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The heterogeneity and interrelationships among theory of mind, executive function, and reading comprehension deficits in Hong Kong Chinese children with Autism

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Abstract

Reading comprehension difficulties exhibited by children with autism are related to executive function (EF) and theory of mind (ToM) deficits. However, the potential heterogeneity of ToM, EF, and reading comprehension abilities, and their interrelationships, among Chinese children with autism remains unclear. Using comprehensive sets of ToM and EF tasks, the present study assessed basic and advanced ToM, EF, and reading comprehension skills for 36 seven- to nine-year-old Hong Kong Chinese children with autism and 36 typically developing (TD) peers. Despite comparable age, intelligence, and working memory, children with autism performed significantly worse than their TD peers on advanced ToM and EF tasks and overall reading comprehension skills. Moreover, linear mixed-effects modelling analyses revealed that specific impairments in EF and ToM were associated with different components of reading comprehension deficits and language abilities in children with autism. These findings suggest that children with autism have multiple but specific cognitive and reading comprehension difficulties and that EF and ToM uniquely contribute to their deficits in reading comprehension.

Keywords Autism · Theory of mind (ToM) · Executive function (EF) · Reading comprehension

Children with high-functioning autism (HFASD) frequently experience various cognitive dysfunctions that impede their reading comprehension skills (McIntyre et al., 2018) and, ultimately, their academic performance (Whitby & Mancil, 2009). The executive dysfunction (EF) hypothesis of autism proposes that a deficiency in EF is fundamental to cognitive and behavioural problems in autism (Pennington

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& Ozonoff, 1996). EF, which engages in the regulation of thoughts, actions, and emotions, includes necessary skills for a goal-directed behaviour (e.g., inhibition, cognitive flexibility, and planning) (Hughes & Russell, 1993; Ozonoff et al., 1991) and is a critical predictor of children's developmental outcomes and academic performance (Blair & Razza, 2007). Whereas intact EF enables a flexible allocation of mental resources for the selective processing of task-relevant information over competing irrelevant information (Bunge et al., 2002), EF deficits are related to the perseveration of certain behaviours or interests and an inability to adjust to rapidly changing conditions (Braver et al., 2002), as well as poorer attention and emotional control leading to behavioural disruptions (Hughes & Russell, 1993). Furthermore, language comprehension, which is constrained by executive dysfunction, influences reading comprehension abilities in school-aged children with autism (Ellis Weismer et al., 2018).

Another cognitive account of autism involves theory of mind (ToM), a set of social-cognitive skills for attribution of mental states (e.g., beliefs, emotions, intentions, knowledge, and desires) (e.g., Frith et al., 1991). According to this account, ToM underpins social interactions (Joseph & Tager-Flusberg, 2004) and reading performance in children (Tong et al., 2019) such that impairments in ToM and abnormal developments of self-concept cause social-interpersonal and academic difficulties (Bauminger-Zviely, 2013). Focusing on Chinese school-age children with autism and their typically developing peers (TD), Tong et al. (2019) demonstrated that the development of age-appropriate reading comprehension abilities is hindered by advanced ToM deficits. This link between children's ToM abilities and their inferential reading comprehension is significant as poor ToM skills impede the understanding of others' mental representations. Thus, the abilities required during empathic processing and appropriate responding, such as perspective-taking and inference-making of others' mental states, are challenged. In addition, Dore and colleagues (2018) suggested that increased ToM enhances the understanding and inferencing of mental states in narrative texts, which leads to better reading comprehension abilities. Therefore, impairments in EF and ToM may be the key that unlocks our understanding of reading comprehension difficulties experienced by children with autism.

Processes of reading development and variability across orthographies

When reading, the decoding of symbols ranges from individual word recognition to textual comprehension. Reading comprehension is an interactive process of meaning construction that occurs when readers integrate new information with previous knowledge (Block & Pressley, 2002; Zwaan, 2003). According to the simple view of reading (SVR, Gough & Tunmer, 1986), proficient reading comprehension requires intact word recognition, which comprises key elements such as phonological awareness and phonological memory (Bishop & Snowling, 2004) and oral language comprehension, which is related to structural language and higher-order linguistic (i.e., metalinguistic) skills. Structural language involves phonology, semantics, and syntactic processing, whereas higher-order language skills involve inference-making and reasoning.

Readers of alphabetic languages (e.g., English) follow both lexical and phonological routes for decoding, while readers of non-alphabetic languages (e.g., Chinese) rely more on orthographic and semantic relationships between radicals (Tong et al., 2019). In Chinese, the mapping between orthography and semantics is direct, but the mapping between orthography and phonology is less systematic. Thus, when processing the meaning of Chinese characters, logographic script users can acquire more reliable information from written forms than phonological forms (Tong et al., 2019). However, there is currently no consensus on what contributes to Chinese reading comprehension. For example, Joshi et al. (2012) used three languages (i.e., English, Spanish, and Chinese) to compare how decoding and listening comprehension are associated with reading comprehension and showed that among the three languages, Chinese decoding and listening comprehension exhibited the lowest predictive relationship with reading comprehension (25% to 42%), compared to English (50%) and Spanish (60%). Similarly, Yeung et al. (2016) found that decoding (i.e., word reading accuracy and text reading fluency) and linguistic comprehension (i.e., listening comprehension, oral vocabulary, and syntactic skills) explained 36% of the variance in reading comprehension for Hong Kong Cantonese-speaking children in Grades 1 to 3.

Additionally, compared to alphabetic languages, Chinese character recognition may require a longer time to master and likely exerts a strong influence on reading comprehension (Joshi et al., 2012). Having an opaque orthography with numerous homophones and semantic cues from radicals, Chinese enables readers to infer meaning from its written form and depend less on phonological decoding (Tong et al., 2019). Thus, to understand reading difficulties in Chinese children with autism, it is necessary to consider how reading differs between alphabetic and non-alphabetic logographic scripts.

