Title: Is there a generalized timing impairment in Autism Spectrum Disorders across time scales and paradigms?

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Abstract

Individuals with ASD have abnormal motor and perceptual functions that do not currently form diagnostic criteria of ASD, but nevertheless may affect everyday behaviour. Temporal processing seems to be one of such non-diagnostic yet impaired domains, although the lack of systematic studies testing different aspects of timing in the same sample of participants prevents a conclusive assessment of whether there is a generalized temporal deficit in ASD associated with diagnostic symptoms. 17 children diagnosed with ASD and 18 typically developing age- and IQ-matched controls carried out a set of motor and perceptual timing tasks: free tapping, simultaneity judgment, auditory duration discrimination, and verbal duration estimation. Parents of participants filled in a questionnaire assessing the sense and management of time. Children with ASD showed faster and more variable free tapping than controls. Auditory duration discrimination thresholds were higher in the ASD group than controls in a sub-second version of the task, while there were no group differences in a supra-second discrimination of intervals. Children with ASD showed more variable thresholds of simultaneity judgment, and they received lower parental scores for their sense and management of time. No group differences were observed in the verbal duration estimation task in the minute-range. Different timing functions were correlated in the ASD group but not among controls, whilst several timing measures correlated with ASD symptoms. We conclude that children with ASD show a broad range of abnormalities in temporal processing tasks including motor timing, perceptual timing, and temporal perspective.

Keywords: Autism Spectrum Disorders; motor timing; perceptual timing; temporal perspective.

Introduction

Autism Spectrum Disorder (ASD) is marked by persistent and severe deficits in social communication and interaction, and repetitive patterns of action, behaviour or interests. Primary symptoms present from early childhood and affect everyday functioning (American Psychiatric Association, 2013). Furthermore, both clinical reports and research literature suggest that the primary diagnostic characteristics of ASD are commonly accompanied by secondary difficulties, such as atypical motor (Ming et al., 2007) and sensory (Blake et al., 2003; Milne et al., 2002) processing. Among such secondary characteristics, difficulties in timing might be a key part of the autistic cognitive profile (e.g., Allman et al., 2011; Bebko et al., 2006; Boucher et al., 2007; Brodeur et al., 2014; Falter et al., 2012a; Falter et al., 2012b; Falter et al., 2013; Gepner & Féron, 2009; Gowen & Miall, 2005; Karaminis et al., 2016; Kargas et al., 2015; Kwakye et al., 2011; Maister & Plaisted-Grant, 2011; Martin et al., 2010; Szelag et al., 2004; Whiting & Dixon, 2015; Ribeiro Zukauskas et al., 2009; for review and clinical discussion, see Allman & Falter, 2015; Boucher, 2001; Falter & Noreika, 2014; Stevenson et al., 2016; Welsh et al., 2005). However, timing deficits in ASD are not unequivocal (e.g., Bebko et al., 2006; Gil et al., 2012; Glazebrook et al., 2008; Jones et al., 2009; Jones et al., 2017; Kwakye et al., 2011; Mostofsky et al., 2000; Wallace & Happé, 2008).

Temporal processing functions can be divided into motor timing, perceptual timing and temporal perspective. Neurocognitive processing of these timing functions involves both shared and function-specific neural mechanisms (Frost & McNaughton, 2017; Merchant et al., 2013; Muller & Nobre, 2014; Schubotz et al., 2000). Motor timing refers to the temporal resolution of motor behaviour, which is typically tested using free or synchronized motor tapping tasks. Even though motor timing has not been widely studied in ASD, a preliminary study of synchronized tapping found that individuals with Asperger syndrome in comparison to typically developing controls responded earlier and more variably to the pacing stimuli (Gowen & Miall, 2005), indicating that ASD may be associated with impaired motor timing. Arguably, abnormal timing patterns could contribute to other motor impairments in ASD (Ming et al., 2007; Sacrey et al., 2014), although replication studies of tapping tasks are needed before drawing any firm conclusions.

While motor timing does not require explicit judgment of duration or temporal succession of stimuli, perceptual timing refers to perceptual evaluation of temporal processing, which can be further subdivided into event timing, interval timing and retrospective tasks. Event timing (also termed temporal event-structure coding) comprises the perception and judgment of the relative timing of events, which can be assessed for instance by measuring judgments of simultaneity and temporal order. In two previous studies of visual simultaneity judgments we have found abnormal temporal event-structure coding in ASD (Falter et al., 2012a; Falter et al., 2013). In particular, adults with high-functioning autism and Asperger syndrome had lower simultaneity thresholds (Falter et al., 2012a) and were more able to discriminate between real and apparent simultaneity (Falter et al., 2013) than typically developing controls, pointing to increased resolution of the timing of events in ASD. In contrast to simultaneity judgments, temporal anticipation of events seems to be comparable between adults with ASD and controls (Glazebrook et al., 2008). Another study reported impaired auditory but not visual temporal order judgments in children with ASD (Kwakye et al., 2011), whilst a study measuring preferential looking at asynchronous stimuli found a deviant looking pattern in young children with ASD (mean age of 5), but only when linguistic stimuli were used (Bebko et al., 2006). Overall, performance on event timing tasks in ASD seems to strongly depend on task requirements and the modality tested.

Interval timing refers to the judgment of explicitly attended duration, which can be tested using a wide range of tasks, including duration reproduction, production, discrimination, bisection and generalization. Importantly, interval timing depends on the activation of the timing mechanisms while a person is making time judgements. Studies on interval timing in ASD have yielded mixed results, uncovering either intact (Gil et al., 2012; Jones et al., 2009; Jones et al., 2017; Mostofsky et al., 2000; Wallace & Happé, 2008) or abnormal performance in individuals with ASD (Allman et al. 2011; Brodeur et al., 2014; Falter et al., 2012b; Karaminis et al., 2016; Kargas et al., 2015; Maister & Plaisted-Grant, 2011; Martin et al. 2010; Szelag et al. 2004). Several studies reported less accurate and more variable duration reproduction in ASD (Maister & Plaisted-Grant, 2011; Martin et al. 2010; Szelag et al. 2004), whereas one study reported increased accuracy of duration reproduction in children with ASD (Wallace & Happé, 2008), which might be due to task specificities (Falter & Noreika, 2014). A decreased sensitivity and at the same time increased consistency of time judgments across different intervals and modalities was found in adults with ASD using a temporal generalization task (Falter et al., 2012b). Similarly, a reduced sensitivity to interval timing in ASD was found using a temporal bisection task (Allman et al., 2011; Brodeur et al., 2014). While two studies reported decreased duration discrimination in the ASD group (Karaminis et al., 2016; Kargas et al., 2015), other studies testing time bisection (Gil et al., 2012; Jones et al., 2017) and duration discrimination found no differences between ASD and control groups (Jones et al., 2009; Mostofsky et al., 2000). Thus, again performance on interval timing tasks in ASD might depend on task specificities and sampling.

While interval-timing tasks involve prospective estimation of durations, i.e. forewarning participants that they will be asked to estimate the duration of an event, retrospective timing judgements are made when a person is unexpectedly asked to estimate the length of time between two events. As such, retrospective timing relies on the storage of memories rather than an internal estimation of passing time, making it mechanistically different from interval timing (Wearden, 2005). While retrospective timing has been tested in another developmental disorder, attention-deficit/hyperactivity disorder (ADHD; McGee et al., 2004), we are unaware of any studies investigating it in ASD.

The third class of timing functions can be broadly referred to as temporal perspective, i.e. an ability to relate past, present and future in everyday tasks and reasoning, including a capacity to derive useful conclusions from the past experiences as well as an awareness of the future consequences of current decisions and actions. Temporal perspective can be studied using computerized tasks, such as delay discounting, standard questionnaires, and interviews. Preliminary observations indicate that individuals with ASD might have impaired temporal perspective, e.g. impulsivity is a frequent problem in ASD, which could be related to delay intolerance (Whiting & Dixon, 2015). Anecdotal and qualitative evidence suggests that individuals with ASD have an altered experience of the flow of time (Gepner & Féron, 2009) and their own temporal perspective in it (Ribeiro Zukauskas et al., 2009). Children with ASD were also found to show deficits in diachronic thinking, i.e. the abilities to perceive links between the past, present and future, to understand that events evolve through time, and to conceive successive events as one entity (Allman et al., 2011; Boucher et al., 2007).

