

Predictive language processing in preschool children with autism spectrum disorder: An eye-tracking study

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

Abstract: Sentence comprehension relies on the abilities to rapidly integrate different types of linguistic and non-linguistic information. The present study investigated whether Mandarin-speaking preschool children with autism spectrum disorder (ASD) are able to use verb information predictively to anticipate the upcoming linguistic input during real-time sentence comprehension. 26 five-year-olds with ASD, 25 typically developing (TD) five-year-olds and 24 TD four-year-olds were tested using the visual world eye-tracking paradigm. The results showed that the 5-year-olds with ASD, like their TD peers, exhibited verb-based anticipatory eye movements during real-time sentence comprehension. No difference was observed between the ASD and TD groups in the time course of their eye gaze patterns, indicating that Mandarin-speaking preschool children with ASD are able to use verb information as effectively and rapidly as TD peers to predict the upcoming linguistic input.

Keywords: predictive language processing; anticipatory eye movements; visual world paradigm; autism spectrum disorder; child sentence comprehension

According to the *Diagnostic and Statistical Manual of Mental Disorders, fifth edition* (DSM-5; American Psychiatric Association, 2013), Autism Spectrum Disorder (ASD) is diagnosed on the basis of two symptom clusters: (1) persistent deficits in social communication and social interaction, and (2) restricted, repetitive patterns of

behaviour, interests, or activities. DSM-5 has introduced significant changes in the diagnostic criteria of ASD, among which one is that impairments in language abilities that are not employed in social communication are no longer included as a core symptom. However, a delay in language onset is one of the primary triggers for parents seeking referrals for their children who are eventually diagnosed with ASD (Robins et al. 2014).

There is enormous variability in the language profiles of children with ASD, especially in their expressive language. Some children with ASD never acquire functional spoken language; some have relatively good structural language, some exhibit deficits in both lexical and grammatical domains, and some demonstrate impaired grammar (Eigsti, Bennetto, & Dadlani, 2007; Garraffa, Coco, & Branigan, 2018; Kjelgaard & Tager-Flusberg, 2001; Naigles & Chin, 2015; Naigles & Tek, 2017; Smith, Mirenda, & Zaidman-Zait, 2007; Su, Naigles, & Su, 2018; Tager-Flusberg, 2016; Tager-Flusberg & Kasari, 2013; Tek et al., 2014; Wittke et al., 2017). In addition, receptive language seems to be relatively more impaired than expressive language (Hudry et al., 2010; Kasari et al., 2013; Kjelgaard & Tager-Flusberg, 2001; Luyster et al., 2008; Plesa-Skwerer et al., 2016). Previous research seems to suggest that the language comprehension abilities of children with ASD might be particularly impaired (Boucher, 2012; Eigsti et al., 2007, 2011; Howlin, 2003; Hudry et al., 2010; Koning & Magill-Evans, 2001; Kover et al., 2014; Perovic, Modyanova, & Wexler, 2013; Rapin & Dunn, 2003; Riches et al., 2012; Tager-Flusberg, 1981; Tager-Flusberg et al., 2005).

However, as Tager-Flusberg (2000) pointed out that the poor language comprehension abilities are likely to be related more to these children's overall lack of social responsiveness than to language processing deficits (see also Rutter,

Maywood, & Howlin, 1992). Note that much previous research that assessed the language comprehension abilities of children with ASD used offline tasks like standardized tests or caregiver reports. These offline tasks often require high response demands or interactions with the experimenters, which might pose particular difficulties for children with ASD, because children with ASD often exhibit various kinds of challenging behaviours or symptoms which might interact with the high task and communication demands, and thus frequently mask the comprehension abilities of these children (for an overview of methods for assessing receptive language in children with ASD, see, e.g., Kasari et al., 2013 and Plesa-Skwerer et al., 2016).

More recently, researchers have begun to explore alternative methods that can alleviate the task and communication demands, and thus directly and effectively assess the language comprehension abilities of children with ASD. For example, online methods, like eye tracking, have been used to study language comprehension in children and adolescents with ASD (Bavin, Kidd, Prendergast, & Baker, 2016; Bavin et al., 2016; Brock et al., 2008; Chita-Tegmark et al., 2015; Diehl et al., 2015; Naigles et al., 2011; Naigles & Fein, 2017; Naigles & Tovar, 2012; Norbury, 2017; Plesa-Skwerer et al., 2016; Swensen et al., 2007; Tovar, Fein, & Naigles, 2015; Venker et al. 2013). Compared with standardized tests and other offline tasks, eye tracking is a more sensitive testing paradigm to demonstrate children's comprehension abilities. It is sensitive to the time course of the comprehension process, and requires no explicit motor or language responses from a participant, and thus making it a promising paradigm to study younger children and minimally verbal children with ASD.

For example, Bavin, Kidd, Prendergast and Baker (2016) investigated whether 5- to 9-year-old English-speaking children with ASD were able to use lexical

information during real-time sentence comprehension. The results showed that the children with ASD, like their typically developing (TD) peers, can use lexical information during sentence comprehension. However, in the study by Bavin and colleagues, there was a huge variability in the ages of the participants with ASD. Their ages ranged from 5 to 9 years and it was not clear how many participants were included in each age group. Diehl et al. (2015) investigated the use of prosodic cues in real-time sentence comprehension by English-speaking children and adolescents with ASD, and found that school-age children and adolescents with ASD, like their TD peers, were able to use prosodic cues to resolve syntactic ambiguity when there is no need to revise their initial interpretation. However, the children in their study were between the ages of 8 and 12. It remains largely unclear how preschool children with ASD process a sentence as it unfolds in real time. Real-time sentence comprehension is an under-investigated area of language comprehension in children with ASD. Sentence comprehension relies on the abilities to rapidly integrate different types of linguistic and non-linguistic information. Thus, understanding how children with ASD comprehend a sentence using both linguistic and non-linguistic cues will enable us to better understand the nature of the sentence processing mechanism in ASD.