Language-related reading difficulties in children with autism

Although language impairment is not a diagnostic criterion, language functioning in early age is a key determinant of long-term prognosis of autism (Tager-Flusberg et al., 2005). According to Boucher (2011), structural language impairments in autism are universal and persistent throughout development, even in higher-functioning individuals. More specifically, children with autism have shown profound difficulties in lexical/semantic development and organization but comparable abilities in formal aspects of language or syntactic knowledge (Naigles & Tek, 2017).

Furthermore, research to date on children with autism using alphabetic languages has demonstrated that despite their overall delayed but appropriate development of vocabulary, these children may have specific difficulties with words related to emotions (Losh & Capps, 2003) and mental states (Bang et al., 2013), as well as with lexical and semantic organization (e.g., Eigsti et al., 2011). Similarly, two studies with Mandarin-speaking Chinese children with autism have shown a significantly delayed phonological development in 3-to 6-year-olds with autism than their age-matched TD peers (Wu et al., 2020) and an uneven expressive language profile in three subgroups of preschoolers with autism, all of whom had relative strengths in vocabulary and grammatical production but weaker pragmatic language abilities (Su et al., 2018).

These structural language difficulties exhibited by children with autism, particularly in vocabulary and semantic organization, significantly contribute to their reading difficulties, regardless of the orthography type (for a review, see Brown et al., 2013). In a meta-analysis of 36 studies comparing reading comprehension in children with and without autism, Brown et al. (2013) demonstrated that due to varying impairments in decoding, semantic skills, and social knowledge (i.e., understanding of society, social behaviours, and common rules), different levels of reading comprehension deficits may exist among children with autism, even though these children experienced less difficulties on integration and inferencing tasks that did not require social knowledge. Furthermore, although significant variability of word recognition and decoding exists within the autism population, the language impairments of poor readers with autism may exacerbate their reading comprehension difficulties (McIntyre et al., 2017). Thus, it seems plausible that the heterogeneity in language abilities and the demand for social knowledge may be significant predictors of reading comprehension.

In fact, one study with Hong Kong Cantonese-speaking Chinese children with autism showed that despite having word reading skills comparable to TD children, Chinese children with autism demonstrated a weakness in reading comprehension, and that ToM mediated the link between autism status and inferential reading comprehension difficulties (Tong et al., 2019). However, it should be noted that Tong et al.'s (2019) study only focused on ToM skills without considering the role of EF and its connection with ToM. Thus, it is critical to extend the previous study of reading comprehension difficulties in these children by examining the synergetic effect of cognitive factors such as ToM and EF and their relation in explaining variabilities in reading comprehension deficits among Chinese school-aged children with autism.

Executive function-related reading difficulties in children with autism

Although ample evidence suggests that a deficiency in EF is fundamental to cognitive and behavioural problems in autism (e.g., Pennington & Ozonoff, 1996), a controversy exists regarding which EF skills are most impaired. Some studies suggest that children with autism experience a wide range of difficulties in lower levels or more basic processes of EF, such as attention, impulse control, and inhibition (Demetriou et al., 2018; Geurts et al., 2014). Other studies, however, have proposed that EF impairments in children with autism are limited to higher or more advanced levels (i.e., planning, cognitive flexibility, and organization) (e.g., Brian et al., 2003; Ozonoff & Jensen, 1999). As EF is a promising endophenotype in autism (Craig et al., 2016) and effectively facilitates cognitive processes of children (Cannon et al., 2011), it is critically important to clarify which EF skills are most problematic for children with autism.

Furthermore, deficiencies in EF may be associated with poor reading comprehension abilities in autism because of the close link between EF and language skills. For example, Ellis Weismer et al. (2018) reported that language comprehension predicted non-verbal EF abilities in children with autism. In their linear regression analyses, receptive language and shifting were related in children with autism with language impairment, whereas receptive language and inhibition were related in children with autism without language impairment. The authors pointed out that receptive language and their EF tasks share processing demands whereas expressive vocabulary (i.e., language production) requires EF skills not included in their assessment (i.e., planning and organization), which explained the greater contribution of receptive language over expressive language. Other studies also demonstrated an interplay between language and EF abilities in children with autism, at least for some specific components (Ellis Weismer et al., 2017; Haebig et al., 2015). Corbett et al. (2009) found consistent evidence that receptive but not expressive language is associated with EF when inhibition, cognitive flexibility, and working memory were assessed. When controlling for verbal IQ, Liss et al. (2001) reported the disappearance of significant group differences of EF between children with high-functioning autism and those with developmental language disorder. On the other hand, Joseph et al. (2005) found no specific association between EF (i.e., working memory, inhibitory control, and planning) and language abilities (i.e., expressive and receptive vocabulary) in the autism group, while EF performance was positively correlated with language abilities in the TD group.

Despite all this research, no studies have investigated the connection between EF and reading abilities in Chinese children with autism. In particular, the questions of whether Chinese children with autism exhibit comprehensive or specific deficits in basic or advanced EF, and if so, how the EF deficits contribute to their reading comprehension difficulties remain unexplored, which is also one of the goals of the present study.

Theory of mind-related reading difficulties in children with autism

Basic and advanced ToM tasks are commonly used to assess different levels of ToM skills, with the former referred to as explicit and involving sequential processing of information based on clear directions that assess first-order perspective while the latter is defined as implicit and involving the parallel processing of multiple strains of information that assess second- or higher-order perspectives. Studies to date have not reached consensus regarding which specific ToM skills are impaired in children with autism. Some studies have reported that these children have intact basic ToM skills (e.g., emotion recognition, first-order false-beliefs) but impaired advanced ToM skills (e.g., understanding irony, second-order false-beliefs) (Tong et al., 2019). Moreover, advanced ToM deficits have been found to be more serious than basic ones (Frith, 2012) and more closely associated with poor social interactions (Hughes & Leekam, 2004). Conversely, one study with a large sample size showed comparable advanced ToM abilities (e.g., second-order false-beliefs) in children and adolescents with autism before and after controlling for age (Scheeren et al., 2013).

