Generalized timing impairment in Autism Spectrum Disorders
across time scales and paradigms

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Background: Individuals with ASD have abnormal motor and perceptual functions that do not currently form diagnostic criteria of ASD, but nevertheless may affect every day behavior. 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. **Methods:** 17 children diagnosed with ASD and 18 typically developing age- and IQ-matched developing controls carried out a set of motor and perceptual timing tasks: free tapping, simultaneity judgment, auditory duration discrimination, and verbal time estimation. Parents of participants filled in a questionnaire assessing the sense and management of time. **Results:** 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 time 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. **Conclusions:** Children with ASD show a generalized temporal deficit spanning a range of temporal processing tasks including motor timing, perceptual timing, and temporal perspective.

47

Keywords: Autism Spectrum Disorders; children; motor timing; perceptual timing; sense and management of time.

Introduction

Autism Spectrum Disorder (ASD) is an umbrella category for specific types of pervasive neurodevelopmental conditions. ASDs are marked by persistent and severe deficits in social communication and interaction, and repetitive and restricted patterns of action, behaviour or interests. Further, these symptoms must present from early childhood and negatively affect every day functioning (American Psychiatric Association, 2013). Both clinical reports and research literature suggest that individuals with ASD also suffer from difficulties in motor coordination (Ming et al. 2007) and sensory perception (Blake et al. 2003; Milne et al. 2002). In relation, cumulative research evidence is beginning to point toward ASD-related problems in temporal processing (Allman et al. 2011; Bebko et al. 2006; Boucher et al. 2007; Falter et al. 2013; Falter, Elliott, et al. 2012; Falter, Noreika, et al. 2012; Gepner & Féron, 2009; Gowen & Miall, 2005; Kwakye et al. 2011; Maister & Plaisted-Grant, 2011; Martin et al. 2010; Szelag et al. 2004; Wallace & Happé, 2008; Whiting & Dixon, 2015; Ribeiro Zukauskas et al. 2009); for review, see (Allman & Falter 2015; Falter & Noreika 2014; Stevenson et al. 2016; Welsh et al. 2005). However, the literature is not entirely consistent and some timing functions may remain intact in ASD (Bebko et al. 2006; Glazebrook et al. 2008; Jones et al. 2009; Kwakye et al. 2011; Mostofsky et al. 2000).

Temporal processing functions can be divided into motor timing, perceptual timing, and temporal perspective. 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 cognitive 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 and interval timing tasks. Event timing (also called temporal event-structure coding) comprises the perception and judgment of the relative timing of events, which can be assessed 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, Elliott, et al. 2012; Falter et al. 2013). In particular, adults with high-functioning autism and Asperger syndrome had lower simultaneity thresholds (Falter, Elliott, et al. 2012) and higher discriminability 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 using preferential looking at asynchronous stimuli paradigm found a temporal impairment 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 modality tested.

Interval timing refers to the judgment of attended temporal intervals or durations, which can be tested using a wide range of tasks, including duration reproduction, production, estimation,

discrimination, bisection and generalization. Studies on interval timing in ASD have, with a few exceptions (Jones et al. 2009; Mostofsky et al. 2000), uncovered abnormal performance in individuals with ASD (Allman et al. 2011; Falter, Noreika, et al. 2012; Maister & Plaisted-Grant, 2011; Martin et al. 2010; Szelag et al. 2004; Wallace & Happé, 2008) but see (Jones et al. 2009; Mostofsky et al. 2000). Three 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, Noreika, et al. 2012). Similarly, a reduced sensitivity of interval timing in ASD was found using a temporal bisection task (Allman et al. 2011). However, two studies testing 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.

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 individuals with ASD to 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. tendency to relate past and future in a current situation, ability to understand that events evolve through time, and the ability to conceive successive events as one entity (Boucher et al. 2007; Allman et al. 2011).

The reviewed literature presented above leads to a twofold conclusion that calls for further research. First, there is preliminary evidence of temporal processing abnormalities in ASD in all domains: motor timing, perceptual timing, and temporal perspective. Second, and generally in line with perception studies in ASD (Falter, 2013), the findings are frequently inconsistent with different studies reporting impaired, intact or superior timing in ASD. Arguably, many of these inconsistencies of evidence can be attributed to the diversity of behavioural and perceptual profiles that fall within ASD. Combined with sampling and diagnostic differences across studies, this could arguably lead to inconsistent findings regarding temporal processing in ASD. Furthermore, it remains unclear whether individuals who have impairment in one timing function would also show abnormalities in other functions.