Previous research suggests that TD children incrementally compute the meaning of a spoken sentence using both structural and semantic information of the sentence (Andreu, Sanz-Torrent, & Trueswell, 2013; Choi & Trueswell, 2010; Fernald et al., 2008; Huang et al., 2013; Lew-Williams & Fernald, 2007; Nation, Marshall, & Altmann, 2003; Omaki, 2010; Sekerina & Trueswell, 2012, Trueswell et al., 1999; Van Heugten & Shi, 2009; Zhou, Crain, & Zhan, 2014; Zhou & Ma, 2018). Much research has focused on how hearers incrementally establish reference during sentence interpretation while integrating linguistic and visual information in the

scene. This line of research was initiated by Altmann and colleagues. The key question is how and when linguistic information from spoken sentences is integrated with information retrieved from the visual environment, and anticipatory eye movements are often taken as an indicator of incremental sentence processing (e.g., Altmann & Kamide, 1999; 2007; Kamide, Altmann, & Haywood, 2003; Kamide, Scheepers, & Altmann, 2003; Zhan, 2018; Zhan, Crain, & Zhou, 2015).

For example, Altmann and Kamide (1999) first reported that when interpreting a sentence, the selectional information of a verb was activated by adults to predict the upcoming object noun phrase, which resulted in anticipatory eye movements towards the most plausible object in the visual display. In the study, the participants heard sentences like *The boy will eat the cake* and *The boy will move the cake* while viewing an image of a scene with a boy, a cake, and a few toys. In the former sentence the verb *eat* can take only one of the objects in the visual scene as its argument, namely the cake, whereas the verb *move* in the latter sentence can take any of the objects as its argument. Altmann and Kamide found that the participants were more likely to fixate on the picture of a cake when hearing *The boy will eat...* than when hearing *The boy will move....* This effect occurred even before the onset of the object noun *cake*. This is taken as evidence that upon hearing the verb its selectional information was activated immediately to predict the upcoming linguistic input.

Using the paradigm by Altmann and colleagues, previous research found that like adults, TD children are also able to predictively use the selectional information of verbs to establish reference during real-time sentence comprehension. This verb-based anticipatory effect has been observed in English-speaking TD 3-year-olds (Andreu et al., 2013; Fernald et al., 2008) and 11-year-olds (Nation et al., 2003).

However, few studies have looked at whether or not preschool children with ASD are able to use the selectional information of verbs to predict the upcoming linguistic input. In the current study, we investigate whether Mandarin-speaking preschool children with ASD, like their TD peers, can predictively use the selectional information of verbs (e.g., *eat* versus. *move*) to establish reference during real-time sentence comprehension, and thus exhibiting anticipatory eye movements. To anticipate our results, we found that the selectional information of verbs triggered anticipatory eye movements in both TD children and children with ASD, indicating that children with ASD are able to use the semantic properties of verbs to predict the upcoming linguistic input. The present study is, therefore, the first investigation that identifies the predictive sentence processing in Mandarin-speaking preschool children with ASD. The findings have important implications for understanding the nature of the sentence processing mechanism in ASD, because identifying both the impaired and the spared components of language comprehension is a crucial step towards a better understanding of the nature of the language processing mechanism in ASD, and we found that their ability to incrementally process a sentence using the verb information is spared.

In addition, most previous research used English as the target language. The present study focused on a less-studied language, Mandarin Chinese. While the primary goal of the present study was to understand predictive processing in ASD and the findings should hold cross-linguistically, this research also provides the first investigation of TD Mandarin-speaking children's predictive use of verb information during real-time sentence comprehension. Another goal of the study was to explore the potential of running eye-tracking studies on sentence comprehension by preschool children with ASD. In particular, we used the visual world paradigm (Tanenhaus et

al., 1995). The underlying assumption of this paradigm is that when participants are simultaneously presented with spoken language while viewing a visual scene, their eye movements are very closely synchronised to the referential processing of the concurrent linguistic input (Tanenhaus et al., 1995; Cooper, 1974). To date, few studies have used this paradigm to explore moment-to-moment sentence comprehension in preschool children with ASD.

The paradigm has at least two advantages. First, it is sensitive to the time course of sentence comprehension and thus can provide rich information about how sentence comprehension unfolds over time. Second, it requires minimal task and communication demands, and thus is ideally suited for testing children with ASD. To further minimize the computational burden of children, the present study measured eye movements that arise as automatic responses to the linguistic input rather than measuring eye movements that accompany conscious responses to spoken instructions.