Despite the controversy on specific ToM deficits in children with autism, converging evidence has shown the link between ToM and reading comprehension (Boerma et al., 2017; Ricketts et al., 2013; Tong et al., 2019). As both ToM and text reading comprehension share specific brain mechanisms (Mar, 2011) and extract meanings from symbols, the ability to infer others' mental states is crucial for text comprehension and making accurate predictions (Carnahan et al., 2011; Tomasello, 2010). Previous research suggested that ToM directly predicted unique variance in reading comprehension in younger and older TD children (Boerma et al., 2017). For example, using verbal and non-verbal ToM tasks, Ricketts et al. (2013) demonstrated that ToM was a unique predictor of reading comprehension in adolescents with autism after controlling for word reading and oral language. Social behaviour and understanding of mental states were significantly associated with reading comprehension, indicating that social cognition may explain the heterogeneity in reading comprehension.

Similarly, Tong et al. (2019) found that ToM was significantly associated with both literal (explicit) and non-literal (inferential) reading comprehension for Hong Kong Cantonese-speaking children with autism but not for their TD peers. Moreover, ToM was a partial mediator of group status and reading comprehension after controlling for non-verbal intelligence, working memory, word reading, and oral vocabulary skills. Interestingly, the mediation effect was significant for inferential, but not literal, reading comprehension skills. However, these previous studies have solely focused on ToM, without considering other cognitive impairments, such as executive dysfunction. As executive dysfunction and reading comprehension difficulties are the consistent deficits in autism, identifying which aspects of ToM are impaired in children with autism is necessary to understand how different ToM components relate to other cognitive and reading difficulties.

The present study

Although reading comprehension difficulty is commonly recognized in children with autism (e.g., Brown et al., 2013; McIntyre et al., 2017), how different aspects of reading comprehension (i.e., literal and inferential) are associated with language impairments and cognitive phenotypes of autism remains unclear. Previous studies have illustrated potential connections between reading difficulties in autism with deficits in vocabulary and semantic organization (e.g., Brown et al., 2013), EF (e.g., Ellis Weismer et al., 2018; Haebig et al., 2015), and ToM (e.g., Ricketts et al., 2013). Given that most previous studies exploring the contribution of either EF or ToM to reading comprehension focused on children using alphabetic languages (e.g., Brown et al., 2013; Ellis Weismer et al., 2017, 2018; Haebig et al., 2015; Ricketts et al., 2013), the co-occurring deficits of EF and ToM and their relationships with reading comprehension difficulties remain unexplored in children who use non-alphabetic Chinese logographic script.

Thus, in the present study, we examined how EF and ToM deficits are characterized and associated with reading comprehension difficulties in Hong Kong school-aged Chinese children with autism compared to their TD peers. Specifically, to identify each group's general strengths and weaknesses, we first compared their EF (basic and advanced), ToM (basic and advanced), and reading comprehension (literal and inferential) skills, along with other cognitive and language abilities. Moreover, to better understand how their varying levels of impairments in EF, ToM, and language abilities contribute to reading comprehension difficulties, we evaluated the influence of these specific impairments on literal and inferential reading comprehension separately.

Method

Participants

Seventy-two 8- to 10-year-old Chinese children participated in this study. Thirty-six of them (33 males; Mean age = 9 years; 0 months, $SD = 6$ months) had been formally diagnosed as autistic by a clinical psychologist or pediatrician based on the criteria in the Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition (DSM-IV) (American Psychiatric Association, 2000). The other 36 children were typically developing age-matched peers (TD, 32 males; Mean age = 8 years; 1 month, $SD = 6$ months). All participants were native Cantonese-speakers studying in Hong Kong mainstream primary schools where Cantonese was the primary medium of instruction.

The autism group comprised 13 children with autism, five with high-functioning autism (HFA), nine with Asperger syndrome (AS), and nine with Pervasive Developmental Disorder Not Otherwise Specified (PDD-NOS). As the DSM-IV outlines, the core clinical symptoms of autism disorders are (1) persistent impairments in social communication and social interaction across multiple contexts, and (2) noticeably restricted and repetitive patterns of behaviour, interests, or activities. In addition to the usual autism symptoms, children with HFA generally have an average to above-average cognitive ability and better visual-spatial and motor skills. Children with AS meet the autism diagnostic criteria but do not show clinically significant delays in language and cognitive development or age-appropriate skills. Children with PDD-NOS, also known as atypical autism, do not fully meet the autism diagnostic criteria or PDD but still exhibit social interaction difficulties, communication problems, and/or stereotypic behaviour patterns. The inclusion of this wide range of autism subtypes enabled us to depict a more comprehensive picture of reading comprehension abilities in children with autism.

All children in the autism group had normal IQ (IQ > 70) as reported by their parents. All TD children reported no history of developmental and psychiatric disorders. The two groups were matched on the levels of parents' education, with the father's average education being secondary 4–7, $F(1, 70) = 0.12$, $p = 0.726$, while the mother's average education was secondary 1–3, $F(1, 70) = 0.40$, $p = 0.531$.