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 whether there is a generalized timing deficit that spans across several timing functions in individuals with ASD. To address these questions, we aimed to test a whole battery of timing tasks, tapping different time scales and functions, in the same 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) that had received a diagnosis of Asperger syndrome (F84.5) at Turku University Hospital, Finland, between 2005 and 2014. Eligible children were searched from electronic medical records based on diagnosis and age (8-15 years). Exclusion criteria were other neurological and psychiatric diagnoses than Asperger syndrome. Written information about the study was sent to all eligible children and their families. Those who returned parents' informed consent and child's assent sheet were invited for research participation. The Autism Diagnostic Observation Schedule (ADOS) (Lord et al. 2000) and Social Communication Questionnaire (SCQ-Lifetime) (Rutter et al. 2003) were used to verify diagnosis. Two children did not meet the cut-off scores in ADOS. After this finding, their medical records were examined. As their diagnosis was based on a multi-professional clinical opinion, they were decided to be included in the study. To examine the intellectual abilities, the Wechsler Intelligence Scale for Children (WISC-IV) was administered (Wechsler, 2003).

Controls. The control group consisted of 18 typically developed (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. The groups were matched on gender, age ($U = 135$, $P = .568$), and IQ ($t(33) = -1.582$, $P = .123$). Demographic data can be found in Table 1.

Ethical considerations. Study protocol was approved by the Ethics Committee of the University of Turku and Turku School of Economics.

174 **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	105	20	73 – 151	109	11	93 – 129
WMI	100	21	73 – 133	105	14	82 – 142
PSI	97	12	73 – 121	105	12	94 – 141
FSIQ	100	18	73 – 144	109	10	92 – 127
ADOS-A	2.59	1.06	0 – 4			
ADOS-B	6.88	2.96	2 – 12			
ADOS-C	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			

175 *Note.* Means, standard deviations, and ranges of age (years:months), Verbal Comprehension
176 Index (VCI), Perceptual Reasoning Index (PRI), Working Memory Index (WMI), Processing
177 Speed Index (PSI), and Full Scale IQ (FIQ) of participants with ASD and TD participants.
178 ADOS-G Communication Domain (ADOS-A), ADOS-G Reciprocal Social Interaction

Domain (ADOS-B), and ADOS-G Stereotyped Behaviours and Restricted Interests Domain (ADOS-C), SCQ: Lifetime Social Interaction Domain (SCQ-A), SCQ: Lifetime Communication Domain (SCQ-B), SCQ: Lifetime Stereotyped Behaviour Domain (SCQ-C) of participants with ASD.

Temporal processing tasks

Motor timing: Free tapping. The free tapping task was used to assess motor timing. 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 each 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 (Millisecond Software, 2003).

Perceptual event timing: Simultaneity judgment task. Participants were presented with two ‘angry birds’ figures on a black computer display. The stimulus onset asynchrony (SOA) between the two figures was either 0 ms, i.e. physically simultaneous, or physically asynchronous in one of 12 SOAs defined by the monitor refresh rate of 120 Hz, i.e. $[1:12] \times 8.33$ ms. In a two-alternative forced-choice procedure, participants were instructed to judge whether the two birds appeared on the screen at the same time or not by pressing one of two keys on the response box (see Fig. 1B). For each participant a psychometric function (a logistic curve) based on responses (proportion of ‘simultaneous’ responses across SOAs) was

fitted from which individual thresholds of simultaneity, operationalized as the inflection point of the psychometric function, were derived. The task was programmed using Inquisit 3 (Millisecond Software, 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. 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. 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 software (Audacity Team, 2010), and presented to both ears at the same comfortable volume using regular headphones. 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 – using a varying duration of a shorter beep – auditory discrimination thresholds were estimated (see Supplementary Methods).

Perceptual interval timing: Verbal duration estimation (minute-range). 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. When the participant was seated, 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.

Sense and management of time: *It’s About Time – Questionnaire*. 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). IAT summary score was used as a key measure with a higher score indexing better sense and management of time.