Overall, the reviewed literature presented above leads to a twofold conclusion that calls for further research. Firstly, there is preliminary evidence of temporal processing abnormalities in ASD in all domains: motor timing, perceptual timing, and temporal perspective. In addition, individuals with ASD have disrupted circadian rhythm and sleep/wake cycles, including a delayed sleep-wake phase (Baker & Richdale, 2017) and frequent nocturnal awakenings (Schreck et al., 2004), which has been linked to abnormal melatonin synthesis in ASD (Melke et al., 2008). Secondly, and generally in line with perception studies in ASD (Falter, 2013), findings are inconsistent and different studies report impaired, intact or superior timing in ASD. Arguably, many of these inconsistencies could be attributed to the diversity of behavioural and perceptual profiles that fall within the autistic spectrum and to sampling and diagnostic differences across studies. Importantly, it remains unclear whether temporal processing abnormalities can be found across functions within individuals, converging to a generalised temporal processing deficit in ASD.

Aims of the study

Given that experimental studies are typically restricted to a single timing function, it remains difficult to identify the relationship between key temporal abnormalities in ASD, and determine whether there is a generalized timing deficit that spans across several timing functions. To address these issues, we used a battery of timing tasks, investigating different time scales and functions, in a single sample of participants. This design allowed us to assess which timing functions stand out as the key timing impairments, whether different timing tasks are inter-related in individuals, and whether they are associated with ASD symptoms.

Material and methods

Participants

ASD. We tested 17 children (two left-handed) who had received a diagnosis of Asperger syndrome (F84.5) at Turku University Hospital, Finland, between 2005 and 2014. Written information about the study was sent to all eligible children and their families, who were identified from the hospital electronic medical records based on ASD diagnosis and age (8-15 years). Exclusion criteria were any other comorbid neurological and psychiatric diagnosis, and Full Scale IQ below 70. In total, families of 61 children were contacted and a positive reply was received from 19 children with ASD. Once parents' informed consent and child's assent sheet were signed, they were invited to take part in the study. The Autism Diagnostic Observation Schedule (ADOS) (Lord et al., 2000) and the Social Communication Questionnaire (SCQ) Form: Lifetime (Rutter et al., 2003) were used to verify diagnosis. Three children did not meet the diagnostic criteria on one of the ADOS subscales. After this finding, their medical records were examined. As their diagnosis was based on a multi-professional clinical opinion, we have decided to include them in the study. To examine their intellectual abilities, the Wechsler Intelligence Scale for Children (WISC-IV) was administered (Wechsler, 2003). Two of the invited children were excluded because of low Full Scale IQ (62 and 65).

Controls. The control group consisted of 18 typically developing (TD) and voluntarily participating children (two left-handed) living in the same area. Children in the control group were recruited by distributing handouts via teachers and psychologists. To ensure the typicality of their development, a developmental history, based on parental information, and intelligence measures were assessed. ASD and TD groups were matched on gender, age (U=135, p=0.568), and IQ scores, including Verbal Comprehension Index (t(33)=-1.607, p=0.118), Perceptual Reasoning Index (t(33)=-0.569, p=0.574), Working Memory Index (t(33)=-0.393, p=0.677), Processing Speed Index (t(33)=-1.744, p=0.09), and Full Scale IQ (t(33)=-1.582, p=0.123). Demographic data can be found in Table 1.

Ethical considerations. The study protocol was approved by the Ethics Committee of the University of Turku and Turku School of Economics, and the investigation was carried out in accordance with the latest version of the Declaration of Helsinki.

<insert Table 1>

Temporal processing tasks

Motor timing: Free tapping. Motor timing was evaluated using a free tapping task, which assesses the rhythm and consistency of self-produced finger taps. The task has been used previously for testing motor timing in children with attention-deficit/hyperactivity disorder (ADHD) (Rubia et al., 2003). Participants were instructed to tap a button on an 8-button response box (RB-844, Cedrus Corporation) at a freely chosen speed. Tapping was carried out using either the left hand or the right hand index finger (see Fig. 1A). The task consisted of four blocks of 50 taps each, two blocks per hand with the following order: Left-Right-Left-Right or Right-Left-Right-Left, counterbalanced between participants. Before the main task, participants practiced tapping until the experimenter felt confident the task instructions were properly understood. Two measures were used to assess tapping performance: mean inter-tap interval and tapping coefficient of variation, calculated as the standard deviation of inter-tap intervals divided by the mean inter-tap interval. The task was programmed using Inquisit 3 (2003).

Perceptual event timing: Simultaneity judgment. Perceptual event timing was assessed using a simultaneity judgment task, which has previously been applied to adults with ASD (Falter et al., 2012a; Falter et al., 2013). This task estimates an individual’s threshold of visual temporal resolution, with lower threshold values indicating more accurate event timing. Aiming to make the task more child-friendly, participants were presented with two 'angry birds' figures on a black computer display, whereas two vertical bars were used in the previous studies (Falter et al., 2012a; Falter et al., 2013). In a two-alternative forced-choice procedure, participants were instructed to judge whether the two 'angry birds' appeared on the black screen at the same time or not by pressing one of two keys on the response box (see Fig. 1B). The angry bird stimuli subtended a visual angle of 3.8° (horizontal) and 4.3° (vertical) with a child sitting approximately 60 cm from the screen. The visual angle was 4.96° from the centre of the fixation point to the centre of angry birds. The stimuli were presented either simultaneously or asynchronously, i.e. the stimulus onset asynchrony (SOA) between the two figures was either 0 ms, in which case both stimuli appeared at the same time, or physically asynchronous in one of 12 SOAs defined by the monitor refresh rate of 120 Hz, i.e. [1:12] x 8.33 ms, in which case there was a fixed delay (8.33 ms, 16.33 ms, [...], or 99.96 ms) between the onset of the first and the second stimulus. The stimulus luminance was increased incrementally over 5 frames, i.e. reaching 100% in 42 ms. There were 10 trials per each SOA condition (5 left stimulus first), which were presented in a random order in 5 blocks of 24 trials. To analyse task performance, a psychometric logistic function was fitted to individual rates of 'simultaneous' responses across SOAs using a least squares procedure (Arnold, 2002; Cavallini, 1993). Subsequently, individual thresholds of simultaneity, operationalized as the inflection point of the obtained sigmoidal curve, as well as individual slopes of simultaneity judgment at the point of inflection were derived and compared between ASD and TD groups. Simultaneity thresholds indicate temporal stimulus onset resolution, and the steepness of the function slope reflects the response criterion, i.e. the steeper the slope the sharper the distinction between the simultaneous and asynchronous perception (Falter et al., 2012a). The task was programmed using Inquisit 3 (2003).

Perceptual interval timing: Auditory duration discrimination (sub-second and supra-second range). The auditory duration discrimination task was designed as a simple child-friendly computer game with dinosaurs (Sutcliffe & Bishop, 2005), aiming to assess individual discrimination thresholds, i.e. the shortest duration required to distinguish several intervals. Given that sub-second and supra-second timing might rely on distinct neural mechanisms (Lewis & Miall, 2003a, 2003b), participants conducted two task versions, one in the sub-second and another in the supra-second interval range. In each trial, three colourful dinosaurs were shown on the computer screen, one at the top and two at the bottom. The dinosaur stimuli differed slightly in size, but on average they subtended a visual angle of 4.5° (horizontal) and 3.8° (vertical) with a child sitting approximately 60 cm from the screen. First, the top dinosaur jumped and, after a pause of 500 ms, produced a reference beep of 200 ms duration in the sub-second version and 2000 ms duration in the supra-second version. Afterwards, the bottom left dinosaur jumped and produced its beep, followed by the bottom right dinosaur. One of the bottom dinosaurs, either the left or the right, produced the same beep duration as the top dinosaur, whereas the other bottom dinosaur produced a shorter beep. Participants were instructed to report by mouse click, which of the two bottom dinosaurs produced a shorter beep compared to the top dinosaur (see Fig. 1C). Participants had as much time to respond as needed. Small tokens appearing on the left side of the screen rewarded correct answers. All beeps played were 1000 Hz tones with 5 ms fade in and fade out envelopes. Auditory stimuli were created using Audacity® 1.3.12 (2010), and presented to both ears at the same volume using regular headphones. The dB level was adjusted individually for each participant to a comfortable level, in order to avoid possible effects of auditory sensitivity. Participants initiated the next trial via button press, following which the next trial started after a fixed 1000 ms inter-trial interval. The experiment continued until auditory discrimination thresholds were estimated (see Supplementary Methods).

