws gaze without explicit search instructions, this made it ideal for children with weak or no receptive language skills.

We used the point where the integration and segmentation performance functions intersect to estimate the TIW duration [Freschl et al., 2019]. We also computed individual and group difference scores, which reflect the relative performance on integration and segmentation tasks that would reveal any differences in temporal tuning. In addition, studies of neurotypical adults have shown sex differences in temporal processing (for instance, adult males have higher temporal frequency thresholds than females in an attentional tracking task [Roudaia & Faubert, 2017], and shorter motion discrimination thresholds in males [Murray et al., 2018]). A study of motion discrimination thresholds found that males with ASD had lower thresholds than neurotypical males [Foss-Feig, Tadin, Schauder, & Cascio, 2013]. Given these findings, we assessed the effect of sex on difference scores. We also conducted individual-level analyses looking at the relationship between temporal processing and measures using the Mullen Scales of Early Learning assessment and ADOS-2.

As discussed above, prior developmental work is sparse. Overall, studies show a gradual narrowing of TIWs in vision and multisensory perception over development, in which toddlers, both TD and ASD, have longer TIWs compared to adults [Freschl et al., 2019; Wutz et al., 2016] – suggesting a greater ability to integrate information into a unitary representation across time (facilitating information accrual) at the cost of segmenting information into separate representations (facilitating temporal resolution). Given results showing that temporal integration thresholds were higher in toddlers with Fragile X Syndrome [Farzin et al., 2011b], and multisensory integration windows were longer in 6- to 18-year-old children with autism [Stevenson et al., 2014], we had hypothesized longer TIWs in toddlers diagnosed with ASD compared to TD toddlers. However, this hypothesis was rejected: we found evidence that toddlers diagnosed with ASD had narrower TIWs than age-matched TD toddlers.

Methods

Participants

A total of 60 TD toddlers (mean age = 28.01 months; SD = 5.05; n (females) = 28) and 50 toddlers (mean age = 27.67 months; SD = 5.59; n (females) = 19) diagnosed with ASD were tested. These sample sizes were determined based on minimum sample size estimates for a linear multiple regression test with two predictor values, sufficient to yield 95% power at $\alpha = 0.05$, using G*Power 3.1 [Faul, Erdfelder, Lang, & Buchner, 2007]. Families were recruited from the Greater Boston Area, and toddlers with ASD were recruited through Boston area early intervention centers in collaboration with a large-scale study [Eisenhower et al., 2020]. Diagnosis was based on the Autism Diagnostic Observation Schedule-2 (ADOS-2) [Lord, DiLavore, & Gotham, 2012] (Mod 1: n = 16, Mod 2: n = 1, Mod T: n = 32), and confirmed by a licensed clinical psychologist based on observation of the full assessment and information from parent interviews. Both groups were also assessed using the Mullen Scales of Early Learning (MSEL) [Mullen, 1995]. In the TD group, only 41 of the 60 participants completed the MSEL assessment, due to fatigue. In the ASD group, one participant received a diagnosis off-site and our team did not have access to this participant's ADOS-2 and MSEL scores. Thus the individual-level analyses included 41 TD and 49 participants diagnosed with ASD. Typical development in the TD group was confirmed using the MSEL Early Learning Composite standard score (ELC), Brief Infant-Toddler Social and Emotional Assessment (BITSEA) [Briggs-Gowan, Carter, Irwin, Wachtel, & Cicchetti, 2004], and parental report using the Parent's Observations of Social Interactions (POSI) [Smith, Sheldrick, & Perrin, 2013]. Demographic information and scores on assessments are shown in Table 1. Experimental protocols were approved by the Institutional Review Board at the University of Massachusetts Boston. All participants had normal vision and no first-degree relatives with known color blindness.

Apparatus

Stimuli were generated using Matlab R2017a and PsychToolbox [Brainard, 1997; Kleiner, Brainard, & Pelli, 2007] and presented on the 17-in. display of the Tobii T120 eye tracker (1280 × 1024 pixels at 60 Hz) running Tobii Studio 3.2. Participants were seated on their caregivers' lap approximately 57 cm from the display in a dimly lit testing room. Caregivers were instructed to minimize communication with their child and wore a visor to block their eyes during testing. Preceding test trials, toddlers completed the default infant Tobii five-point calibration. Fixations during testing were determined using the Tobii I-VT filter, using default parameters [Olsen & Matos, 2012]. These default values were also used in an assessment of the accuracy and precision of the Tobii estimates of gaze [Dalrymple, Manner, Harmelink, Teska, & Elison, 2018], and informed our choices of array layout and sizes of our Areas of Interest (AOI).