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

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 (Osborne, 2010) where applicable, otherwise non-parametric tests were applied. The transformations were square root for the mean inter-tap interval data, $[\text{Ln}(\text{data value} \times 100)]$ 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, $[\text{Ln}10(\text{maximum value}+1-\text{data value})]$ for the slopes of the psychometric function in the Simultaneity task, and $[(\text{data value})^{1.5}]$ for the IAT questionnaire–score data. 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, 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

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). All tests were computed on corrected-to-normal variables. ANOVA revealed a statistically significant main effects of Group ($F(1,33)=4.640$, $p=0.039$, $\eta_p^2=0.123$) and Hand ($F(1,33)=4.389$, $p=0.044$, $\eta_p^2=0.117$). 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). Importantly, faster tapping in 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). 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 $\times$ Hand interaction was not significant ($p=0.454$). No significant Group differences were observed in tapping coefficient of variation (SD/M) (see Supplementary Results).

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
 TD group, indicating a reduced sense and management of time in the ASD group. * $p < 0.05$,
 *** $p < 0.0005$.

Perceptual event timing: Simultaneity task

Differences between groups in simultaneity thresholds and transformed-to-normal slopes of
 the psychometric function were analysed using independent samples t-tests. Four participants
 were excluded from further analysis in this task due to random response behaviour preventing
 curve fitting, resulting in 15 participants with ASD and 16 TD controls entering the analysis
 of the Simultaneity task (see Supplementary Table 1). The curve fits yielded average
 goodness of fit of $M = 0.94$ ($SD = 0.058$) in the ASD group and $M = 0.96$ ($SD = 0.017$) in the TD
 group, which was not significantly different ($t(16.27) = -1.480$). Variance of 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. Differences between groups were analysed using independent samples t -tests. The tests were computed on variables corrected to normal. 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% $CI=[16.61, 28.57]$; $t(28.53)=2.15$, $p=0.04$, $\eta^2=0.1$) (see Fig. 2C). The ASD group had statistically significantly higher variance of the sub-second discrimination thresholds 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 $F(1,33) = .145$).

Perceptual interval timing: Verbal time 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).

Sense and management of time: It's About Time – Questionnaire

Parents of 17 ASD and 18 TD participants filled out the IAT-questionnaire. Differences in IAT summary scores between groups were analysed using independent samples t-tests. The tests were computed on variables corrected to normal. 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 ($r_s(18)=-0.023$, $p=0.93$) (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. Similarly, several other inter-task correlations were significant before Bonferroni–Holm correction in the ASD, but not among TD participants (see Supplementary Results).

Figure 3. Correlations between different timing measures, calculated separately across ASD and TD individuals, who are depicted as blue and black circles respectively. * $p < 0.025$.

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. 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 ($r(12) = 0.78$, $p = 0.003$). 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).

Correlations between timing measures and ASD symptoms

Figure 4. Correlations between timing measures and ASD social communication symptoms.

* $p < 0.025$; ** $p < 0.0025$.

Discussion

We have applied a large battery of timing tasks to test a group of children with ASD and a group of typically developing 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; Falter, Elliott, et al. 2012; Falter, Noreika, et al. 2012; Gepner & Féron, 2009; Gowen & Miall, 2005; Kwakye et al. 2011; Maister & Plaisted-Grant, 2011; Martin et al. 2010; Szelag et al. 2004; Wallace & Happé, 2008; Whiting & Dixon, 2015; Ribeiro Zukauskas et al. 2009), our original findings univocally point to a generalized timing impairment in ASD (see Supplementary Table 2). In particular:

1) 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 time perspective that depends on high-level cognitive processing.

2) Children with ASD also 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.

3) Likewise, 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 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.

4) 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). 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 points to a timing-specific motor deficit.

Group difference observed in sub-second duration discrimination task is coherent with other studies reporting abnormal perceptual timing in ASD (Allman et al. 2011; Bebko et al. 2006; Falter, Elliott, et al. 2012; Falter, Noreika, et al. 2012; Falter et al. 2013; Kwakye et al. 2011; Maister & Plaisted-Grant, 2011; Martin et al. 2010; Szelag et al. 2004; Wallace & Happé, 2008). Furthermore, children with ASD had 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, Elliott, et al. 2012; Falter et al. 2013). Arguably, ASD-related enhancement of temporal resolution does not hold when more complex stimuli are presented, such as 'angry birds' used in the present study.

Alternatively, children with ASD have not yet developed strategies that produce the enhanced visual temporal resolution that we observe in adults. We also observed no significant group difference in the interval timing tasks involving relatively long time-scales, i.e. supra-second duration discrimination task (> 2 s) and verbal time estimation (90 s). Nevertheless, children with ASD still tended to have higher thresholds and longer time estimates than healthy controls, in line with a 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.