Perceptual retrospective timing: Verbal duration estimation (minute-range). Participants were tested using a verbal duration estimation task, which has previously been applied to study retrospective time processing in children with ADHD (McGee et al., 2004). Participants were asked to estimate the duration of two 1.5 min breaks held between the other temporal processing tasks. The first break was a 'dull' break, where participants were asked to "sit down and wait" while the researcher was preparing for the next task. The second one was an 'interesting' break, where participants were asked to choose a task from presented activities (drawing, reading, building with Lego blocks) while waiting. We expected participants to give longer time estimates after the 'dull' break. When the participant was seated, the researcher switched on a stopwatch hidden from the participant. After a 1.5 min time period the researcher asked the participant to "estimate how long he/she has sat and waited?" (see Fig. 1D). Participants were not informed explicitly about the forthcoming 'dull' or 'interesting' break. Likewise, children were not told they would be asked to estimate the duration of breaks, and their time estimation largely depended on retrospective memories and cognitive assessment of time passage. Nevertheless, it is possible that some children may have expected to be asked about time after the end of the 'interesting' break, in which case their task performance would have depended on the prospective interval timing mechanisms.

Aiming to avoid order effects, all experimental tasks, including sub-second and supra-second duration discrimination, were presented in a counter-balanced order, which was randomly shuffled across participants.

Temporal perspective: Sense and management of time. Parents of all participants filled in the *It's About Time (IAT) – Questionnaire* (Barkley, 1998). It contains 25 multiple-choice questions about the child's sense and management of time, i.e. awareness of the passage of time and tendency to notice temporal information in everyday situations. The IAT was previously used in studies assessing sense of time in children with ADHD (Barkley et al., 1997; Bauermeister et al., 2005; Quartier et al., 2010) and autism (Allman et al., 2011). The IAT summary score was used as a key measure with a higher score indexing better sense and management of time.

<insert Figure 1>

Statistical analyses

Behavioural performance in different timing tasks was compared between ASD and TD groups using mixed-factors ANOVA and/or independent-samples t test. Distributions violating the normality assumption, as indicated by the Shapiro-Wilk test, were normalized via a Box−Cox transformation (Box & Cox, 1964; Osborne, 2010) where applicable, otherwise the non-parametric Mann-Whitney U test was applied. The Box−Cox transformations were square root for the mean inter-tap interval data, [Ln(data value×100)] for the tapping coefficient of variation data, [$(\text{data value}-4.64)^{0.62}$] for the discrimination thresholds, natural logarithm for the reaction times of the auditory duration discrimination data, [Ln10(maximum value+1-data value)] for the slopes of the psychometric function in the Simultaneity judgment task, and [$(\text{data value})^{1.5}$] for the IAT questionnaire–score data. The Pearson correlation (r) was used when the Shapiro-Wilk test result was not significant for both distributions, and the correlation was linear. Otherwise, when one or both distributions violated the normality assumption or the correlation was curvilinear, a Spearman correlation (r_s) was carried out. The Bonferroni–Holm multiplicity correction (Holm, 1979) was applied for correlations. All statistical tests were 2-tailed. Statistical analyses were computed with IBM SPSS Statistics 22. Back-transformed values are reported in the main text of Results, whereas raw values are reported in Figures 2-4 and Supplementary Table 2.

Results

Motor timing: Free tapping

Seventeen participants with ASD and 18 TD controls performed the free tapping task. Differences in mean inter-tap intervals were analysed using mixed 2×2 ANOVA with a between-participants factor of Group (ASD, TD) and a within-participants factor of Hand (dominant, non-dominant). ANOVA revealed statistically significant main effects of Group (F(1,33)=4.640, p=0.039, η_p^2=0.123) and Hand (F(1,33)=4.389, p=0.044, η_p^2=0.117). On average, the ASD group tapped faster (back-transformed inter-tap intervals in ms: M=622.75, SD=419.69, 95% CI=[424.98, 858.20]) than the TD group (M=983.58, SD=573.55, 95% CI=[736.85, 1265.94]) (see Fig. 2A). Mean inter-tap interval (ms) was shorter for the Dominant hand (M=756.64, SD=544.59, 95% CI=[589.76, 944.27]) than the Non-dominant hand (M=830.07, SD=519.03, 95% CI=[668.53, 1009.08]). Group × Hand interaction was not significant (p=0.454). No significant Group differences were observed in tapping coefficient of variation (SD/M) (see Supplementary Results). Importantly, faster tapping in the ASD group could not be derived from possible group differences in reaction times (RT), as the groups did not differ in RT in a perceptual timing task (see Supplementary Results). However, there was a significant negative correlation between the Full Scale IQ and the mean tapping speed in the ASD group, indicating that the ASD and TD group difference was partially driven by increased tapping speed among ASD individuals with relatively low IQ (see Supplementary Results).

<insert Figure 2>

Perceptual event timing: Simultaneity judgment

Four participants were excluded from the analysis due to random response behaviour preventing curve fitting, leaving 15 participants with ASD and 16 TD controls (see Supplementary Table 1). The remaining curve fits yielded an average coefficient of determination (R^2) of M=0.94 (SD=0.058) in the ASD group and M=0.96 (SD=0.017) in the TD group, which were not significantly different (t(16.27)=-1.480). Variance of individual thresholds was significantly higher in the ASD group compared to the TD group (Levene's F(1,29)=4.54, p=0.042) (see Fig. 2B). The thresholds (ms) did not differ (t(19.03)=0.336, p=0.74) between ASD group (M=42.18, SD=14.32, 95% CI=[34.26, 50.12]) and TD group (M=40.83, SD=6.34, CI=[37.45, 44.22]) in this sample though. Neither did the slopes of the psychometric function (t(29)=-0.951, p=0.349). Back-transformed slope values for groups were: ASD: M=-2.32, SD=1.04, 95% CI=[-3.15, -1.71] and TD: M=-2.70, SD=0.51, 95% CI=[-3.24, -2.26].

Perceptual interval timing: Auditory duration discrimination

Seventeen participants with ASD and 18 TD controls performed the auditory duration discrimination task. Duration discrimination thresholds were higher for the ASD group on the corrected variables transformed back to milliseconds in the sub-second version of the task (M=34.26, SD=12.48, 95% CI=[24.26, 45.76]) compared to the TD group (M=22.2, SD=9.06, 95% CI=[16.61, 28.57]; t(28.53)=2.15, p=0.04, η^2=0.1) (see Fig. 2C). Likewise, group-level variance of individual sub-second discrimination thresholds was significantly higher in the

ASD group compared to the TD group (Levene's F(1,33)=6.97, p=0.013). There were no statistically significant group differences between supra-second discrimination thresholds (t(33)=1.01, p=0.321) or their variances (Levene's F(1,33)=0.145).

Perceptual retrospective timing: Verbal duration estimation

Seventeen participants with ASD and 18 TD participants estimated the length of the 'dull' and the 'interesting' break (both 90 s). The ASD group overestimated (Mdn=120, range 30−900) and the TD group underestimated (Mdn=75, range 35−900) the length of the 'dull' break but there was no statistically significant difference between the groups (U=146.5, p=0.83, Hodges-Lehman estimate=0.00, r=−0.04). Both ASD and TD groups underestimated the length of the 'interesting' break. Medians were the same (60 s) in both groups (ASD range 20−900, TD range 27−240) and there was no statistically significant difference between the groups (U=116, p=0.23, Hodges-Lehman estimate=20, r=−0.21) (see Fig. 2D). It was noted that several children gave very large estimates of up to 15 min (see Fig. 2D). Hence, we have repeated our analyses by excluding estimates that were more than twice the actual duration of breaks (>180 sec). From the ASD group, two children were excluded from both conditions, one child from the 'interesting' break condition and another child from the 'dull' break condition. From the TD group, one child was excluded from both conditions. No significant group differences were found in the duration estimates of the 'dull' break (U=108.0, p=0.65, Hodges-Lehman estimate=0.00, r=−0.08) or the 'interesting' break (U=102.0, p=0.48, Hodges-Lehman estimate=0.00, r=−0.13) corroborating the findings from the full sample.