Stimuli and Procedure

We modified the missing dot task [Di Lollo, 1980; Wutz et al., 2016] to work as a pop-out visual search task, where a unique item (the target) automatically grabbed attention and gaze. Leveraging pop-out means the toddler's "task" of finding the target required no instructions, making it appropriate for the given age range, and pre/nonverbal participants. Each test trial consisted of a rapid, 4 sec sequence of two alternating displays (ABAB…), each exposed for a parametrically varied stimulus-onset asynchrony (SOA) of 33, 67, 133, or 267 ms (Fig. 1). Each display had a 4×4 virtual grid ($14.3^\circ \times 14.3^\circ$ of visual angle) that could be occupied by visual stimuli depending on task condition. On *integration trials*, Display A

Table 1. T-Scores for MSEL

	ASD, mean (SD)	TD, mean (SD)	*P*	Effect size (*d*)
N	50 (49 with MSEL)	60 (41 with MSEL)	-	-
Females	19	28	-	-
Age (months)	27.67 (5.59)	28.01 (5.05)	0.73	0.07
Range (months)	18–36	18–36	-	-
Mullen VR	28.20 (9.91)	57.63 (13.34)	<0.001	2.50
Mullen FM	27.69 (9.99)	47.25 (10.46)	<0.001	1.88
Mullen RL	22.49 (6.73)	53.88 (10.02)	<0.001	3.75
Mullen EL	27.31 (7.83)	54.40 (12.81)	<0.001	2.56
Mullen ELC	58.27 (10.98)	109.17 (19.60)	<0.001	3.26
ADOS SA	8.41 (1.50)	-	-	-
ADOS RRB	9.53 (0.76)	-	-	-
ADOS CSS	8.86 (1.37)	-	-	-
Ethnicity				
Hispanic or Latinx	10	-	-	-
Not Hispanic or Latinx	37	-	-	-
Not reported	3	60	-	-
Race				
Asian	0	3	-	-
Black/African American	15	1	-	-
White	20	35	-	-
Other/multiple/not reported	15	21	-	-

The Early Learning Composite score (ELC) is derived from VR, FM, RL, and EL scales. Autism Diagnostic Observation Schedule-2 (ADOS-2) Calibrated Severity Scores (CCS) and domain scores are reported: Social Affect (SA) and Restricted, Repetitive Behavior (RRB). Independent-sample *t*-tests were used to test differences in age and MSEL scores between the TD and ASD group.

EL: Expressive Language; FM: Fine Motor; RL: Receptive Language; VR: Visual Reception.