Methods

Participants

Thirty-three 5-year-old Mandarin-speaking children with ASD participated in the study, recruited from the Enqi Autism Platform in Beijing. Their diagnoses were confirmed by paediatric neurologists at hospitals using both DSM-IV-TR (APA, 2000) and DSM-5 (APA, 2013). In addition, each of the 33 children was further evaluated independently by an expert clinician using the Autism Diagnostic Observation Schedule (ADOS; Lord, Rutter, DiLavore, & Risi, 1999). In order to

reduce the variability in the participants, we only included participants who met the autism cut-off on the ADOS. Two children did not meet the autism cut-off on the ADOS, and the other 31 children all met the autism cut-off on the ADOS and participated in the experimental task. Five of the 31 children did not complete the experimental task, because they became distressed during the task, and refused to continue. The other 26 children (age range 5;4-5;10, mean 5;7) successfully completed the task and were included in the final analyses. In addition, 49 TD children participated in study: 25 (age range 5;5-5;10, mean 5;6) were matched to the children with ASD for age, and 24 (age range 4;2-4;10, mean 4;6) were matched for Mean Length of Utterance (MLU) and verbal IQ. The TD children were recruited from the Beijing Taolifangyuan Kindergarten. This study was approved by the Ethics Committee of the School of Medicine, Tsinghua University, 20170018. Written informed consent has been obtained from each participant's parents.

The participants' MLU was calculated by dividing the total number of words by the number of utterances in each speech sample. We recorded 100 utterances for each participant from their interactions with their parents, and then divided the total number of words in each participant's utterances by the total 100 utterances that were recorded for them. MLU indicates children's sentence complexity levels. The participants' verbal IQ was assessed using the Wechsler Preschool and Primary Scale of Intelligence™ - IV (CN) – a standardised IQ test designed for Mandarin-speaking children between the ages of 2; 6 and 6;11 (Li & Zhu, 2014). The test showed that all the participants had verbal IQ scores above 90 including those with ASD, indicating that the ASD group were high-functioning children with autism. The mean IQ score and MLU for each participant group are presented in Table 1. The 5-year-olds with ASD were matched with the TD 4-year-olds on both MLU levels ($t(48) = 0.83, p =$

0.41, Cohen's $d = 0.62$) and IQ scores ($t(48) = 0.21, p = 0.84$, Cohen's $d = 0.60$).

Compared with their age-matched TD peers, the 5-year-olds with ASD had significantly lower MLU level ($t(49) = 22.80, p < .001$, Cohen's $d = 1.02$) and IQ score ($t(49) = 3.56, p < .001$, Cohen's $d = 0.90$).

TABLE 1 INSERT HERE

Materials and design

A total of 16 target items were constructed each consisting of a visual image and two spoken sentences, one with a verb that exhibits a strong bias in the selection of objects (hereafter 'bias' condition) and one with a verb that is neutral in the selection of objects (hereafter 'neutral' condition). The picture stimuli were always about two characters (either the boy character Kangkang or the girl character Meimei). The two characters had stereotypical boy and girl appearances. In each picture, there were always three objects in which one object matched the 'bias' condition and all the three objects were compatible with the 'neutral' condition. In order to control for potential preferences for looking at particular displayed objects, the position of the three objects was counterbalanced across trials. In addition, the boy character Kangkang appeared on half of the trials and the girl character Meimei appeared on the other half. All the target sentences had the same structure: Subject noun phrase (Subject NP) + Modal phrase + Verb + Locative phrase + Object noun phrase (Object NP). The subject NP was either the boy character's name *Kangkang* or the girl character's name *Meimei*. The modal phrase was always *yao qu* 'is going to' across trials. The verb was always a one-syllable word in Mandarin. The three-syllable locative phrase *di shang de* 'floor-top' was added between the verb and the object NP, in order to

maximise the chances of observing an anticipatory effect triggered by the verb. The object NP was always a two-syllable word in Mandarin.

To describe one visual image in detail (see Fig. 1): it contained the boy character Kangkang and three objects: a bike, a cake and a ball. For this image, two target sentences were recorded as in (1), one with the verb *chi* ‘eat’ as in (1a) and one with the verb *zhao* ‘find’ as in (1b). The verb *chi* ‘eat’ in (1a) exhibits a clear bias in the selection of objects: it can only take ‘edible’ objects, in this case, the cake in the visual scene. The verb *zhao* ‘find’ in (1b) is neutral in the selection of objects: it can take any of the three objects in the visual scene. (1a) and (1b) formed minimal pairs. Except for the verbs, the other words in (1a) and (1b) were exactly the same.

FIGURE 1 INSERT HERE

(1) a. Kangkang yao qu **chi** di-shang-de dangao.

Kangkang will go eat floor-top cake

‘Kangkang is going to eat the cake on the floor.’

b. Kangkang yao qu **zhao** di-shang-de dangao.

Kangkang will go find floor-top cake

‘Kangkang is going to find the cake on the floor.’

The 16 target items were divided into two lists with each participant seeing each visual image but hearing only one of the two target sentences that could accompany the image. Target sentences with ‘bias’ verbs and those with ‘neutral’ verbs were counterbalanced across the two lists with 8 ‘bias’ verbs and 8 ‘neutral’ verbs in each list. In addition, 12 filler items were added to each experimental list.

Each filler item consisted of a visual image and a spoken sentence. The visual images were similar to those used in the target items. The spoken sentences had the same structure: Subject NP + Verb + Object NP. Like in the target sentences, the subject NP in the filler sentences was either the boy character's name *Kangkang* or the girl character's name *Meimei*. The verb was always *you* 'have'. The object NP always contained a measure word and an object name. The object NP in each spoken sentence referred to one of the three objects in the visual scene. An example filler sentence is given in (2).

(2) Meimei you yi-pi xiaoma.

Meimei have one-Classifier horse

'Meimei has a horse.'