Temporal perspective: Sense and management of time

Parents of 17 ASD and 18 TD participants filled out the IAT–questionnaire. IAT scores were higher in the TD group on the corrected variables transformed back to the IAT-scale

(M=48.83, SD=20.24, 95% CI=[44.41, 53.06]), compared to the ASD group (M=31.2, SD=20.8, 95% CI=[25.07, 36.77]; $t(33)=-5.32$, $p<0.001$, $\eta^2=0.47$).

Correlations between temporal processing tasks

The average inter-tap interval of both hands correlated statistically significantly with the simultaneity threshold in the ASD group ($r(15)=0.64$, $p=0.01$), but not in the TD group ($r(16)=0.34$, $p=0.2$; Bonferroni–Holm corrected α-level=0.025) (see Figure 3). The faster the average tapping speed, the lower the simultaneity threshold. Furthermore, the average inter-tap interval correlated statistically significantly with the IAT sum score in the ASD group ($r_s(17)=0.57$, $p=0.018$), but not in the TD group ($r_s(18)=-0.023$, $p=0.93$; Bonferroni–Holm correction was not applied for this comparison as only one measure per task was tested) (see Figure 3). The worse the sense of time according to the IAT, the shorter the interval between two consecutive taps in the ASD group. Several other inter-task correlations were significant before Bonferroni–Holm correction in the ASD, but not among TD participants (see Supplementary Results).

<insert Figure 3>

Correlations between ASD symptom severity and timing measures

In order to explore the relationship between temporal processing and symptom severity, we correlated timing measures with SCQ total scores (all subscales included) and ADOS total and stereotyped behaviour scores (as not included in total) in the ASD sample, excluding three participants scoring 0 in one of the included ADOS scales. The ADOS total score is the communication and social interaction subscores summed, and the stereotyped behaviour scores is the stereotyped behaviours and restricted interests subscore.

We found a significant correlation between simultaneity thresholds and SCQ total score ($r(12)=-0.66$, $p=0.02$) as well as simultaneity slopes with SCQ total score ($r_s(12)=0.75$, $p=0.005$). These results show that the better the temporal resolution (i.e. the lower the simultaneity thresholds) and the clearer the decision criterion between simultaneity and non-simultaneity (i.e. the steeper the slope of the psychometric function), the stronger the observed symptom severity in communication and social interaction (see Figure 4). Furthermore, we found a correlation between SCQ total scores and time estimation in the dull break ($r_s(12)=-0.59$, $p=0.045$) although it missed significance after Bonferroni-Holm correction. Finally, SCQ total scores correlated significantly with the IAT scores ($r(12)=-0.79$, $p=0.002$) (see Figure 4). In addition, several trends of correlation were observed between ADOS scores and different timing measures (see Supplementary Results).

<insert Figure 4>

Discussion

We applied a large battery of timing tasks to test a group of children with ASD and a group of TD controls, aiming to assess whether there is a generalized timing impairment in ASD, which would manifest in abnormalities across a wide range of time-scales, different sensory modalities, and different timing functions. Alternatively, group differences in a sub-set of tasks would indicate a restricted domain-specific timing impairment. Taken together with previous reports of time processing abnormalities in ASD (Allman et al., 2011; Bebko et al., 2006; Boucher et al., 2007; Brodeur et al., 2014; Falter et al., 2012a; Falter et al., 2012b; Falter et al., 2013; Gepner & Féron, 2009; Gowen & Miall, 2005; Karaminis et al., 2016; Kargas et al., 2015; Kwakye et al., 2011; Maister & Plaisted-Grant, 2011; Martin et al., 2010; Szelag et al., 2004; Whiting & Dixon, 2015; Ribeiro Zukauskas et al., 2009), our original findings point to a broad timing impairment in ASD as we outline in the following (see also Supplementary Table 2).

First, we observed ASD-related abnormalities in a broad time-range spanning from sub-second duration discrimination thresholds (~37 ms) and more variable simultaneity thresholds (~42 ms) to shorter inter-tap intervals (~693 ms), and to an impaired sense and management of time incorporating awareness of the past, present and future. Thus, individuals with ASD have atypical time processing ranging from very brief sub-second time scales, which are processed largely automatically (Lewis & Miall, 2003a; Lewis & Miall, 2003b), to the broadest temporal perspective that depends on high-level cognitive processing.

However, it is important to note that no significant group differences were found in the supra-second interval range, as assessed by prospective and retrospective timing tasks, i.e. supra-second duration discrimination thresholds and verbal duration estimates. Arguably, supra-second timing requires a relatively high load of executive functions, including working memory and sustained attention, which was equally demanding for children with ASD and TD controls. Nevertheless, children with ASD still tended to have higher thresholds and longer time estimates than healthy controls, in line with the significant group difference observed in the sub-second discrimination task (> 200 ms). We are thus hesitant to conclude that supra-second interval timing is intact in ASD, given a relatively small sample size and a possibility of Type II error.

Second, children with ASD showed atypical timing in all sensory modalities tested, i.e. in the auditory duration discrimination and visual simultaneity judgment tasks, as well as in the free tapping task that involved a continuous loop between motor output and tactile input. Thus, timing deficits in ASD are not restricted to a single-modality, but instead they are spread across different sensory systems.

Third, timing tasks showing abnormalities in the ASD group were based on a wide range of behavioural and cognitive functions, such as motor control in the free tapping task, spatial attention in the simultaneity judgment task, and working memory in the duration discrimination task. Parent-rated sense and management of time and temporal foresight were largely dependent on the child's long-term memory and planning skills. Our findings thus suggest that timing deficits in ASD are not dependent on a single behavioural or cognitive function.

Fourth, ASD-related timing impairments were observed in all three broad classes of time processing functions, i.e. motor timing, perceptual event- and interval-timing, and temporal perspective. Regarding motor timing, we replicated the earlier preliminary findings of faster tapping speed in ASD (Gowen & Miall, 2005), although contrary to the free tapping task used in the current study, Gowen and Miall (2005) instructed their participants to tap as fast as possible. Given that we found no group differences in motor processing speed as revealed by the RT analysis, our observation of the shorter inter-tap intervals in children with ASD reveals atypical timing of rhythmic motor processing. Notably, free tapping speed was considerably slower in our TD group (dominant hand: M=1053 ms) compared to previous reports of healthy 9-year-old children (M=723 ms; Rubia et al., 2003) or adults (bimodal M=272 ms and 450 ms; Collyer et al., 1994). Our participants tapped in blocks of 50 taps, whereas a sequence of 80 taps was used by Rubia and colleagues (2003), although it is uncertain whether a longer sequence could lead to the faster tapping. Further research is needed to establish a typical free tapping speed in a paediatric population, and to assess factors that might contribute to faster tapping in ASD, such as impulsivity, higher level of motivation to end the task, or increased arousal.

The group difference observed in the sub-second duration discrimination task is coherent with other studies reporting abnormal perceptual timing in ASD (Allman et al. 2011; Bebko et al. 2006; Brodeur et al., 2014; Falter et al. 2012a; Falter et al., 2012b; Falter et al. 2013; Karaminis et al., 2016; Kargas et al., 2015; Kwakye et al. 2011; Maister & Plaisted-Grant, 2011; Martin et al. 2010; Szelag et al. 2004). Furthermore, children with ASD showed more variable thresholds of simultaneity judgments compared to control participants, although the mean of thresholds did not differ between the groups. We have previously found decreased simultaneity thresholds in adults with ASD, when simple vertical bars were used as visual stimuli (Falter et al., 2012a; Falter et al., 2013). Arguably, the use of more complex and potentially more distracting stimuli like the "angry birds" might have increased task demands and simultaneity thresholds in some individuals with ASD. Interestingly, some individuals with ASD showed exceptionally low simultaneity thresholds, resembling the lower end of thresholds found in our previous sample (Falter et al., 2012a). This together with the generally significantly larger variability of thresholds, points towards subgroups of individuals with ASD with different cognitive profiles.

Our finding of impaired sense and management of time in children with ASD replicates a previous study that used the same IAT questionnaire (Allman et al., 2011). In addition to the parent-rated assessment, future studies should employ more stringent experimental paradigms for the assessment of temporal perspective in ASD, such as delay discounting tasks known to be sensitive to the developmental maturation of future orientation (Steinberg et al., 2009).