Table 1 Cognitive and language profiles of children with autism and their typically Developing (TD) controls

Measures (Max.)	Autistic Group *M (SD)*	TD Group *M (SD)*	$F(1, 70)$	Cohen's d [95% CI] Autistic vs. TD
Age (in years)	9.05 (.47)	8.87 (.51)	2.32	.37 [−.10, .84]
Nonverbal intelligence (30)	16.80 (3.29)	18.10 (3.50)	2.66	.39 [−.09, .86]
Forward digit span (9)	7.33 (1.26)	7.69 (1.21)	1.53	.29 [−.18, .76]
Backward digit span (9)	3.75 (1.79)	4.31 (1.88)	1.65	.31 [−.16, .77]
Receptive vocabulary (50)	45.60 (.35)	46.40 (.35)	2.47	.39 [−.09, .85]
Expressive vocabulary (75)	52.70 (13.00)	58.60 (6.50)	5.88*	.58 [.09, 1.06]

Max. maximum possible score

$^{***}p<.001$; $^{**}p<.01$; $^{*}p<.05$; $^{\dagger}p<.10$

Additionally, no significant difference was found in the monthly family income level between the two groups, $F(1, 70)=1.97$, $p=0.165$.

As shown in Table 1, the autism group and the TD group did not differ significantly in terms of chronological age ($p=0.133$), non-verbal intelligence ($p=0.107$), forward digit span, ($p=0.221$), and backward digit span ($p=0.204$). This study obtained ethics approval by the Human Research Ethics Committee from the University of Hong Kong, and written informed consent was obtained from each caregiver of all participating children prior to testing.

Measures

Non-verbal intelligence

Children's non-verbal reasoning abilities were assessed using the Matrix Reasoning subtest from the Wechsler Abbreviated Scale of Intelligence, Second Edition (WASI-II; Wechsler, 2011). After presented with an incomplete matrix, participants were instructed to choose the most appropriate option out of five to complete the matrix. The test included 30 items and was terminated after three consecutive mistakes. Each item was worth one point, and a raw score was computed. Cronbach's alpha for non-verbal intelligence was *acceptable* ($\alpha=0.70$).

Digit span tasks

One of our self-developed forward and backward digit span tasks were administered to assess children's short-term memory and working memory, respectively (Tong et al., 2019). Each task consisted of nine levels, with two items each, resulting a total of 18 itmes After verbally presented with a sequence of digits, children were instructed to repeat the sequence of digits in the same order for the forward digit span task and in the reverse order for the backward digit span task. Testing was terminated if both items in the same level were incorrect. The maximum level that children reached before termination of the task was recorded for the analysis. Cronbach's alpha for working memory was *good* ($\alpha = 0.81$).

Expressive and receptive vocabulary

Cantonese expressive vocabulary was assessed with a picture naming task (Ng, 2015) that consisted of 75 picture items in ascending difficulty. Children were asked to use a two-character Cantonese word to name each picture. One point was assigned upon successful naming of a picture, and a raw score was calculated for analysis. The test was discontinued after five consecutive errors. Cronbach's alpha for Cantonese expressive vocabulary was *excellent* ($\alpha = 0.93$).

Additionally, a 50-item Cantonese-translated version of Peabody Picture Vocabulary Test (PPVT-IV) (Dunn & Dunn, 2007) was used to assess children's receptive vocabulary. After listening to a verbally presented word, children were asked to point to a corresponding picture that represented the spoken target word. Cronbach's alpha for this test was close to *acceptable* ($\alpha = 0.61$).

Chinese word reading

A 150-item Chinese word reading subtest from the Hong Kong Test of Specific Learning Difficulties in Reading and Writing for Primary School Students (HKT-P II; Ho et al., 2007) was administered to measure Chinese word reading accuracy. Participants were asked to read aloud isolated two-character words as accurately and quickly as possible, and the test was terminated upon 15 consecutive incorrect responses. A raw score was computed by assigning one point for each correct item. Cronbach's alpha for this test was *excellent* ($\alpha = 0.96$).

Chinese reading comprehension

Children were presented with three reading passages (two narrative and one expository), with the first and the second translated and adapted for a Hong Kong context from York Assessment of Reading for Comprehension (Snowling et al., 2009), and the third adopted from a previous study (Tong et al., 2019). Each passage contained 150 to 350 Chinese characters, and a total of 38 questions (19 literal and 19 inferential) were included. Question items for the first and second passages contained multiple-choice answers, while the third passage included short answer questions. The literal questions were used to test simple recall or identification of information explicitly stated in the passage. The inferential questions required the children to infer ideas that were not explicitly provided in the text. Cronbach's alpha for the Chinese reading comprehension task was *good* ($\alpha = 0.83$).

Executive function (EF)

Two computerized tasks were administered to assess inhibition and planning of EF performance. The Hearts and Flowers task in Chinese (Ng, 2015) was administered with E-prime 2.0 software (Psychology Software Tools, Pittsburgh, PA) on a DELL laptop. It consisted of congruent (12 trials), incongruent (12 trials), and mixed (33 trials) conditions. The congruent condition required participants to press an arrow key that matched the direction of the heart stimulus presented on screen. In the incongruent condition, children had to press an arrow key that indicated the opposite direction of the flower stimulus presented on screen. This required children to suppress irrelevant information and thus tested the inhibition ability of EF (Brocki & Tillman, 2014). The mixed condition involved random presentation of both congruent and incongruent trials and required participants to utilize their shifting skills. Cronbach's alpha for the Hearts and Flowers task was *good* ($\alpha = 0.81$).

Additionally, a 21-item Tower of London (ToL) test (SANZEN Tower of London test, 2017) was administered on a DELL laptop to measure advanced EF planning skills. For each item, the children, using as few moves as possible, had to re-arrange coloured beads on a number of sticks at the bottom of the screen to match the pattern of the target stimulus (i.e., same number of sticks with coloured beads) presented at the top of the screen. Feedback was provided after each item to show the total number and target number of moves. Cronbach's alpha of the ToL task was *good* ($\alpha = 0.88$).