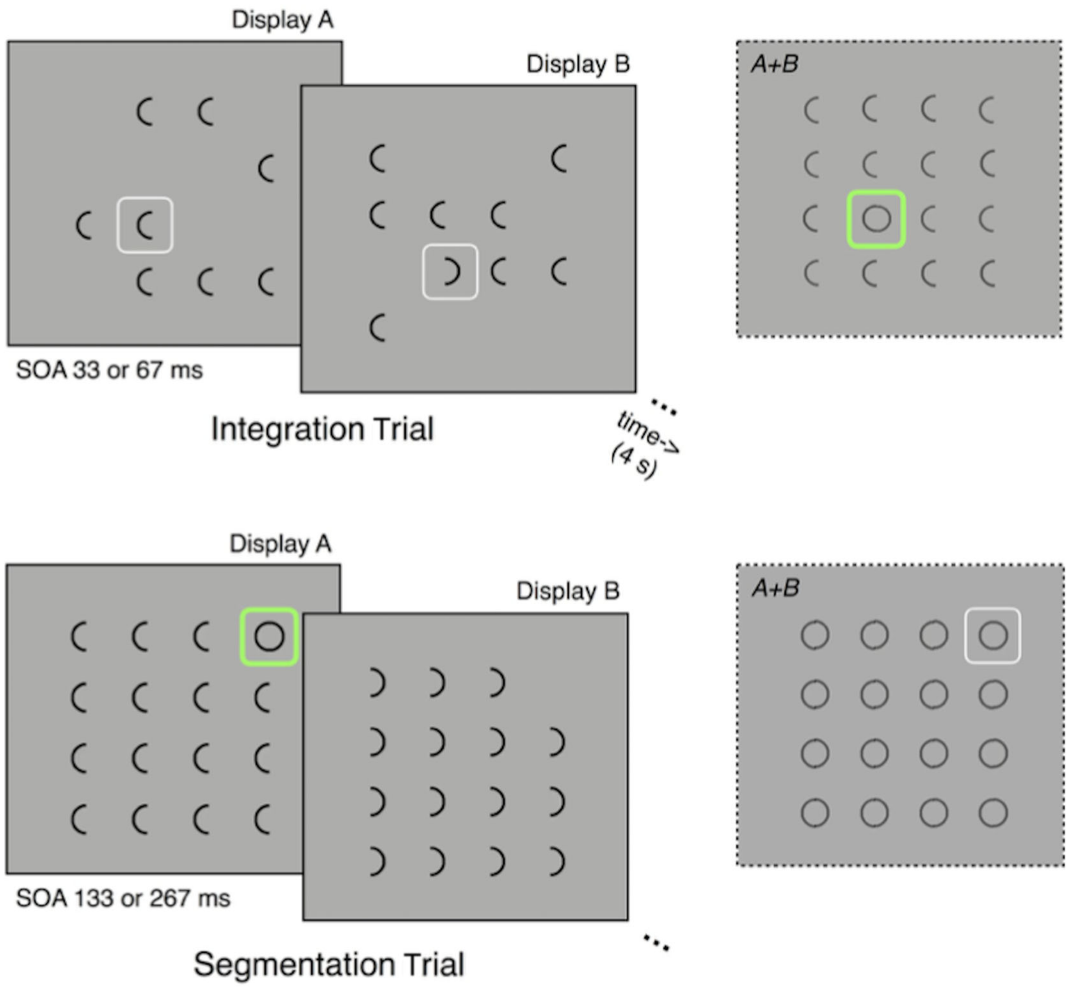

Figure 1. Trial sequence for integration and segmentation test trials. Using an eye-tracker, toddlers were presented with a sequence of displays containing a circle target hidden in a cluttered display of task-irrelevant distractor items. The pace of the display sequence determined the visibility of the target. Slower speeds facilitated segmentation while higher speeds, integration – thereby increasing the likelihood of finding the respective targets.

consisted of eight half-circles and Display B consisted of nine half-circles. Each display when viewed alone did not contain a target, such that only when integrated across time (A+B) did the two half circles from each display align to form a full circle integration target. So if (and only if) a participant integrates the two displays visually over time, the target will be visible and draw gaze. On segmentation trials, in contrast, Display A consisted of 15 half circles and Display B, 15 complementary half circles and one full circle segmentation target. If (and only if) a participant segments these two displays, the full circle segmentation target will become visible, drawing attention and gaze. Importantly, the likelihood of perceiving a target is directly influenced by the duration for which the displays are presented. Longer durations (slowing the pace of the A/B sequence or longer SOAs) make the integration target harder to detect, but increase the chances of the segmentation target pop-out. In contrast, as the display duration gets shorter (shorter SOAs), integration becomes easier and segmentation harder.

A session consisted of four familiarization and 48 test trials. First, participants were presented with the four familiarization trials, which consisted of a 4 sec display with one, randomly positioned, full circle target amidst a field of half-circles (the perceptual display relevant to both integration and segmentation targets). These trials served to familiarize participants with the target and display sequence. This was followed immediately with a randomized, mixed block of the 48 test trials, each with a particular display duration (33, 67, 133, or 267 ms) and trial type (integration or segmentation). There were 12 trials for each condition (integration condition: 33 and 67 ms SOA; segmentation condition; 133 and 267 ms SOA). Each trial began with a gray 1 s display with a central, black fixation cross. All trials included an engaging "galloping horse" sound effect during the 4 sec display sequence, followed by a 1 sec feedback where the circle-target turned green with a "horn" sound effect. Gaze patterns were determined by $3.5^\circ \times 3.5^\circ$ AOIs around each location in the display array. We confirmed that the calibration was sufficiently precise by checking fixation rates to the target during the familiarization trials (see *Results*), as fixation rates to the target should be highest then.