Fifth, performance measures of different timing tasks were inter-related within the ASD group but not among healthy controls, as demonstrated by significant correlations between tapping speed and simultaneity thresholds as well as IAT scores. Significant associations between motor timing, perceptual timing and temporal perspective suggest that individuals with ASD might be employing similar generic processing strategies for different timing function requirements. The lack of timing function-specific processing is coherent with more general observations that individuals with ASD have difficulties in tasks and situations requiring cognitive and behavioural flexibility (Green et al., 2007; Memari et al., 2013); instead, they tend to employ the same strategy irrespective of a given task. Arguably, a somewhat lower and more spread IQ could have been one of such unifying factors in the ASD group. Alternatively, as we argue below, inter-task associations could be driven by a shift from the local to the global neural generators of timing having a decisive role in task performance.

Sixth, simultaneity thresholds, slopes and time management skills were correlated with symptom severity in the ASD group, replicating earlier reports of a significant association between perceptual timing and language and communication symptoms in ASD (Allman et al., 2011; Falter et al., 2012b). Given that optimal timing accuracy is essential for the processing of language (Wearden, 2008) and social communication (Schirmer et al., 2016), our findings and previous reports (Allman et al., 2011; Falter et al., 2012b) provide converging evidence for a direct relationship between timing functions and the pathology of ASD (Boucher, 2001).

Follow-up research into timing impairments in ASD should look into possible interactions between time-related processes and key symptoms and comorbid deficits of autism. Arguably, such deficits as impaired detection of temporal cues of eye gaze, stereotypical repetitive behaviours, and difficulties in language comprehension could partially stem from the more fundamental impairments in time processing. Recently, Stevenson et al. (2016) proposed one such mechanistic link: temporal deficits in ASD might trigger difficulties in speech communication by preventing optimal audio-visual integration of sensory information. New experimental approaches are needed to disambiguate whether timing impairment plays a specific role in the ontology of the ASD phenotype, or alternatively if it is secondary to the core impairments. Furthermore, assuming the potential of a causal link between timing deficits and ASD symptoms, perceptual learning therapies should be considered, aiming to recalibrate atypical timing (Stevenson et al., 2016).

Importantly, timing abnormalities are not specific to ASD (Falter & Noreika, 2011; Falter & Noreika, 2014), as they are also widespread in other developmental disorders such as attention-deficit/hyperactivity disorder (Noreika et al., 2013; Toplak et al., 2006) and developmental dyslexia (Farmer et al. 1995; Goswami, 2011). Comparative studies are strongly encouraged to establish whether some of the timing deficits are disorder-specific, and whether any of the timing deficits could be used as a cognitive-diagnostic marker of ASD (Falter & Noreika, 2011; Falter & Noreika, 2014).

Finally, the possible neurophysiological mechanisms underlying a generalized timing impairment in ASD are still largely unknown. Timing research in healthy individuals is characterized by two main competing theoretical accounts that have been developed in the last 20 years. The task-dependent account implies multiple relatively autonomous neural mechanisms of timing whose involvement in a particular timing task depends on time-scale, modality, automaticity and other relevant features (Hayashi et al. 2014; Lewis & Miall, 2003). In contrast, the task-independent account suggests a single core timing mechanism in the brain that is involved in all-timing tasks (Merchant et al., 2013; Schubotz et al., 2000). ASD literature on mechanisms is very scarce, but findings from neuroscience can inform the question of neurofunctional differences underlying abnormal timing patterns in ASD. For instance, an association was found between atypical visual event timing and patterns of magnetoencephalography (MEG) visual evoked potentials in the occipital region in individuals with ASD (Falter et al., 2013), which implies modality-specific mechanisms of timing function relied upon in ASD. On the other hand, a theoretical proposal that impairment of the inferior olives may disrupt temporal brain synchronization, which could eventually lead to multiple deficits in autism (Welsh et al., 2005), represents a preliminary task-independent account of timing in ASD.

Arguably, the inter-task correlations across timing tasks found in the present study point to a common neural underpinning of timing deficits in ASD. Particularly appealing is the task-independent proposal that a cortico-thalamic-basal ganglia circuit forms the core timing mechanism, which actively interacts with other timing task- and modality-dependent circuits (Merchant et al., 2013). Given widely reported abnormalities of basal ganglia (Sears et al., 1999) and their interaction with the thalamus (Haznedar et al., 2006) and neocortex (Prat et al., 2016) in individuals with ASD, the cortico-thalamic-basal ganglia hypothesis of generalized timing impairments opens a promising avenue for future cognitive neuroscience studies of time processing in ASD.

The present study had several limitations that should be considered when interpreting the results. A relatively small sample size may have led to false positive or false negative results, and further replication studies are needed to assess different timing functions in ASD. Likewise, despite correction for multiple comparisons, results from the correlation analyses should be regarded as preliminary and interpreted with caution.

Even though there were no significant group differences in IQ scores, participants with ASD tended to have lower scores on all IQ subscales, which was a likely contributor to the increased tapping speed in the ASD group. At the same time, the highest individual IQ score was a remarkable Perceptual Reasoning Index of 151 observed in the ASD group, highlighting a large heterogeneity in our ASD sample, which could have led to different timing profiles and affected ASD and TD comparisons. Furthermore, three children with a clinical diagnosis of ASD scored 0 on one of the ADOS subscales, possibly showing milder symptoms in some domains. These and other individual differences could have increased timing variability in the ASD group. For instance, a violin plot of the sub-second duration discrimination thresholds indicates that measures of central tendency did not accurately represent performance of the ASD group, with individual thresholds clustering either below or above the group mean (see Fig 2C). Nevertheless, increased variance in the ASD group was not observed for each timing task, e.g. while the ASD group showed a higher threshold variance in the sub-second duration discrimination task, no difference was observed in the supra-second version of the same task. This task-specific observation points to time scale-dependent, rather than generic variability of responses.

When choosing the tasks, we aimed to cover different timing functions, intervals and modalities. While this enabled an efficient assessment of many different aspects of timing in ASD, it also complicated inter-task comparisons. In particular, abnormalities in one task but not another task, such as group differences in duration discrimination but not in simultaneity thresholds, could be due to unspecific task differences, such as the sensory modality of stimuli. Likewise, we were able to incorporate feedback only in one task, and hence participants' motivation may have been lower when carrying out other tasks. Ideally, a larger study sample would be recruited with subgroups of participants taking different subsets of timing tasks, which could circumvent some of these limitations.

In conclusion, while the current results point towards a generalised temporal processing abnormality in ASD in a series of tasks spanning different functions, scales and modalities, some results show mixed evidence and performance in a typical range in the ASD group. In particular, even though group differences were found on a wide range of temporal processing tasks including motor timing, perceptual timing, and temporal perspective, we observed intact supra-second interval timing as well as retrospective time estimation. Nevertheless, several intact timing aspects, in particular simultaneity thresholds and slopes, were associated with clinical ASD symptoms. Together with the increased performance variability, this pattern of results highlights the complex interactions between time processing functions and ASD symptomology and the large heterogeneity of autistic cognitive profiles that keeps representing a challenge for autism research.