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 in future orientation (Steinberg et al. 2009).

5) 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 time 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.

6) Finally, 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, Noreika, et al. 2012). 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, Noreika, et al. 2012) provide converging evidence for a direct relationship between perceptual timing functions and diagnostic criteria of ASD.

Thus, 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. New experimental approaches are needed to disambiguate whether the generalized timing impairment plays a specific role in the ontology of the ASD phenotype, or alternatively if it is secondary to the core impairments. 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, neurophysiological mechanisms underlying generalized timing impairment in ASD are still largely unknown. Timing research in healthy individuals is characterized by two main competing theoretical accounts continuously being developed further in the last 20 years. The

task-dependent account implies multiple relatively autonomous neural mechanisms of timing whose involvement in a particular timing task depend 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 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.

In conclusion, we found a generalized timing impairment in children with ASD spanning a range of temporal processing tasks including motor timing, perceptual timing, and temporal perspective. Correlation of task performance in the ASD group, and a lack of thereof in the

TD group, points towards less differentiation and specification of timing functions in ASD that might underlie impairments in certain timing tasks.

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Conflict of interest

None.

Ethical standards

The authors assert that all procedures contributing to this work comply with the ethical standards of the relevant national and institutional committees on human experimentation and with the Helsinki Declaration of 1975, as revised in 2008.

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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 (Taylor & Creelman, 1967; Findlay, 1978). 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 correct responses, the discrimination difficulty was initially increased by 15 steps (30 ms for the sub-second and 300 ms for the supra-second task). Once an error was made, the discrimination was made easier. 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 ($F(1,33)=3.43$, $p=0.073$, $\eta_p^2=0.09$) and a statistically significant main effect of Hand ($F(1,33)=5.1$, $p=0.031$, $\eta_p^2=0.134$). The ASD group showed a slight tendency towards 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% $CI=[0.08, 0.13]$). 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 $\times$ 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% $CI=[1124.62, 1407.68]$; $t(33)=-1.310$, $p=0.2$, $\eta^2=0.05$). 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 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 of 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 ($r_s(12)=0.54$, $p=0.072$).

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758 **Supplementary tables**

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

	ASD (N=12)			TD (N=13)		
	Mean	SD	Range	Mean	SD	Range
Age	11:3	2:1	8:2 – 14:3	10:8	1:7	8:7– 14:4
VIQ	98	19	72 – 132	109	7	96 – 120
PRI	108	22	73 – 151	110	11	93 – 129
WMI	103	22	73 – 133	105	17	82 – 142
PSI	95	12	73 – 115	101	7	94 – 115
FSIQ	101	21	73 – 144	110	10	92 – 125
ADOS-A	2.50	0.80	2 – 4			
ADOS-B	6.75	2.53	2 – 12			
ADOS-C	2.58	1.44	1 – 5			
SCQ-A	6.25	3.19	1 – 11			
SCQ-B	6,58	3.32	2 – 14			
SCQ-C	4.17	1.64	2 – 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 (FIQ) 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-C), SCQ: Lifetime Social Interaction Domain (SCQ-A), SCQ: Lifetime Communication Domain (SCQ-B), SCQ: Lifetime Stereotyped Behaviour Domain (SCQ-C) of participants with ASD.

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Supplementary Table 2: Means (standard deviations) in different conditions in temporal processing tasks except for medians (range) in verbal time estimation

			ASD	Control
Free tapping <i>N</i> = 35	Inter-tap interval, ms	Dominant	648.98* (476.89)	1052.60 (647.58)
		Non-dominant	736.54* (445.35)	1080.26 (534.97)
Simultaneity judgment <i>N</i> = 31	Logistic function	Threshold, ms	42.19 (14.32)*	40.83 (6.35)
		Slope	-2.71 (1.68)	-2.85 (0.90)
Duration discrimination <i>N</i> = 35	Discrimination threshold, ms	Sub-second	36.98* (20.28)*	23.72 (12.03)
		Supra-second	425.74 (233.92)	346.12 (179.72)
	Reaction time, ms	Sub-second and Supra-second averaged	1168.67 (345.05)	1289.13 (296.97)
Verbal time estimation <i>N</i> = 35	Estimate, s	Dull break	120 (30-900)	75 (35-900)
		Interesting break	60 (20-900)	60 (27-240)
IAT – questionnaire <i>N</i> = 35	Summary scores		30.19*** (11.36)	48.41 (9.20)

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