Results

Basic Measures of Overall Task Performance and Eye Movement Patterns

To begin with, we compared measurements of overall task performance[1]. Performance was measured by calculating the proportion of trials that the integration or segmentation target (always a circle) was fixated as a function of the display duration (SOA). We did not find any significant differences in gross measures of performance or gaze between the ASD and the TD groups. Toddlers in both groups completed approximately nine valid trials (a trial is valid if it contains at least one fixation) per condition (TD Median = 8.00, SD = 2.35; ASD Median = 9.75, SD = 2.10, Z = −1.35, $P = 0.18$, $\eta^2 = 0.02$), that is, approximately 75% of the 12 trials per condition. Toddlers in both groups fixated approximately 2.4 unique items per valid trial (TD Median = 2.38, SD = 0.55; ASD Median = 2.48, SD = 0.57; $Z = -1.25$, $P = 0.21$, $\eta^2 = 0.01$). Overall percent correct performance, that is, likelihood to fixate the target on a valid trial (collapsed across condition) was also indistinguishable (TD Median = 43.1% correct, SD = 0.16, ASD Median = 43.9% correct, SD = 0.18; $Z = 0.21$, $P = 0.84$, $\eta^2 = 0.00$). Finally, we compared performance on familiarization trials. On these trials, the search display was static, thereby providing insight into classic pop-out (or efficient) [Wolfe & Horowitz, 2004] search performance. Again, the results of the two groups were indistinguishable (TD Median = 75% correct, SD = 0.23, ASD Median = 75%, SD = 0.26; $Z = 1.37$, $P = 0.17$, SD = 0.24, $\eta^2 = 0.02$).

Group Level Analysis (Temporal Integration Windows)

We used performance as a function of SOA to estimate the duration of the TIW itself [Freschl et al., 2019; Wutz et al., 2016] (Fig. 2). Based on the estimated cross-over point, the TIW for the TD group was found to be 142 ms, while the TIW for the ASD group was 108 ms. Both toddler groups' TIWs (125 ms) were longer than adults', which were found to be approximately 65 ms in previous studies, using versions of the current paradigm [Freschl et al., 2019; Wutz et al., 2016].

Group Level Analysis (Difference Scores)

All else being equal, a difference in temporal tuning will affect relative performance on integration versus segmentation. A visual system tuned to be more sensitive to change will perform relatively well on segmentation, while one biased to accumulate information over time will perform relatively well on integration. Here, we measured this relative performance by computing a *scaled difference score* based on overall percent correct performance in the two conditions: (*integration* − *segmentation*)/(*integration* + *segmentation*). With this measure, larger difference scores reflect larger temporal integration windows (i.e. slower tuning). In typical development, studies have shown sex differences in temporal processing, for instance, adult males have higher temporal frequency thresholds than females in an attentional tracking task [Roudaia & Faubert, 2017], and shorter motion discrimination thresholds in males [Murray et al., 2018] with ASD males having even shorter motion dscrimination thresholds than TD males [Foss-Feig et al., 2013]. To assess this, we performed a Kruskal-Wallis *H*-test [Kruskal & Wallis, 1952], with Group and Sex as factors. This revealed a significant difference between ASD and TD toddler groups ($H(1)) = 5.54$, $P = 0.02$, $\eta^2 = 0.04$), however, there was no significant difference between boys and girls ($H(1) = 2.17$, $P = 0.14$, $\eta^2 = 0.01$, see Fig. 3).

Individual Level Analysis (Effects of Age, Mental Age, and Clinical Measures)

We next assessed the relationship between *differences scores* and chronological age using a Kendall correlation [Kendall, 1948] and found no significant correlation in either the ASD ($\tau_B = 0.01$; $P = 0.89$; $n = 60$) or in the TD group ($\tau_B = 0.11$; $P = 0.20$; $n = 50$) (Fig. 4). As well, there were no significant relationships between chronological age and overall performance (average performance on integration and segmentation tasks combined) in either group (TD: $\tau_B = 0.12$, $P = 0.19$; ASD: $\tau_B = 0.19$; $P = 0.07$).