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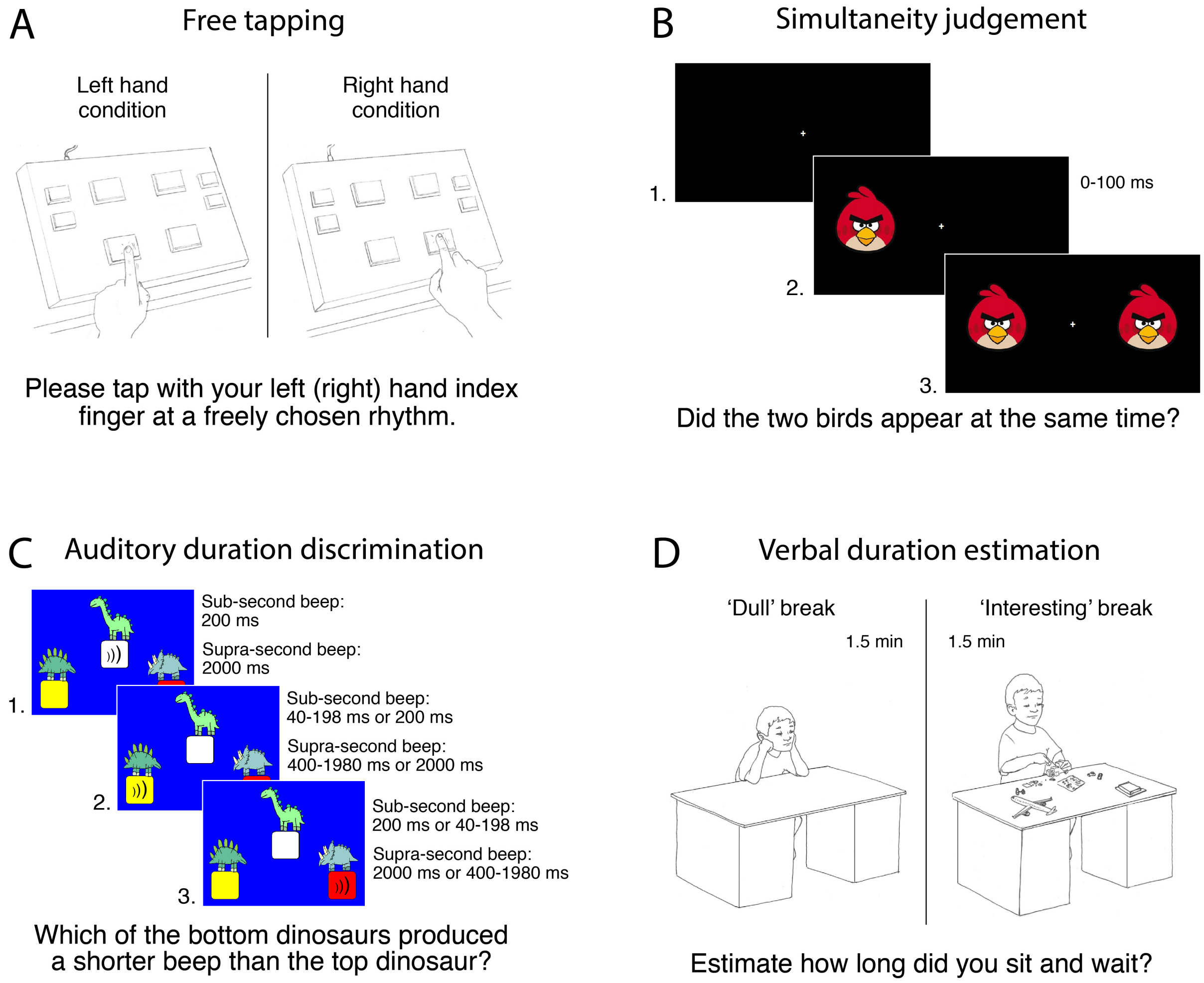
Table

Table 1. Age, neuropsychological profile, and symptom severity of study participants

	ASD (N=17; 2 female)			TD (N=18; 3 female)		
	Mean	**SD**	**Range**	**Mean**	**SD**	**Range**
Age	11:0	2:4	8:1 – 14:3	10:4	1:7	8:0 – 14:3
VCI	99	16	72 – 132	107	12	88 – 134
PRI	106	20	73 – 151	109	11	93 – 129
WMI	103	21	73 – 133	105	14	82 – 142
PSI	98	12	73 – 121	105	12	94 – 141
FSIQ	102	18	73 – 144	109	10	92 – 127
ADOS-A	2.59	1.06	0 – 4			
ADOS-B	6.88	2.96	2 – 12			
ADOS-D	2.29	1.57	0 – 5			
SCQ-A	6.00	2.78	1 – 11			
SCQ-B	6.24	3.19	2 – 14			
SCQ-C	4.29	2.05	1 – 8			

Note. Means, standard deviations, and ranges of age (years:months), Verbal Comprehension Index (VCI), Perceptual Reasoning Index (PRI), Working Memory Index (WMI), Processing Speed Index (PSI), and Full Scale IQ (FSIQ) of participants with ASD and TD participants. ADOS-G Communication Domain (ADOS-A), ADOS-G Reciprocal Social Interaction Domain (ADOS-B), and ADOS-G Stereotyped Behaviours and Restricted Interests Domain (ADOS-D), SCQ: Lifetime Social Interaction Domain (SCQ-A), SCQ: Lifetime Communication Domain (SCQ-B), SCQ: Lifetime Stereotyped Behaviour Domain (SCQ-C) of participants with ASD.

Figures and figure captions



Free tapping

Please tap with your left (right) hand index finger at a freely chosen rhythm.

Simultaneity judgement

Did the two birds appear at the same time?

Auditory duration discrimination

Which of the bottom dinosaurs produced a shorter beep than the top dinosaur?

Verbal duration estimation

Estimate how long did you sit and wait?

Figure 1. Experimental tasks carried out by ASD and TD participants: (A) free tapping; (B) simultaneity judgment; (C) sub-second and supra-second versions of the auditory duration discrimination, and (D) naturalistic verbal duration estimation.

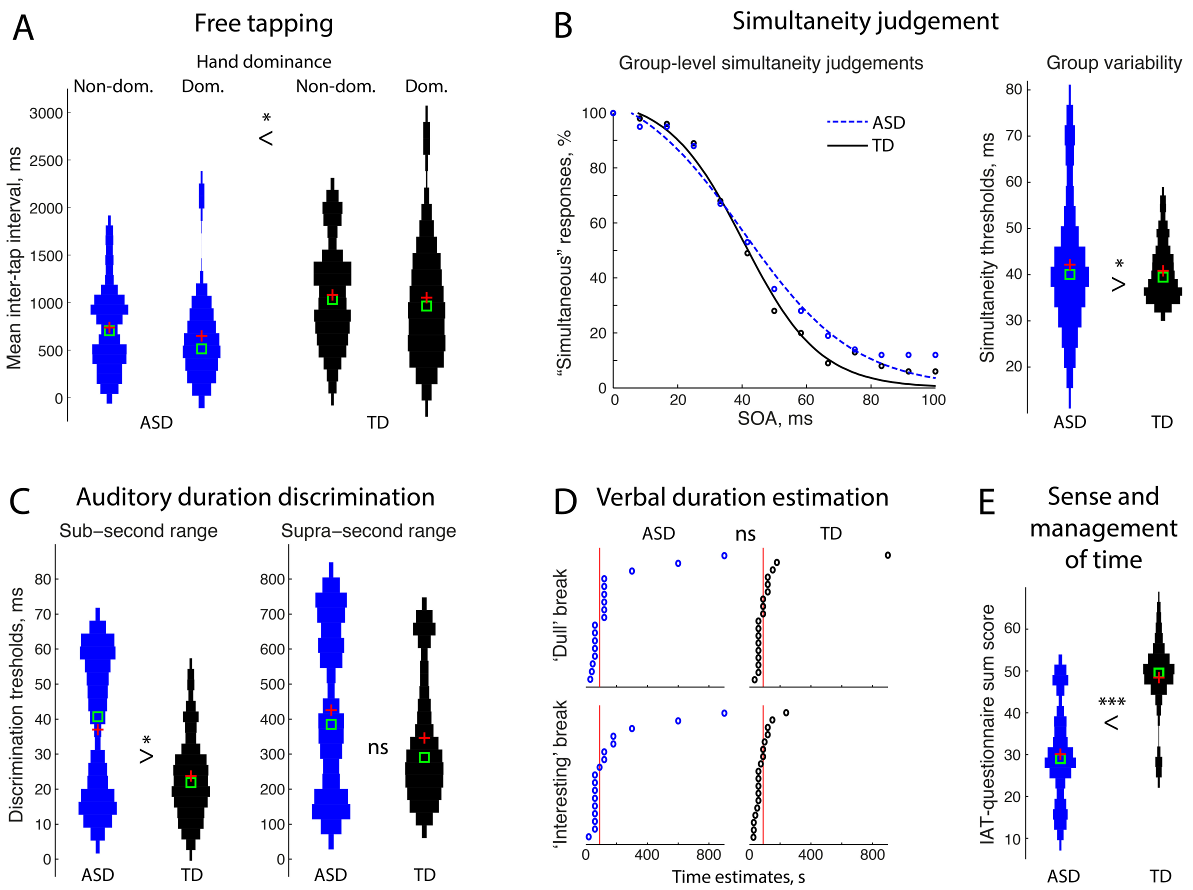


Figure 2. Distributions of experimental timing measurements in ASD (blue) and TD (black) participants. (A) Free tapping task: Violin plots of the mean inter-tap interval presented separately for each hand and experimental group. Negative values are due to the smoothing of probability density. In these and other violin plots, the red cross depicts the mean, and the green square shows the median value of a given distribution. The tapping speed was significantly faster in the ASD group. (B) Simultaneity judgment task: logistic functions fitted to the proportions of trials with reported simultaneity across 12 stimulus onset asynchronies, averaged separately within ASD and TD groups (left). Violin plots of simultaneity thresholds as assessed from individual logistic fits (right). Individuals with ASD had a significantly higher variance of thresholds compared to TD group. (C) Violin plots of individual thresholds in the sub-second (left) and supra-second (right) versions of the auditory duration discrimination task. Individuals with ASD had significantly higher sub-second thresholds

compared to TD group. Interestingly, a sub-second violin plot revealed a binomial distribution in the ASD group. (D) Verbal duration estimation task: individual participants sorted by the smallest to the largest estimate of 90 s ‘dull’ (top) and ‘interesting’ (bottom) breaks. The actual intervals of 90 s are marked as red verticals. No significant group differences were observed. (E) Violin plots of individual It’s About Time (IAT) questionnaire sum scores, as rated by participants’ parents. Individuals with ASD had significantly lower IAT scores compared to the TD group, indicating a reduced sense and management of time in the ASD group. Raw (untransformed) values are plotted in the figure; however, the significance levels are derived from the tests that were carried out on the corrected-to-normal variables where appropriate. *$p<0.05$, ***$p<0.0005$.