Table 2 Examples of theory of mind (ToM) subtasks

Theory of Mind Subtasks	Examples of Test Questions
Basic ToM	
Emotion recognition	Please point at the happy face.
Desire-based emotion	If Xiaofen gets cookies, how would she feel?
Seeing-leads-to-knowing	Where does Xiaoxin think his glasses are?
Line-of-sight	When Xiaomei looks at the statue, what would she see?
Perception-based action	Where would Wenjian find his key?
First-order false-belief	Where would Zhiqiang first look for the book?
Advanced theory of mind	
Belief-based emotion	When Minghui believes that his dad bought a toy airplane for himself, how would he feel?
Reality-based emotion	When Minghui receives a toy train, how would he feel?
Second-order belief-based emotion	When Minghui's dad gives a toy train to Minghui, how would he think Minghui feels?
Message-desire discrepancy	What kind of food does Xiaoxuan want?
Second-order false-belief	How would Xiaohao's mom answer grandpa's question? (What does Xiaohao think he received as his birthday gift?")

Theory of mind (ToM)

A multifaceted ToM task battery (Tong et al., 2019) was modified from Hutchins et al. (2008) for use in Hong Kong context made suitable for a Hong Kong context. This task battery included six basic ToM and five advanced ToM (see Table 2 for examples). Children were presented with a story book that contained short vignettes about each ToM subtask. After seeing colour illustrations and related texts about each ToM subtask, they were instructed to answer 24 test questions, either by pointing to the correct picture out of four for multiple choice questions or responding verbally for short answer questions. In some subtasks, a bonus mark was given for follow-up explanations, but only if the target question was first answered correctly. Questions were arranged from easiest to hardest.

The basic ToM questions were related to emotion recognition, social referencing, basic understanding, and use of mental representations to predict the behaviours of others. The individual basic ToM subtasks were (1) emotion recognition, (2) desire-based emotion, (3) seeing-leads-to-knowing, (4) line-of-sight, (5) inference of perception-based action, and (6) first-order false-belief. *Emotion recognition* tested children's ability to identify emotional states of pictures with facial expressions (i.e., happy, sad, angry, and scared). *Desire-based emotion* assessed children's ability to understand emotions based on the fulfillment of a protagonist's wish or desire. *Seeing-leads-to-knowing* tested children's ability to accurately perceive a situation from their point-of-view, whereas *line-of-sight* required them to understand a situation from a protagonist's point-of-view. *Inference of perception-based action* tested children's ability to deduce a protagonist's next action given the protagonist's partial understanding of the situation. *First-order false-belief* assessed children's ability to correctly infer a protagonist's mental state when a situation changes without the protagonist's knowledge.

The advanced ToM questions were related to social cognition, which involved extracting relevant information in context, and interpreting mental representations through subtle social cues to make accurate social judgments (Garfield et al., 2001). The advanced ToM subtasks were (7) first-order belief-based emotion, (8) reality-based emotion, (9) second-order belief-based emotion, (10) message-desire discrepancy, and (11) second-order false-belief. *First-order belief-based emotion* tested children's ability to understand a protagonist's belief and accompanying emotion when faced with a contrasting reality. *Reality-based emotion* tested children's ability to understand a protagonist's emotion after the protagonist realizes something new about a given situation. These nine subtasks involved first-order perspectives and required the children to understand the mental state or emotions of a protagonist. The remaining two subtasks involved second-order perspectives that required the children to infer another character's point-of-view or feelings based on the protagonist's emotional or mental state. *Second-order belief-based emotion* tested children's ability to understand another character's emotional state based on that character's belief about the protagonist. *Message-desire discrepancy* tested children's ability to infer another character's belief when the protagonist's statement of desire did not match with reality. *Second-order false-belief* tested children's ability to make inferences about another character's belief based on that character's understanding of the protagonist's mental representations.

In addition to these target question items for basic and advanced ToM, control questions were included but not analyzed. Cronbach's alpha of the ToM task battery was *good* ($\alpha = 0.85$).

Procedure

Prior to testing, parents or caregivers of all participants provided informed written consent and completed a language and social background questionnaire. Individual testing sessions were conducted in a sound-shielded HKU research laboratory or in a quiet room at the participant's home. Parents or caregivers of children with autism also completed an autism background questionnaire. A single testing session lasted for approximately two hours, with an interim break of fifteen minutes after the first hour. Tasks were administered in a fixed order: non-verbal intelligence, working memory, expressive and receptive vocabulary, Chinese word reading, reading comprehension, ToM, and EF. Since visual strategies can help children with autism better understand the task at hand and thus reduce their anxiety (Bryan & Gast, 2000; Hodgdon, 1995), an arrow flow chart outlining the task sequence and activity details was provided.

Data analysis

Five domains of measures including EF (Hearts and Flowers task, ToL), ToM (11 subtasks), reading (literal and inferential reading comprehension, Chinese word reading), other cognitive (non-verbal intelligence and digit span tasks), and oral language (expressive vocabulary and receptive vocabulary) measures were all continuous data. All data were examined for multivariate outliers by using Mahalanobis Distances, but no outliers were detected. Some measures were not normally distributed in our samples, and Pillai's trace was used to report test statistics for these measures (See Fig. 1 and 2 for scatterplots).

To establish the cognitive and language profiles of children with autism and their TD peers, we first conducted a multivariate analysis of variance (MANOVA) for each of the five domains to compare the total scores of these measures between the two groups. Next, follow-up univariate analyses were conducted to examine which tests indicated group differences. After checking for multicollinearity ($VIF < 4$) and homogeneity of covariances (Box's M test) and applying Bonferroni corrections to adjust for Type I error, we built separate linear mixed-effects (LME) models to examine the influence of EF and ToM on literal and inferential reading comprehension. As autism populations are usually diverse and not normally distributed (Waterhouse, 2013), LME models are ideal for controlling inter-individual variability while identifying the relationship between predictors and outcomes (Gordon, 2019). The lme4 package in R (Version 4.0.0; CRAN project; *R*) was used to build models for comparison.