In each experimental list, the 16 target and 12 filler items were arranged in random order. Participants in each group were randomly assigned to one of the two lists, with thirteen 5-year-olds with ASD, thirteen TD 5-year-olds and twelve TD 4-year-olds run on List 1, and thirteen 5-year-olds with ASD, twelve TD 5-year-olds and twelve TD 4-year-olds run on List 2.

Procedure

The participants were tested using the visual world paradigm (Tanenhaus et al., 1995). They were presented with a spoken sentence while viewing a visual scene and their eye-movements were recorded using an EyeLink 1000 plus eye tracker (by SR Research Ltd., Mississauga, Ontario, Canada) interfaced with a PC computer. The EyeLink 1000 plus allows remote eye tracking, without a head support. The eye

tracker provides information about the participant's point of gaze at a sampling rate of 500 Hz, and it has accuracy of 0.5 degrees of visual angle. The visual stimuli were displayed on the monitor. Spoken sentences were presented to the participants through the PC computer connected to two external speakers. The distance between the participants' eyes and the monitor was about 60 cm.

The participants were tested individually. Two experimenters were involved during the test. One experimenter monitored the participant on the computer, and one stood behind the participant and gently rested her hands on the participant's shoulders to minimise the participant's sudden movements. The experimenter who monitored data collection used the live viewer mode to observe the participants' looking behaviour in real time and signalled to the second experimenter to reorient the participants when their eye gaze wandered off computer screen. To minimise the computational burden of the participants, in particular those with ASD, we did not ask them to make any conscious judgements about the spoken sentences. They were simply told to listen to the spoken sentences while viewing the pictures. We measured their eye movements that arose as automatic responses to the linguistic input.

Before the actual test, we had an introduction session. The two experimenters first introduced the participant to the research environment where the test was conducted, and they interacted with the participant to establish a good rapport with the participant. The introduction session was also used to familiarise the participants with the test procedure as well as the objects that were presented in the visual stimuli. The introduction session was followed by the actual test session. The test session began with two practice trials followed by 28 test trials (16 target and 12 filler trials).

The practice trials were similar to the filler trials. The spoken sentence started 500 ms after the appearance of the visual stimulus. Participants' eye movements were recorded from the onset of the spoken sentence until the sentence was completed.

Predictions

If the selectional information of verbs was used by the participants to predict the upcoming linguistic input during real-time sentence comprehension, then hearing the target sentences with 'bias' verbs should trigger more fixations on the target area than hearing those with 'neutral' verbs. This effect should occur after the onset of the verb and before the onset of the object NP. On the example trial, the participants were expected to fixate more on the area of the cake when hearing the 'bias' verb *chi* 'eat' than when hearing the 'neutral' verb *zhao* 'find'. The expected effect should occur before the onset of the object NP *dangao* 'cake'.

Results

We analysed the eye gaze patterns in two interest periods: the verb period and the object NP period.

Verb Period

To analyse the eye movement data, we first categorically partitioned the data from the onset of the verb into eight bins, each with a duration of 500 ms. Among the eight bins, three were located prior to the onset of the verb, thus providing a baseline for the comparison, and the remaining five bins were located after the onset of the verb. The eight bins were labelled as -1.0, -0.5, 0, 0.5, 1.0, 1.5, 2.0, and 2.5 respectively,

indicating the offset of the temporal bin with respect to the onset of the verb. We then divided each visual image into four areas of interest containing the character and the three objects respectively (e.g., the four areas of interest in Fig.1 were the area containing the boy character, the one containing the bike, the one containing the ball, and the one containing the cake). The proportion of fixations on a particular area in a specific temporal bin was treated as the dependent variable. For example, if we recorded 4 fixation points in a temporal bin, with 1 fixation point located in a specific area, then the proportion of fixations on that area was $\frac{1}{4}$. The critical area was the target area containing the referent of the object NP, e.g., the cake in Fig.1.

To provide an overview of the eye movement data, the results are first presented in the form of a descriptive graph, as in Fig.2, followed by more detailed statistical analyses. Fig.2 gives the average fixation proportions in the target area in the ‘bias’ condition and the ‘neutral’ condition by the 5-year-olds with ASD, the TD 5-year-olds and the TD 4-year-olds. The figure indicates that the three groups exhibited similar eye gaze patterns in the target area in the two conditions. The 5-year-olds with ASD, the TD 5-year-olds and the TD 4-year-olds all looked more at the target area when hearing the ‘bias’ verbs (e.g., *chi* ‘eat’) than when hearing the ‘neutral’ verbs (e.g., *zhao* ‘find’). The effect occurred after the onset of the verb and before the onset of the object NP.

FIGURE 2 INSERT HERE

To assess the fixation patterns statistically, we transformed the fixation proportions using the empirical logit formula (Barr, 2008): $probability = \ln((y+0.5)/(n-y+0.5))$, where y is the number of fixations on the areas of interest during a particular

temporal bin; n is the total number of fixations in that temporal bin. We then fitted a series of linear mixed-effects models to the transformed data. In the full model, the fixed effects included the temporal bin, the condition, the participants' group, and their interactions; the random effects included items and participants, where both their intercepts and slopes were allowed to vary among all the fixed effects (Baayen, Davidson, & Bates, 2008; Barr et al., 2013). The full model's complexity was then reduced to see whether the reduced model could explain the same variance as the full model (Bates et al., 2015). If it could, we would accept the simplified model. The final model we used can be found in the footnote of Table 2 where the statistical results are reported. Analyses were conducted on the raw data with no aggregation. When conducting the analyses, the temporal bins were rescaled and grand-mean centred, to avoid issues involving collinearity. We conducted the fitting process via functions *lmer* from package *lme4* (v1.1-12) (Bates, Maechler, & Bolker, 2013) of the R (v3.2.5) software environment (R Development Core Team, 2017). We then used Wald test to compute p -values for each fixed effect.