Not all participants in our TD sample were able to complete the MSEL assessment due to fatigue (41 out of 60). For one participant with ASD, diagnosis was made offsite, and our team did not have access to this participant's MSEL and ADOS-2 scores. The subset of participants with MSEL scores were included in individual – level analyses looking at the relationship between difference scores and mental age (ASD: $n = 49$, TD: $n = 41$). Kendall correlations revealed no significant correlation between mental age (measured by the Mullen Early Learning Composite score) and difference score in either of the two groups (TD: $\tau_B = 0.17$, $P = 0.13$; ASD: $\tau_B = 0.13$, $P = 0.20$).

[1]In most cases, the distribution of these measurements deviated from normality (according to a Lilliefors test). Given that, we have used robust statistics throughout, summarizing data with medians and performing hypothesis testing with non-parametric tests.

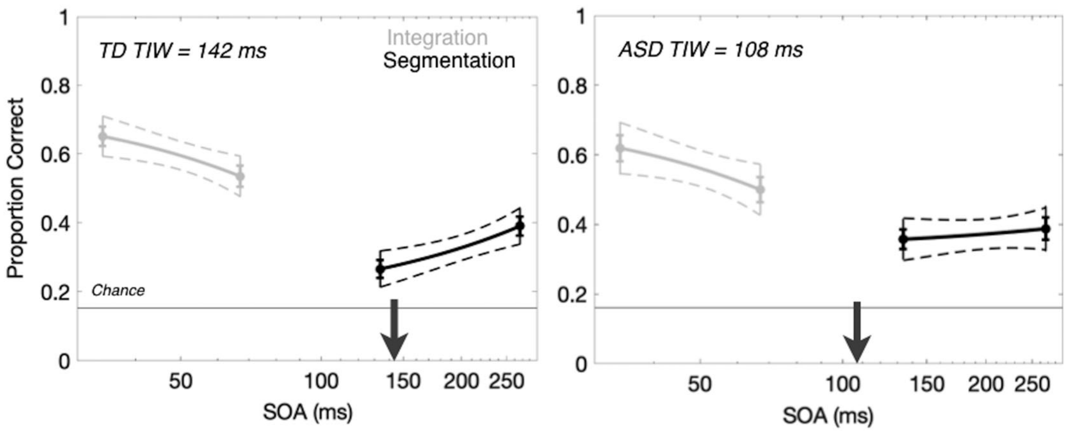

Figure 2. Performance in the integration (gray) and segmentation (black) as a function of stimulus onset asynchrony (overall pace of the display sequence). The intersection of the integration and segmentation performance functions provides the estimate of the temporal integration window (TIW) (intersections were derived from linear fits; data are shown here on semilog axes). The TD group had a TIW of 142 ms and the ASD group had a TIW of 108 ms. Error bars indicate one SEM and whiskers the 95% confidence intervals. The arrow indicates the TIW. Dotted lines show confidence intervals around the least squares fits of the data.

We also did not find a significant relationship between difference scores and ADOS-2 Calibrated Symptom Severity scores in the ASD group ($\tau_B = 0.03$; $P = 0.82$; $n = 49$). Kendall correlations between difference scores and the two subscales of the ADOS, Social Affect (SA) scores and Restricted and Repetitive Behavior scores were not significantly correlated either ($\tau_B = 0.08$; $P = 0.39$; $\tau_B = 0.03$; $P = 0.81$, respectively). In exploratory analyses, we also tested the relationship between Response to Joint Attention measures (ADOS-2; restricting measures to just Module T participants, $n = 33$) and difference scores, and found no significant correlation ($\tau_B = 0.09$; $P = 0.49$). Additionally, we looked at the relationship between Unusual Sensory Interest in Play Material/Person scores (ADOS-2, all modules, $n = 49$) and difference scores, but found no significant correlation ($\tau_B = 0.10$; $P = 0.35$).