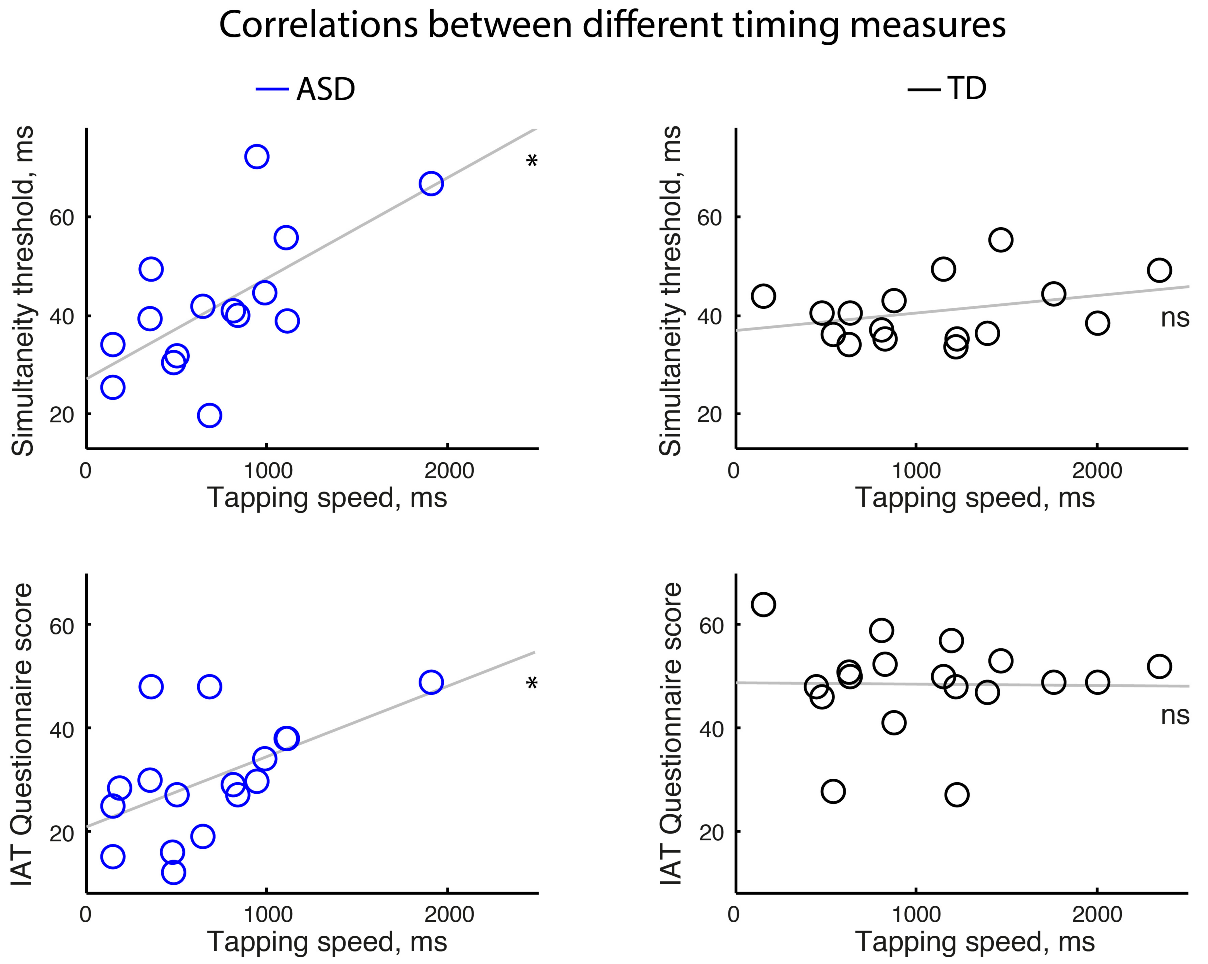


Figure 3. Correlations between different timing measures, calculated separately across ASD and TD individuals, who are depicted as blue and black circles respectively. Raw values are presented, and the least-squares lines are plotted to visualize an association that was assessed either with Pearson or Spearman correlation test. *p<0.025.

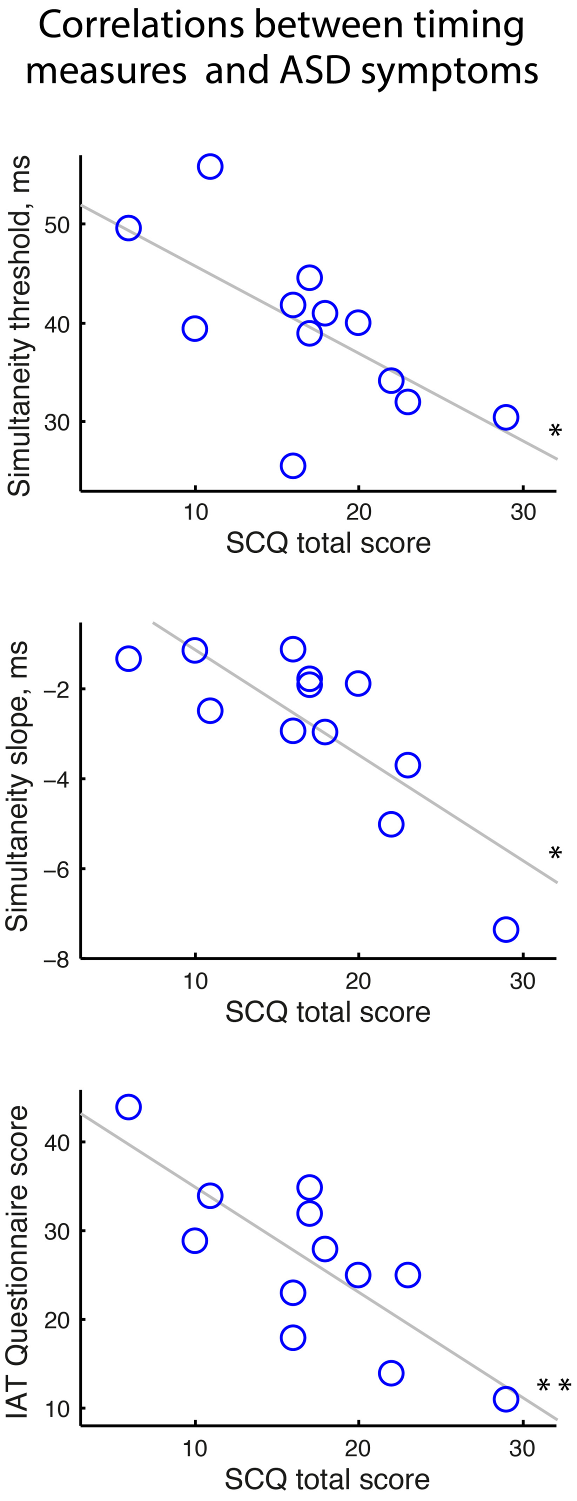


Figure 4. Correlations between timing measures and ASD social communication symptoms. Raw values are presented, and the least-squares lines are plotted to visualize an association that was assessed either with Pearson or Spearman correlation test. *p<0.025; **p<0.0025.