The results of the best-fitting model were summarised in the upper panel of Table 2. In the model, the fixed effect *condition* has two levels: 'neutral' and 'bias', where the 'neutral' condition was treated as the baseline. The fixed effect *participants' group* has three levels: the TD 4-year-olds, the TD 5-year-olds and the 5-year-olds with ASD, where the group of the 5-year-olds with ASD was treated as the baseline. So, for example, an effect of 'Bias' in the table means that there was a significant difference between the 'neutral' condition and the 'bias' condition in the 5-year-olds with ASD; an effect of '*TD 4-yr-olds*' means that there was a significant difference between the 5-year-olds with ASD and the TD 4-year-olds. As indicated in the table, prior to the onset of the verb, no difference was observed between the 'bias'

condition and the ‘neutral’ condition ($b = -0.04$, $t = -0.32$, $p = 0.75$); in addition, no difference was found between different participant groups (the 5-year-olds with ASD vs. the TD 4-year-olds: $b = 0.01$, $t = 0.09$, $p = 0.93$; the 5-year-olds with ASD vs. the TD 5-year-olds: $b = 0.03$, $t = 0.25$, $p = 0.80$). These results provide evidence that all the effects observed after the onset of the verb can be securely attributed to the effect of the verb. As the temporal bin increases, the 5-year-olds with ASD tended to fixate more on the target area in the ‘bias’ condition than in the ‘neutral’ condition ($b = 0.08$, $t = 2.20$, $p = 0.03$). There was no significant difference between the 5-year-olds with ASD and the TD 4-year-olds in their eye gaze patterns ($b = 0.05$, $t = 1.36$, $p = 0.17$). However, a significant difference was observed in the eye gaze patterns of the 5-year-olds with ASD and the TD 5-year-olds. More specifically, the observed difference between the ‘bias’ condition and the ‘neutral’ condition was bigger in the TD 5-year-olds than in the 5-year-olds with ASD ($b = 0.10$, $t = 2.51$, $p = 0.01$). To explore when the reported effect started to occur, we applied a LMM model (excluding the temporal bin from both the fixed effects and the random effects) to each temporal bin. The results indicated that the 5-year-olds with ASD showed increased looks to the target area in the ‘bias’ condition than in the ‘neutral’ condition until 2 seconds after the onset of the verb, which was located in the last temporal bin of the verb period ($b = 0.49$, $t = 3.09$, $p = 0.00$). The difference between the 5-year-olds with ASD and the TD 5-year-olds also occurred 2 seconds after the onset of the verb.

TABLE 2 INSERT HERE

Object NP Period

We assessed the eye gaze patterns in the object NP period statistically using the same analysis methods. The results showed that the fixation patterns observed in the verb period extended into the object NP period (see the lower panel of Table 2). More specifically, for the 5-year-olds with ASD, hearing the ‘bias’ verbs triggered more eye fixations in the target area than hearing the ‘neutral’ verbs ($b = 0.32$, $t = 2.58$, $p = 0.01$). The difference between the 5-year-olds with ASD and the TD 5-year-olds also extended into the object NP period ($b = 0.50$, $t = 2.77$, $p = 0.01$). To explore how long these observed effects lasted, we also applied a LMM model to each temporal bin. The results indicated that both the effect between the two conditions in the 5-year-olds with ASD and the group difference between the 5-year-olds with ASD and the TD 5-year-olds continued and lasted for about 1.5 seconds after the onset of the object NP.

The eye gaze patterns displayed in Fig.2 were supported by the statistical modeling. The 5-year-olds with ASD, the TD 5-year-olds and the TD 4-year-olds exhibited similar eye gaze patterns: they all launched more fixations to the target area (e.g., the cake in Fig.1) when hearing target sentences with ‘bias’ verbs (e.g., *chi* ‘eat’) than when hearing those with ‘neutral verbs’ (e.g., *zhao* ‘find’). For all the three groups, the difference between the two conditions occurred after the onset of the verb and before the onset of the object NP. There was no difference in the time course of their eye gaze patterns. This is evidence that the 5-year-olds with ASD, like their TD peers, are able to use the selectional information of verbs to predict the upcoming linguistic input.

However, a group difference was observed between the 5-year-olds with ASD and their age-matched TD peers, mainly due to the difference in the overall fixations they launched to the target area. More specifically, the 5-year-olds with ASD

exhibited fewer looks to the target area compared to the TD 5-year-olds. No difference was observed between the 5-year-olds with ASD and the younger TD group, the TD 4-year-olds. Note that the 5-year-olds with ASD were matched with the TD 4-year-olds on both MLU and verbal IQ (see Table 1). We discuss the implications of the findings in the following section.

Discussion

In the present study, we sought to investigate whether Mandarin-speaking preschool children with ASD are able to use the verb information predictively to anticipate the upcoming linguistic input. Using the visual world paradigm, we found that 5-year-old children with ASD, like their TD peers, exhibited anticipatory eye movements during real-time sentence comprehension. For all the three groups, hearing the ‘bias’ verbs triggered more eye fixations on the target area than hearing the ‘neutral’ verbs, and this effect occurred after the onset of the verb and before the onset of the object NP, indicating that 5-year-olds with ASD are able to use the selectional information of verbs as effectively and rapidly as their TD peers to predict the upcoming linguistic input. This is the first study that investigates and identifies predictive sentence processing in Mandarin-speaking preschool children with ASD.