Discussion

We measured Temporal Integration Windows (TIW), in a group of toddlers aged between 18 and 36 months, during a search task where the target was only visible if

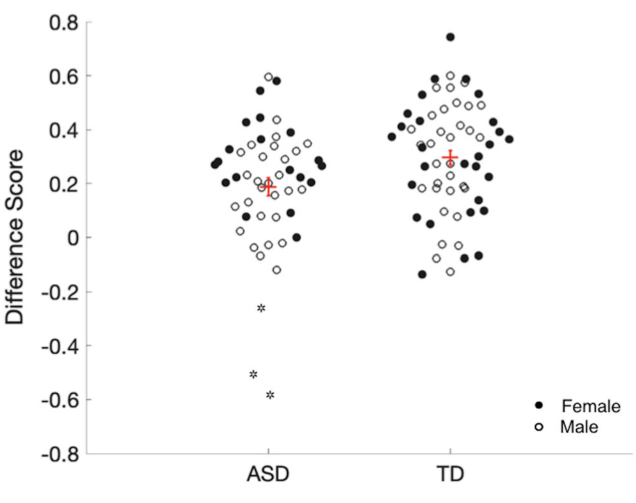

Figure 3. Individual and group scaled difference scores in the ASD and the TD groups. Closed circles: males, open circles: females. Group means with standard errors of the mean are shown in red. (Asterisks indicate values of individual participants ($n = 3$, all ASD males) with a median absolute deviation greater than 2.5 [Leys, Ley, Klein, Bernard, & Licata, 2013]. Outliers were not excluded, but provided a rationale for the use of robust, nonparametric analyses).

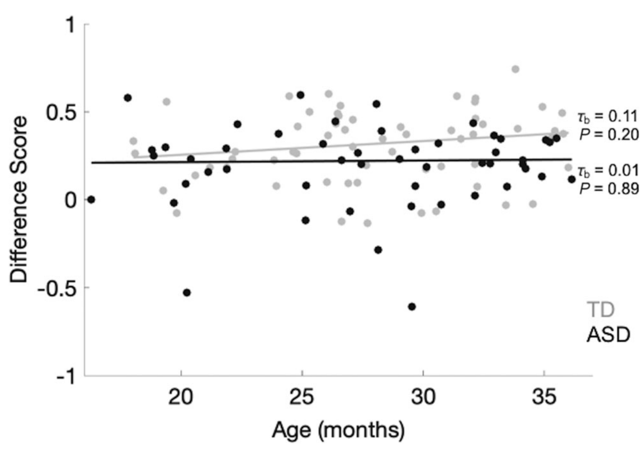

Figure 4. Kendall correlation between scaled difference score and age for individual children (TD:$n = 60$; ASD:$n = 50$). There was no significant age effect on difference scores in either of the two groups. Trend lines generated from a Theil-Sen analysis (the Theil-Sen line is a nonparametric alternative to the least squares regression line) [Wilcox & Keselman, 2012], and a more suitable visualization of the Kendall correlation.

spatial pattern information was *integrated*, or *segmented* (depending on condition), over time. Our study sidestepped some limitations of previous studies, which only measured integration or segmentation separately, and employed different paradigms across age groups. We found that toddlers had significantly longer TIWs (125 ms) than has been reported in adults (65 ms) [Wutz et al., 2016], indicating their visual system is "tuned" toward the accumulation of information over time, as opposed to finer temporal resolution. We had recently shown that 5- to 7-year-old TD children had TIWs similar to that of adults' [Freschl et al., 2019]. Therefore, our current findings suggest that maturation of these temporal processes occurs between 3 and 5 years of age in typical development.

Within our group of participants, we found that toddlers diagnosed with ASD had significantly shorter TIWs (108 ms) compared to chronological age-matched TD children (142 ms); that is, the visual system of toddlers with ASD is tuned for faster-paced events. We found no significant age effect within either of the two groups, suggesting that maturation toward adult levels is protracted. Importantly, by using an innovative paradigm that measured both integration and segmentation ability within the same participant, we could isolate group differences that stem from temporal processing differences, per se, as opposed to differences due to general factors (e.g. task understanding or motivation). Indeed, we found no *overall* performance difference between the TD and ASD groups (TIWs were estimated by contrasting performance on integration versus segmentation; overall performance is the average of the two).