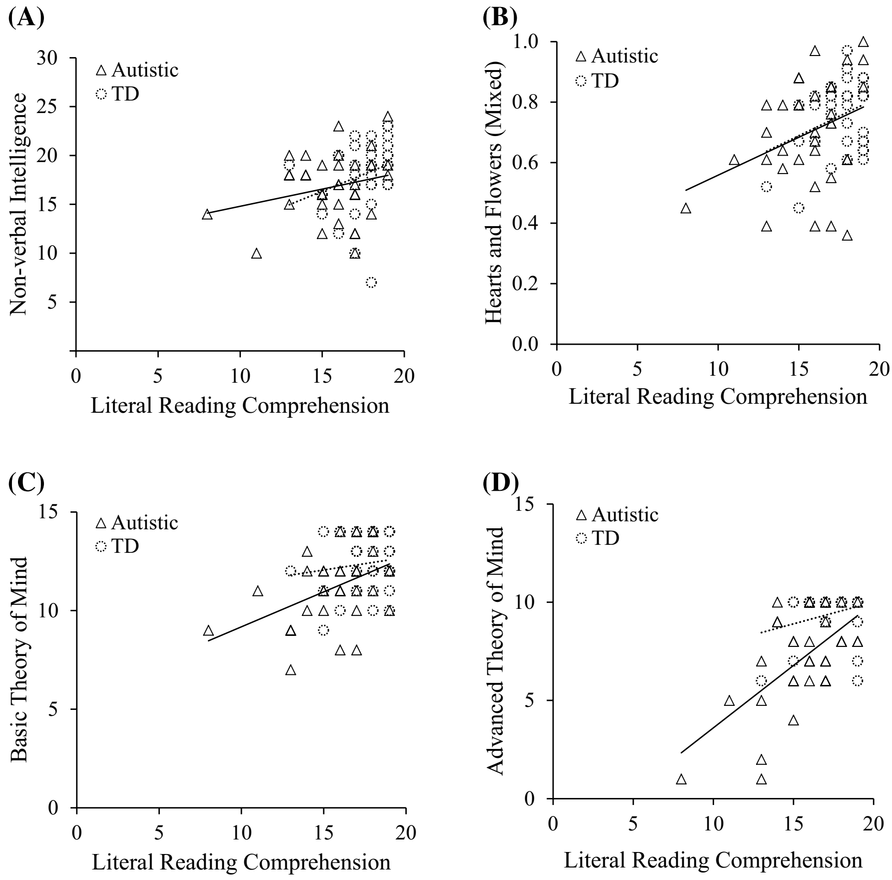

Fig. 1 Scatterplots of Significant Predictors for Literal Reading Comprehension. The scatterplots represent distribution of literal reading comprehension with **A** Non-verbal intelligence **B** Hearts and Flowers–Mixed condition **C** Basic ToM–total scores of six tasks **D** Advanced ToM–total scores of five tasks in children with autism (triangle; straight line) and their TD peers (circle; dashed line)

Additional models were constructed with single or multiple tasks from the five domains, and were compared with the null model using the likelihood ratio test (LRT; Pinheiro & Bates, 2000), which was designed to compare more complex models with nested models.

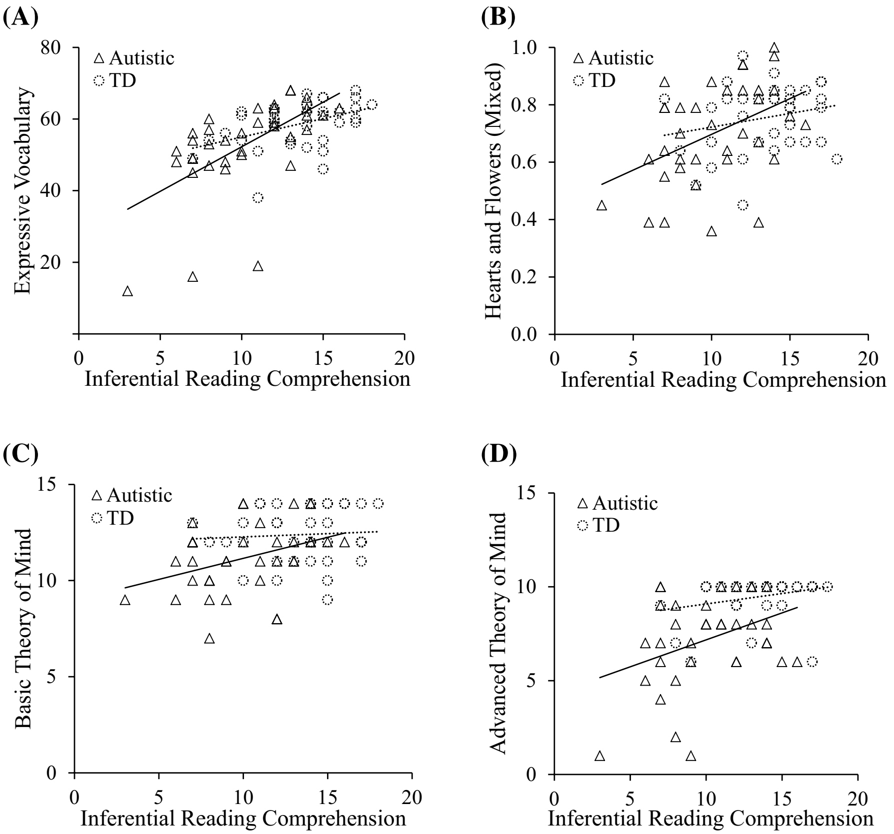

Fig. 2 Scatterplots of Significant Predictors for Inferential Reading Comprehension. The scatterplots represent distribution of inferential reading comprehension with **A** Expressive vocabulary **B** Hearts and Flowers–Mixed condition **C** Basic ToM–total scores of six tasks **D** Advanced ToM–total scores of five tasks in children with autism (triangle; straight line) and their TD peers (circle; dashed line)