The findings have important implications for understanding the nature of the sentence processing mechanism in ASD. Anticipatory eye movements are often taken as an indicator of the incremental nature of our sentence processing mechanism. Prior research has shown that TD children incrementally compute the meaning of a spoken sentence using both linguistic and non-linguistic cues (Andreu et al., 2013; Choi & Trueswell, 2010; Fernald et al., 2008; Huang et al., 2013; Lew-Williams & Fernald,

2007; Nation et al., 2003; Omaki, 2010; Sekerina & Trueswell, 2012, Trueswell et al., 1999; Van Heugten & Shi, 2009; Zhou et al., 2014; Zhou & Ma, 2018). The present study shows that preschool children with ASD, like their TD peers, are also able to incrementally establish reference using the verb information during real-time sentence comprehension, thus exhibiting anticipatory eye movements. The findings point to an incremental nature of the sentence processing mechanism in children with ASD.

The findings also invite us rethink the question of language comprehension abilities of children with ASD. As discussed in the introduction, previous studies seem to suggest that the language comprehension abilities of children with ASD might be severely impaired. However, as pointed out by Kasari et al. (2013) and Plesa-Skwerer et al. (2016), it is often not easy to evaluate the language comprehension abilities of children with ASD using traditional methods like standardized tests and some other off-line tasks, because these tasks often require high response demands or interactions with the experimenters, which might pose particular difficulties for children with ASD. Therefore, the use of these traditional tasks might significantly underestimate their language comprehension abilities. In other words, their poor language comprehension abilities are likely to be related more to these children's overall lack of social responsiveness than to language processing deficits (Rutter et al., 1992; Tager-Flusberg, 2000). Using the visual world paradigm, the present study shows that when minimal task and communication demands are involved, young children with ASD are able to use linguistic cues effectively and rapidly to predict the upcoming linguistic input during real-time sentence comprehension. The findings provide evidence that the poor comprehension performance of children with ASD in previous research is perhaps indeed due to their lack of social responsiveness interacting with the high task and communication

demands involved in these traditional tasks. At least, our study shows that the sentence comprehension ability that involves the predictive use of verb information is preserved in children with ASD.

Although the 5-year-olds with ASD, like the TD 4-year-olds and 5-year-olds, exhibited anticipatory eye movements, and there was no difference in the time course of the eye gaze patterns of the three groups, a difference was observed between the 5-year-olds of the two populations. The 5-year-olds with ASD exhibited fewer looks to the target area compared to the TD 5-year-olds (see Fig.2). This difference in the overall fixation proportions between the two groups is presumably due to their difference in the cognitive control of visual attention. It has been well documented that the cognitive control of visual attention is impaired in ASD (e.g., DiCriscio et al., 2016; Frischen, Bayliss, & Tipper, 2007; Happe et al., 2006; Sasson et al., 2008). This might explain why the children with ASD launched few fixations to the target area than their age-matched TD peers. It requires further research to explicitly investigate how the features of eye gaze patterns are related to the cognitive control of visual attention in ASD. We wish to propose that the difference between the 5-year-olds with ASD and their age-matched TD peers is not due to their difference in linguistic knowledge per se, but rather due to the difference in other cognitive domains like cognitive control and visual attention. The difference between the two populations with respect to their language processing abilities is presumably one of quantity and not of quality. Note that a comparison between the 5-year-olds with ASD and the younger TD group (the TD 4-year-olds) shows that the 5-year-olds with ASD were as capable as the younger TD group in their real-time sentence processing, and no difference was found between the two groups in their eye gaze patterns. The finding seems to suggest that it is perhaps more appropriate to view the difference

between ASD and TD as a developmental continuity, rather than a language processing deficit in ASD.

The present study demonstrates that the ability to incrementally process a sentence using the verb information is preserved in children with ASD. This is a necessary step towards a better understanding of the nature of the language processing mechanism in children with ASD. Both the impaired and preserved components should be taken into consideration if we are to explore the mechanism underlying their language processing. In addition, identifying the preserved components and investigating whether and how the preserved components can be used to compensate for the impaired components is also helpful in designing the treatment plans for children with ASD.

The findings also provide evidence that eye tracking, in particular, the visual world paradigm, is a sensitive measure of real-time language comprehension in children with ASD. Compared with traditional offline methods, eye tracking is a better suited method that can be used with children exhibiting challenging behavioral features. Researchers have started to explore the typical viewing patterns in children and adolescents with ASD when they process language, using the method (Bavin, Kidd, Prendergast, & Baker, 2016; Bavin et al., 2016; Brock et al., 2008; Chita-Tegmark et al., 2015; Diehl et al., 2015; Naigles et al., 2011; Naigles & Fein, 2017; Naigles & Tovar, 2012; Norbury, 2017; Plesa-Skwerer et al., 2016; Swensen et al., 2007; Tovar, Fein, & Naigles, 2015; Venker et al. 2013). To establish eye gaze patterns associated with language processing in ASD will help to identify early clinical markers for ASD. In fact, it has been proposed to use the atypical visual search patterns as early risk markers for ASD (Falck-Ytter, Bölte, & Gredebäck,

2013; Gliga et al., 2015; Guillon et al., 2014; Jones & Klin, 2013; Kaldy et al., 2011; Kaldy et al., 2016).