Our results, indicating shorter TIWs associated with ASD in young children, are in apparent contrast with the literature that found no differences in unisensory visual temporal processing with and without an ASD diagnosis in children between 6 and 18 years of age [Kwakye et al., 2011; Stevenson et al., 2014]. This could be due, in part, to differences in age and ASD symptom severity, with most studies sampling ASD participants without significant cognitive impairment. It is important to note here that our ASD participants had significant developmental delays (MSEL ELC, mean = 58.27, SD = 10.98), compared to our TD participants (mean = 109.17, SD = 19.60), and had a high average symptom severity score (ADOS-2 CSS, mean = 8.86; SD = 1.37). Sample participants in most autism research are in the typical IQ range [Russell et al., 2019]. In a recent meta-analysis, Russell et al., [2019] found that only 6% of participants in published autism research studies had an intellectual disability, even though the prevalence of intellectual disability across the autism spectrum is approximately 55% [Charman et al., 2011]. In studies focusing on visual processing in ASD, the situation is somewhat better, but still only 20% of journal articles sampled participants with autism who had an intellectual disability [Brown et al., 2017]. This major underrepresentation of the disorder in experimental work makes it challenging to accurately generalize results across the autism population. Therefore, it is a particular strength of our study that our young participants had a wide range of mental age, including many children with low mental age.

Implications of Shorter TIWs in Young Children with ASD

Work on perceptual processing differences in ASD has focused mainly on visual spatial processing, informing theories such as the WCC [Frith et al., 1994; Happé & Frith, 2006], which suggests a local spatial bias in ASD at the expense of perceiving global gist, and Enhanced Perceptual Function (EPF) [Mottron et al., 2006; Mottron & Burack, 2001], which suggests individuals with autism default to processing local, featural information (rather than a deficit in global processing, per se). A recent meta-review has argued for a shift from a spatial to a *temporal* explanation for this bias [Van der Hallen et al., 2015]; individuals with ASD prioritize, temporally, the processing of local information. Our results are consistent with this view. Shorter TIWs mean a bias away from the accumulation of information, thereby hampering the formation of global representations. Finer temporal resolution in toddlers with autism can be seen as consistent with both the WCC and EPF theories; further work is needed to see if this bias is obligatory, or determined (and possibility manipulated) by task demands. These findings may also provide insight into other modalities, such as auditory processing, where enhanced perception has also been found in individuals with autism [Mottron, Peretz, & Menard, 2000].

Previous work has shown that individuals with autism have better performance in some visual search tasks [Joseph, Keehn, Connolly, Wolfe, & Horowitz, 2009; Kaldy, Giserman, Carter, & Blaser, 2016; Kaldy, Kraper, Carter, & Blaser, 2011; O'Riordan, Plaisted, Driver, & Baron-Cohen, 2001]. The efficiency of search depends on the similarity between the target and the distractors; greater perceptual difference between the target and distractor leads to a more efficient search [Wolfe & Horowitz, 2004]. In our main task, efficiency was largely dependent on *temporal processing*. If temporal processing demands were eliminated, the visual search task becomes a relatively efficient, "pop-out" search, with the target having a unique-feature spatial pattern. Pop-out search performance for TD and ASD groups is actually similar at this age [Kaldy et al., 2011; Smith, Carter, Blaser, & Kaldy, 2019]. This was confirmed here in the static, *familiarization* trials, where performance was indistinguishable between the groups. There is not much work on temporal-processing dependent visual search in ASD, but our findings are consistent with work showing children diagnosed with ASD are better able to pick targets from an RSVP stream [Hagmann et al., 2016].

Shorter TIWs and the processing of scenes and events. As a first principle, natural scenes contain important events over a broad range of temporal frequencies. Narrower windows facilitate the perception of fast-paced change, allowing an observer to resolve events that occur closely in time, while wider windows allow for greater accumulation of information to facilitate the processing of static objects and slower-paced events [Blake & Lee, 2005; Holcombe, 2009; VanRullen, 2016]. A particular tuning, then, may be more typical, or adaptive, for a particular context and/or developmental stage. It is possible that longer windows may be more advantageous for young children as they are able to gather more information (e.g. color, shape, or size) about objects, aiding individuation and identification [Wutz & Melcher, 2014; Zimmermann, Morrone, & Burr, 2013]. This may align with the development of higher level cognitive abilities like complex social communicative acts in which differences in a speed-accuracy trade off may present challenges for toddlers with ASD.

When it comes to social cognition, we know that timing matters, as it has been shown that slowing down the dynamics of facial movements (eye and mouth movements) leads to increased looking time to faces in children with ASD [Charrier, Tardif, & Gepner, 2017]. That said, as one moves farther from basic perceptual processes the implications of the present work become more speculative. Shorter TIWs may be linked to the development of social cognitive impairments found in autism, including processes that convey important social information such as gaze and face perception [Thye, Bednarz, Herringshaw, Sartin, & Kana, 2018]. Individuals with autism show impairments in attention to facial features including eye contact avoidance [Jones & Klin, 2013], and preference for objects over faces [Chawarska & Volkmar, 2007]. One reason may be that faces are dynamic, and changes in facial featural information need to be integrated over time in order to extract and interpret important social information such as emotions. Social interactions are often fast paced; although the ability to detect these fast changes are enhanced in ASD (relative to TD toddlers), there may still be challenges associated with efficiently combining dynamic social information into meaningful interpretations.