Supplementary material

Supplementary methods

Auditory duration discrimination: Threshold estimation

Discrimination thresholds were estimated using a more virulent version of the parameter estimation by sequential testing (PEST) procedure (Findlay, 1978; Taylor and Creelman, 1967). There were 80 shorter-lasting stimuli available for presentation: from 40 ms to 198 ms, dispersed in steps of 2 ms, for the sub-second version, and from 400 ms to 1980 ms, dispersed in steps of 20 ms, for the supra-second version. The PEST algorithm started with the easiest discrimination of 200 ms and 40 ms intervals for the sub-second run. The supra-second run started with 2000 ms and 400 ms intervals. Following one or several correct responses, the discrimination difficulty was increased, which was initially done by 15 steps (30 ms for the sub-second and 300 ms for the supra-second task). Once an error was made on one or several consecutive trials, the discrimination was made easier. The exact number of consecutive trials at the same stimulus duration varied depending on the accumulating evidence of the proportion of correct responses. Stimulus duration changed when the observed number of correct responses deviated from the expected target value by parameter W (Wald sequential likelihood ratio), and W gradually increased as a function of trial N (Findlay, 1978). The direction of discrimination difficulty kept changing, progressively reducing the step size, until the threshold level at 75% of correct responses was determined. The threshold was computed from the trials following the fourth reversal between correct and mistaken responses.

Supplementary results

Free tapping

Differences in tapping coefficient of variation (SD/M) were analysed using the same mixed ANOVA with one between-participants factor of Group (ASD, TD) and one within-participants factor of Hand (dominant, non-dominant). All tests were computed on corrected-to-normal variables. The ANOVA showed a trend for the main Group effect (F(1,33)=3.43, p=0.073, η_p^2=0.09) and a statistically significant main effect of Hand (F(1,33)=5.1, p=0.031, η_p^2=0.134). The ASD group showed a slight tendency towards a higher tapping coefficient of variation (back-transformed: M=0.19, SD=0.09, 95% CI=[0.11, 0.18]) than the TD group (M=0.12, SD=0.04, 95% CI=[0.08, 0.13]). The tapping coefficient of variation was higher for the non-dominant hand (M=0.13, SD=0.01, 95% CI=[0.11, 0.15]) compared to dominant hand (M=0.11, SD=0.07, 95% CI=[0.09, 0.13]). There was no significant Group × Hand interaction (p=0.47).

Auditory duration discrimination: Reaction times

Aiming to assess reaction times (RT) as a control analysis for the free tapping group differences, mean RTs in the auditory duration discrimination task were analysed. RTs over 4 s were excluded, as they were not representative, e.g. participants occasionally diverted their attention away from the task. RTs of sub-second and supra-second discrimination versions were not different within groups and were averaged. Differences between the groups were analysed with an independent samples t-test, which was computed on variables corrected to normal. The mean RTs did not differ between the ASD group (corrected variables transformed back to milliseconds: M=1128, SD = 302.09, 95% CI=[983.29, 1294.01]), and the TD group (M=1258.15, SD=284.67, 95% CI=[1124.62, 1407.68]; t(33)=-1.310, p=0.2,

η^2=0.05). RTs did not correlate with the average free tapping speed in either of the groups: ASD (r_s(17)=-0.174, p=0.5) and TD (r_s(18)=0.139, p=0.58).

Correlations between IQ and temporal processing tasks

To test whether somewhat lower and wider spread IQ scores could have contributed to the atypical time processing in the ASD group, correlations were carried out between Full Scale IQ and timing measures that yielded the key group differences, namely free tapping speed, sub-second duration discrimination thresholds, and IAT summary scores. The correlation between Full Scale IQ and free tapping speed was statistically significant for the ASD group (r_s(17)=0.61, p=0.009), but not for the TD group (r_s(18)=−0.08, p=0.74). There were no significant correlations between Full Scale IQ and sub-second duration discrimination thresholds (ASD: r_s(17)=−0.08, p=0.75; TD: r_s(18)=0.28, p=0.26), or between Full Scale IQ and IAT summary scores (ASD: r_s(17)=0.25, p=0.34; TD: r_s(18)=−0.29, p=0.24).

Correlations between temporal processing tasks: Trends

We found a correlation in the ASD group between discrimination thresholds in the sub-second dinosaur task and IAT sum scores (r_s(17)=0.49, p=0.048) although it did not reach statistical significance after Bonferroni–Holm correction (α-level=0.025). The lower the IAT score (worse sense of time) the lower (more accurate) were discrimination thresholds in the sub-second dinosaur task in the ASD group. In the TD group there was no statistically significant correlation between the sub-second dinosaur task and the IAT score (r_s(18)=0.005, p=0.98). Time estimation in the dull break correlated with slopes of psychometric functions in the simultaneity task (r_s(15)=0.54, p=0.037) in the ASD group, but not in the TD group

($r_s(16)=0.28$, $p=0.29$), although the correlation did not reach statistical significance after Bonferroni–Holm correction (α-level=0.025).

Correlations between ASD symptom severity and timing measures: Trends

We found a correlation between simultaneity thresholds and ADOS sum scores ($r(12)=-0.638$, $p=0.026$) that just missed significance after Bonferroni-Holm correction (α-level=0.025). Furthermore, there were trends towards correlations between time estimation in the dull break and the total score ($r_s(12)=0.542$, $p=0.07$) and the ADOS stereotyped behaviour scores ($r_s(12)=0.54$, $p=0.072$).

Supplementary references

Findlay, J.M., 1978. Estimates on probability functions: A more virulent PEST. Percept. Psychophys. 23, 181–185. doi:10.3758/BF03208300

Taylor, M.M., Creelman, C.D., 1967. PEST: Efficient estimates on probability functions. J. Acoust. Soc. Am. 41, 782–787. doi:10.1121/1.1910407

Supplementary tables

Supplementary Table 1. Age, cognitive and intelligences scores, and diagnostic measures of study participants performing simultaneity judgment task

	ASD (N=15)			TD (N=16)		
	Mean	**SD**	**Range**	**Mean**	**SD**	**Range**
Age	11:3	2:2	8:2 – 14:3	10:4	1:7	8:0 – 14:3
VCI	98	17	72 – 132	107	8	96 – 120
PRI	108	20	73 – 151	109	10	93 – 129
WMI	105	20	73 – 133	105	15	82 – 142
PSI	96	12	73 – 115	103	7	94 – 115
FSIQ	102	19	73 – 144	109	9	92 – 125
ADOS-A	2.47	1.06	0 – 4			
ADOS-B	6.47	2.80	2 – 12			
ADOS-D	2.27	1.58	0 – 5			
SCQ-A	6.07	2.92	1 – 11			
SCQ-B	6,27	3.22	2 – 14			
SCQ-C	4.20	1.86	1 – 7			

Note. Means, standard deviations, and ranges of age (years:months), Verbal Comprehension Index (VCI), Perceptual Reasoning Index (PRI), Working Memory Index (WMI), Processing Speed Index (PSI) and Full Scale IQ (FSIQ) of participants with ASD and TD participants. ADOS-G Communication Domain (ADOS-A), ADOS-G Reciprocal Social Interaction Domain (ADOS-B), and ADOS-G Stereotyped Behaviours and Restricted Interests Domain (ADOS-D), SCQ: Lifetime Social Interaction Domain (SCQ-A), SCQ: Lifetime Communication Domain (SCQ-B), SCQ: Lifetime Stereotyped Behaviour Domain (SCQ-C) of participants with ASD.

Supplementary Table 2: Means (standard deviations) of timing measures in different study groups

Timing task			ASD	Control
Free tapping *N* = 35	Inter-tap interval, ms		692.76* (448.51)	1066.43 (578.77)
Simultaneity judgment *N* = 31	Logistic function	Threshold, ms	42.19 (14.32)*	40.83 (6.35)
		Slope	-2.71 (1.68)	-2.85 (0.90)
Duration discrimination *N* = 35	Discrimination threshold, ms	Sub-second	36.98* (20.28)*	23.72 (12.03)
		Supra-second	425.74 (233.92)	346.12 (179.72)
Verbal time estimation *N* = 35	Estimate, s	Dull break	120	75
		Interesting break	60	60
Sense and management of time *N* = 35	IAT-questionnaire summary scores		30.19***	48.41

Note. Asterisks represent statistically significant group differences in different conditions of temporal processing tasks: *p<0.05; ***p< 0.001. Statistical values in this table are untransformed. When temporal processing variables were corrected to normal for statistical tests, significance rating refers to tests computed on corrected-to-normal variables.