The present study only tested high-functioning children with ASD. Future research is needed to extend the experimental paradigm to relatively low-functioning children with ASD. Again, the speculation is that the challenging behavioural symptoms exhibited by these children might mask their comprehension abilities. The visual world paradigm is promising in revealing whether the language processing deficits observed in previous research has more to do with the behavioural or other cognitive features of the population than with their linguistic knowledge per se.

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Appendix A

Target and filler sentences in the study (two target sentences were recorded for each visual image, one with a ‘bias’ verb and one with a ‘neutral’ verb); the first 16 pairs are target sentences

- (1) a. Kangkang yao qu **chi** di-shang-de dangao.
Kangkang will go eat floor-top cake
‘Kangkang is going to eat the cake on the floor.’
- b. Kangkang yao qu **zhao** di-shang-de dangao.
Kangkang will go find floor-top cake
‘Kangkang is going to find the cake on the floor.’
- (2) a. Kangkang yao qu **wei** di-shang-de tuzi.
Kangkang will go feed floor-top rabbit
‘Kangkang is going to feed the rabbit on the floor.’
- b. Kangkang yao qu **zhao** di-shang-de tuzi.
Kangkang will go find floor-top rabbit
‘Kangkang is going to find the rabbit on the floor.’
- (3) a. Kangkang yao qu **ti** di-shang-de piqu.
Kangkang will go kick floor-top ball
‘Kangkang is going to kick the ball on the floor.’
- b. Kangkang yao qu **mai** di-shang-de piqu.
Kangkang will go buy floor-top ball
‘Kangkang is going to buy the ball on the floor.’
- (4) a. Kangkang yao qu **kai** di-shang-de qiche.
Kangkang will go drive floor-top car

‘Kangkang is going to drive the car on the floor.’

b. Kangkang yao qu **mai** di-shang-de qiche.

Kangkang will go buy floor-top car

‘Kangkang is going to buy the car on the floor.’

(5) a. Kangkang yao qu **du** di-shang-de baozhi.

Kangkang will go read floor-top newspaper

‘Kangkang is going to read the newspaper on the floor.’

b. Kangkang yao qu **zhao** di-shang-de baozhi.

Kangkang will go find floor-top newspaper

‘Kangkang is going to find the newspaper on the floor.’

(6) a. Kangkang yao qu **wan** di-shang-de wanju.

Kangkang will go play floor-top toy

‘Kangkang is going to play the toy on the floor.’

b. Kangkang yao qu **mai** di-shang-de wanju.

Kangkang will go buy floor-top toy

‘Kangkang is going to buy the toy on the floor.’

(7) a. Kangkang yao qu **zhai** di-shang-de xiaohua.

Kangkang will go pick floor-top flower

‘Kangkang is going to pick the flower on the floor.’

b. Kangkang yao qu **zhao** di-shang-de xiaohua.

Kangkang will go find floor-top flower

‘Kangkang is going to find the flower on the floor.’

(8) a. Kangkang yao qu **qi** di-shang-de xiaochē.

Kangkang will go ride floor-top bike

‘Kangkang is going to ride the bike on the floor.’

b. Kangkang yao qu **zhao** di-shang-de xiaochē.

Kangkang will go find floor-top bike

‘Kangkang is going to find the bike on the floor.’

(9) a. Meimei yao qu **chui** di-shang-de lazhu.

Meimei will go blow floor-top candle

‘Meimei is going to blow the candle on the floor.’

b. Meimei yao qu **zhao** di-shang-de lazhu.

Meimei will go find floor-top candle

‘Meimei is going to find the candle on the floor.’

(10) a. Meimei yao qu **chi** di-shang-de xiangjiao.

Meimei will go eat floor-top banana

‘Meimei is going to eat the banana on the floor.’

b. Meimei yao qu **mai** di-shang-de xiangjiao.

Meimei will go buy floor-top banana

‘Meimei is going to buy the banana on the floor.’

(11) a. Meimei yao qu **he** di-shang-de guozhi.

Meimei will go drink floor-top juice

‘Meimei is going to drink the juice on the floor.’

b. Meimei yao qu **mai** di-shang-de guozhi.

Meimei will go buy floor-top juice

‘Meimei is going to buy the juice on the floor.’

(12) a. Meimei yao qu **zhua** di-shang-de xiaoyu.

Meimei will go catch floor-top fish

‘Meimei is going to catch the fish on the floor.’

b. Meimei yao qu **mai** di-shang-de xiaoyu.

Meimei will go buy floor-top fish

‘Meimei is going to buy the fish on the floor.’

(13) a. Meimei yao qu **chi** di-shang-de dangao.

Meimei will go eat floor-top cake

‘Meimei is going to eat the cake on the floor.’

b. Meimei yao qu **zhao** di-shang-de dangao.

Meimei will go find floor-top cake

‘Meimei is going to find the cake on the floor.’

(14) a. Meimei yao qu **bao** di-shang-de xiaomao.

Meimei will go hug floor-top cat

‘Meimei is going to hug the cat on the floor.’

b. Meimei yao qu **zhao** di-shang-de xiaomao.

Meimei will go find floor-top cat

‘Meimei is going to find the cat on the floor.’

(15) a. Meimei yao qu **qi** di-shang-de xiaoma.