Results

Comparison of cognitive and language profiles between children with autism and typically developing peers

Repeated measures MANOVAs were conducted to examine whether the children with autism exhibited specific impairments in EF, ToM, reading, and/or other cognitive and oral language measures. The MANOVA was conducted on all dependent measures with group (children with autism vs. TD) as the between-subjects factor. A statistically significant effect was found comparing overall measures between the two groups with a large effect size, $F(22, 49)=2.01$, $p=0.021$; Pillai's $V=0.48$, $\eta_p^2=0.48$. According to Cohen (1988), partial eta squared (η_p^2) is interpreted as a small (0.01), medium (0.06) and large (0.14) effect size. Then, separate MANOVAs were performed to examine the group difference on each domain of measures

Table 3 Descriptive statistics and comparisons of executive function tasks between children with autism and their typically developing (TD) peers

Measures	Autistic Group *M (SD)*	TD Group *M (SD)*	$F(1, 70)$	Cohen's d [95% CI] Autistic vs. TD
Hearts and Flowers task [a]				
Congruent	.95 (.08)	.97 (.06)	2.42	.38 [−.10, .85]
Incongruent	.87 (.16)	.92 (.09)	3.56†	.45 [−.03, .92]
Mixed	.70 (.18)	.76 (.11)	2.42	.38 [−.10, .84]
Tower of London test [b]	41.10 (22.80)	29.40 (15.50)	6.52*	.61 [.12, 1.09]

[a]The means and SDs of accuracy rates

[b]The means and SDs of raw scores, and no maximum possible score for this test as it includes the number of excess moves

$^{***}p<.001$; $^{**}p<.01$; $^{*}p<.05$; $^{\dagger}p<.10$

(EF, ToM, reading, other cognitive, and oral language). Significant group differences were observed in the EF domain, $F(4, 67)=2.58$, $p=0.045$; Pillai's $V=0.13$, $\eta_p^2=0.13$, ToM domain, $F(10, 61)=2.62$, $p=0.010$; Pillai's $V=0.30$, $\eta_p^2=0.30$, and reading domain, $F(3, 68)=8.53$, $p<0.001$; Wilk's $\Lambda=0.73$, $\eta_p^2=0.27$, whereas the other cognitive domain, $F(3, 68)=1.47$, $p=0.231$; Wilk's $\Lambda=0.94$, $\eta_p^2=0.06$, and oral language domain, $F(2, 69)=2.91$, $p=0.061$; Pillai's $V=0.08$, $\eta_p^2=0.08$, did not show significant effects.

Table 4 Means and standard deviations of theory of mind tasks of children with autism and their typically developing (TD) peers

Measures (Max.)	Autistic Group *M (SD)*	TD Group *M (SD)*	$F(1, 70)$	Cohen's d [95% CI] Autistic vs. TD
Basic Theory of Mind				
Emotion recognition (4)	4.00 (.00)	4.00 (.00)	1.00	.00 [−.46, .46]
Desire-based emotion (2)	1.92 (.28)	1.97 (.17)	1.05	.22 [−.25, .68]
Seeing-leads-to-knowing (2)	1.86 (.35)	1.97 (.17)	2.95†	.41 [−.07, .87]
Line-of-sight (2)	1.31 (.86)	1.58 (.77)	2.10	.34 [−.14, .80]
Perception-based action (2)	.64 (.87)	1.14 (.90)	5.77*	.57 [.09, 1.05]
First-order false-belief (2)	1.47 (.85)	1.72 (.70)	1.87	.33 [−.14, .79]
Advanced Theory of Mind				
Belief-based emotion (2)	1.75 (.60)	2.00 (.00)	6.18*	.59 [.11, 1.07]
Reality-based emotion (2)	1.50 (.88)	1.97 (.17)	10.04**	.76 [.26, 1.25]
Second-order belief-based emotion (2)	1.72 (.62)	1.97 (.17)	5.55*	.56 [.08, 1.04]
Message-desire discrepancy (2)	1.22 (.87)	1.75 (.60)	9.01**	.72 [.23, 1.21]
Second-order false-belief (2)	1.03 (.94)	1.78 (.59)	16.41***	.97 [.45, 1.48]

Max. maximum possible score

$^{***}p<.001$; $^{**}p<.01$; $^{*}p<.05$; $^{\dagger}p<.10$

Follow-up univariate analyses were conducted to examine the group differences within each domain. In the EF domain, as shown in Table 3, a significant group difference was found in the Tower of London test, $F(1, 70) = 6.52$, $p = 0.013$, $\eta_p^2 = 0.09$. More excess moves were performed by children with autism ($M = 41.1$, *95% CI* [34.6, 47.6]) than the TD peers ($M = 29.4$, *95% CI* [22.93, 35.9]).

In the ToM domain, as shown in Table 4, children with autism scored significantly lower than their TD peers in six tasks, with medium to large effect sizes. Children with autism performed worse than their TD peers in *perception-based action*, $F(1, 70) = 5.77$, $p = 0.019$, $\eta_p^2 = 0.08$ ($M_{diff} = 25.0$, *95% CI* [4.2, 45.8]), *belief-based emotion*, $F(1, 70) = 6.18$, $p = 0.015$, $\eta_p^2 = 0.08$ ($M_{diff} = 12.5$, *95% CI* [2.5, 22.5]), *reality-based emotion*, $F(1, 70) = 10.04$, $p = 0.002$, $\eta_p^2 = 0.13$ ($M_{diff} = 23.6$, *95% CI* [8.8, 38.5]), *second-order belief-based emotion*, $F(1, 70) = 5.55$, $p = 0.021$, $\eta_p^2 = 0.07$ ($M_{diff} = 12.5$, *95% CI* [1.9, 23.1]), *message-desire discrepancy*, $F(1, 70) = 9.01$, $p = 0.004$, $\eta_p^2 = 0.11$ ($M_{diff} = 26.4$, *95% CI* [8.9, 43.9]), and *second-order false-belief* subtasks, $F(1, 70) = 16.41$, $p < 0.001$, $\eta_p^2 = 0.19$ ($M_{diff} = 37.5$, *95% CI* [19.0, 56.0]).