Clinical assessments and temporal processing. We did not find a significant effect of mental age (Mullen ELC scores) on temporal processing. One possible interpretation is that the relatively enhanced ability to segment visual information across time found in toddlers with ASD may not influence performance on the tasks that make up the ELC score. For example, high performance on the tasks in the Visual Reception subscale may not require the ability to resolve rapid change or integrate dynamic information across time. Similarly, the language measures may not capture those aspects of communication that are involved in the dynamics of social interaction such as turn-taking or imitation. For example, interactional synchrony, which has been shown to be impaired in autism [Trevarthen & Daniel, 2005], involves the temporal coordination between two or more individuals, and the integration of social cues across time [Delaherche et al., 2012; Xavier et al., 2016]. Interactional synchrony deficits in autism could be a result of the trade-off between faster temporal segmentation versus weaker temporal integration of information. Another factor in interactional synchrony is the ability to communicate at a similar pace, which might be impaired if one of the participants processes information at a different pace or in a different way to the other, making them essentially "out of sync" with each other.

In addition, joint attention, the ability to coordinate attention or focus through pointing or eye gaze between two individuals toward a shared object or event, is another important building block of communication. It has long been known that joint attention is impaired in autism [Dawson et al., 2004]. Since joint attention involves the integration of certain dynamic social cues between individuals, such as gaze, it could be that this impairment is related to the inability to gather this information across an efficient time scale, which comes at the cost of enhanced temporal resolution. Although we did not find a correlation between joint attention measures (ADOS-2) and temporal processing, it is possible that the effects of temporal processing on joint attention may develop later or that our use of the ADOS-2 items to assess joint attention limited our ability to observe a potential association.

Future Directions

Future work should not only look at an even younger age group to understand the full developmental trajectory of visual temporal processing in typical development, but also look at how TIWs develop in ASD after early childhood. Do TIWs narrow in development in the same way in children with ASD as they do in typical development? Some recent work on the underlying brain mechanisms may shed some light on this issue. EEG and MEG studies with typical adults have shown a relationship between resting state alpha frequency and temporal resolution: individuals with higher peak alpha frequency have higher temporal resolution [Ronconi & Melcher, 2017; Samaha & Postle, 2015; Wutz, Melcher, & Samaha, 2018]. In TD children, peak alpha frequency increases with age and might be related to the increase in their temporal resolution (as it does in adults). However, to our knowledge, no work has directly investigated the relationship between peak alpha frequency and visual temporal processing in development. Importantly, children with ASD do not seem to show this same typical age-related increase in peak alpha frequency [Edgar et al., 2019; John et al., 1980; Matoušek & Petersén, 1973; Marshall, Bar-Haim, & Fox, 2002; Whitford et al., 2007]. Atypical oscillatory activity has been shown in individuals with autism; however, findings so far have been inconclusive. For example, Cornew, Roberts, Blaskey, and Edgar [2012] measured eyes-closed resting state in children (aged 6–15 years) and found that peak alpha frequency did not differ in TD versus ASD groups. However, Dickinson, DiStefano, Senturk, and Jeste [2018] found decreased peak alpha frequency in their ASD sample compared to TD (participants were between 2 and 12 years of age). In contrast, Edgar et al. [2019] found that 6- to 10-year-old boys with ASD had higher peak alpha frequency (9.8 Hz) compared to an age-matched TD group (8.9 Hz). Consistently though, when looking at the relationship between age and peak alpha frequency, individual level analyses show that autism does not present the same age-related increase in peak alpha frequency as it does in TD children [Edgar et al., 2019]. Given the relationship between peak alpha frequency and visual temporal processing, and the lack of a developmental increase in alpha frequency in ASD, these results suggest that atypical alpha activity may be related to differences in TIWs in autism and that the developmental trajectory of TIWs in autism differs from typical individuals.

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