Meimei will go ride floor-top horse

‘Meimei is going to ride the horse on the floor.’

b. Meimei yao qu **zhao** di-shang-de xiaoma.

Meimei will go find floor-top horse

‘Meimei is going to find the horse on the floor.’

(16) a. Meimei yao qu **cai** di-shang-de xiaohua.

Meimei will go pick floor-top flower

‘Meimei is going to pick the flower on the floor.’

b. Meimei yao qu **zhao** di-shang-de xiaohua.

Meimei will go find floor-top flower

‘Meimei is going to find the flower on the floor.’

(17) Meimei you yi-pi xiaoma.

Meimei have one-Classifier horse

‘Meimei has a horse.’

(18) Meimei you yi-ge dangao.

Meimei have one-Classifier cake

‘Meimei has a cake.’

(19) Meimei you yi-ge tiantong.

Meimei have one-Classifier ice cream

‘Meimei has a ice cream.’

(20) Meimei you yi-ge zuqiu.

Meimei have one-Classifier soccer ball

‘Meimei has a soccer ball.’

(21) Meimei you yi-wan mifan.

Meimei have one-Classifier rice

‘Meimei has a bowl of rice.’

(22) Meimei you yi-bei guozhi.

Meimei have one-Classifier juice

‘Meimei has a glass of juice.’

(23) Kangkang you yi-ge qiqiu.

Kangkang have one-Classifier balloon

‘Kangkang has a balloon.’

(24) Kangkang you yi-pen xiaohua.

Kangkang have one-Classifier flower

‘Kangkang has a flower.’

(25) Kangkang you yi-chuan xiangjiao.

Kangkang have one-Classifier banana

‘Kangkang has a bunch of bananas.’

(26) Kangkang you yi-zhi xiaomao.

Kangkang have one-Classifier cat

‘Kangkang has a cat.’

(27) Kangkang you yi-tiao xiaoyu.

Kangkang have one-Classifier fish

‘Kangkang has a fish.’

(28) Kangkang you yi-ge pingguo.

Kangkang have one-Classifier apple

‘Kangkang has an apple.’

Table 1

Verbal IQ scores and MLU of each participant group

	ASD 5-yr-olds	TD 4-yr-olds	TD 5-yr-olds
Verbal IQ			
Mean (SD)	103.72 (11.34)	103.85 (11.67)	105.88 (10.81)
Range	90-125	92-124	94-128
MLU			
Mean (SD)	5.84 (0.15)	5.87 (0.14)	6.86 (0.15)
Range	5.58-6.05	5.55-6.05	6.50-7.05

Table 2

Summary of fixed effects

Period	Fixed effects	Estimate	Std. Error	t value	p value	Sig
Verb	(Intercept)	-0.63	0.09	-6.87	0.00	***
	TD 4-yr-olds	0.01	0.12	0.09	0.93	
	TD 5-yr-olds	0.03	0.13	0.25	0.80	
	Bias	-0.04	0.12	-0.32	0.75	
	Bin	-0.04	0.03	-1.18	0.24	
	TD 4-yr-olds:Bias	-0.11	0.15	-0.70	0.48	
	TD 5-yr-olds:Bias	-0.06	0.15	-0.38	0.70	
	TD 4-yr-olds:Bin	0.02	0.04	0.51	0.61	
	TD 5-yr-olds:Bin	0.00	0.04	0.08	0.94	
	Bias:Bin	0.08	0.03	2.20	0.03	*
	TD 4-yr-olds:Bias:Bin	0.05	0.04	1.36	0.17	
	TD 5-yr-olds:Bias:Bin	0.10	0.04	2.51	0.01	*
Object NP	(Intercept)	-0.53	0.09	-5.84	0.00	***
	TD 4-yr-olds	-0.05	0.13	-0.40	0.69	
	TD 5-yr-olds	-0.07	0.13	-0.52	0.60	
	Bias	0.32	0.13	2.58	0.01	*
	Bin	0.03	0.03	1.12	0.26	
	TD 4-yr-olds:Bias	0.21	0.17	1.21	0.23	
	TD 5-yr-olds:Bias	0.50	0.18	2.77	0.01	**
	TD 4-yr-olds:Bin	0.04	0.03	1.06	0.29	
	TD 5-yr-olds:Bin	0.04	0.03	1.19	0.23	
	Bias:Bin	-0.00	0.04	-0.04	0.97	
	TD 4-yr-olds:Bias:Bin	-0.04	0.04	-1.00	0.32	
	TD 5-yr-olds:Bias:Bin	-0.05	0.04	-1.11	0.27	

Model used in R: $\text{logit proportion} \sim \text{Group} * \text{Condition} * \text{Bin} + (1 + \text{Group} + \text{Condition} + \text{Bin} |$

$\text{Subject}) + (1 + \text{Group} + \text{Condition} + \text{Bin} | \text{Trial})$

* $p < .05$

** $p < .01$

*** $p < .001$

Figure captions

Fig.1. Example visual image used in the study

Fig.2. Average fixation proportions in the target area in the ‘bias’ condition and the ‘neutral’ condition by the 5-year-olds with ASD, the TD 5-year-olds and the TD 4-year-olds; “0” indicates the onset of the verb (left panel) and the onset of the object NP (right panel); the grey areas indicate a significant difference between the ‘bias’ condition and ‘neutral’ condition within each participant group, and a group difference between the 5-year-olds with ASD and the TD 5-year-olds during the temporal bins.

Figure 1



Figure 2