In the reading domain, as shown in Table 5, significant differences between the two groups were found in both literal and inferential question types of reading comprehension with large effect sizes. TD children outperformed children with autism in literal, $F(1, 70) = 16.88$, $p < 0.001$, $\eta_p^2 = 0.19$ (TD: $M = 17.6$, *95% CI* [16.9, 18.2]; autism: $M = 15.7$, *95% CI* [15.0, 16.3]) and inferential questions, $F(1, 70) = 23.41$, $p < 0.001$, $\eta_p^2 = 0.25$ (TD: $M = 13.5$, *95% CI* [12.5, 14.5]; autism: $M = 10.2$, *95% CI* [9.2, 11.1]).

In the oral language domain, as shown in Table 1, a significant group difference was found in expressive vocabulary with a medium effect size, $F(1, 70) = 5.88$, $p = 0.018$, $\eta_p^2 = 0.08$. Children with autism ($M = 52.7$, *95% CI* [49.2, 56.1]) exhibited smaller expressive vocabularies than their TD peers ($M = 58.6$, *95% CI* [55.1, 62.0]). However, no significant group difference was found in any of cognitive domains (all $ps > 0.05$).

Measures associated with literal reading comprehension in children with autism and typically developing peers

Additional linear mixed-effects models were performed to examine how the group differences in EF, ToM, reading, oral language, and other cognitive measures

Table 5 Means and standard deviations of reading tasks of children with autism and their typically developing (TD) peers

Measures (Max.)	Autistic Group *M (SD)*	TD Group *M (SD)*	$F(1, 70)$	Cohen's *d* [95% CI] Autistic vs. TD
Word reading (150)	111.00 (16.40)	118.00 (15.10)	$3.54^{\dagger}$	.45 [− .03, .92]
Reading comprehension				
Literal (19)	15.70 (2.33)	17.60 (1.48)	16.88^{***}	.99 [.47, 1.50]
Inferential (19)	1.20 (3.08)	13.50 (2.75)	23.41^{***}	1.15 [.61, 1.67]

Max. maximum possible score

$^{***}p < .001$; $^{\dagger}p < .10$

Table 6 Final linear mixed-effects model (LME) for literal reading comprehension

Predictors	Estimate	*SE*	*df*	*t*	*p*
Fixed effects					
(Intercept)	7.28	1.33	72	5.46***	< .001
Group	.78	.39	72	2.01*	.048
Hearts & Flower task (Mixed)	3.44	1.24	72	2.78**	.007
ToM: Reality-based emotion	.76	.30	72	2.49*	.015
ToM: Second-order belief-based emotion	1.57	.43	72	3.67***	< .001
Non-verbal intelligence	.13	.05	72	2.42*	.018
Random effects				Variance	*SD*
Participant (Intercept)				.13	.36

Number of observations = 72, Participants = 72

***$p < .001$; **$p < .01$; *$p < .05$

interacted with literal reading comprehension. The fixed effect predictor of group accompanied by a random effect predictor of participant were entered in all constructed models for literal reading comprehension. The null model tested literal reading comprehension by including group and participant (see Table 1 for a summary of the null model in the supplemental materials), and a series of alternate models were constructed to add each of and combinations of the EF, ToM, reading, oral language, and other cognitive measures.

A final model with the best model fit for literal reading comprehension included the mixed condition of the Hearts and Flowers EF task, the *reality-based emotion* and *second-order belief-based emotion* subtasks from ToM, and non-verbal intelligence as the fixed effects in addition to group and participant (see Table 6). Contrasting this alternate model with the null model, a significant result was shown from the LRT statistics, $\chi2$ (4) = 37.97, $p < 0.001$, justifying the inclusion of these measures in the final model for literal reading comprehension as the model fit was greatly enhanced. The final model showed a main effect of group ($p < 0.05$), indicating that children with autism (*M* = 16.2, *95% CI* [15.7, 16.8]) scored significantly lower than their TD peers (*M* = 17.0, *95% CI* [16.5, 17.6]). Additionally, significant contributions were observed for the mixed condition of the Hearts and Flowers EF task ($p < 0.01$), the *reality-based emotion* ($p < 0.05$) and the *second-order belief-based emotion* subtasks from ToM ($p < 0.001$), and non-verbal intelligence ($p < 0.05$).

Measures associated with inferential reading comprehension in children with autism and typically developing peers

LME models for inferential reading comprehension were constructed and compared in the same way as the literal reading comprehension models. The null model included group as the fixed effect predictor and participant as the random effect predictor (see Table 2 for a summary of the null model in the supplemental materials).

Alternate models that included either each of the EF, ToM, reading, oral language, and other cognitive measures or combinations of them were compared with

Table 7 Final linear mixed-effects model (LME) for inferential reading comprehension

Predictors	Estimate	*SE*	*df*	*t*	*p*
Fixed effect					
(Intercept)	− 2.75	1.97	72	− 1.39	.168
Group	1.87	.57	72	3.28^{**}	.002
Hearts & Flower task (Mixed)	5.02	1.82	72	2.77^{**}	.007
ToM: Line-of-sight	.66	.33	72	2.02^{*}	.048
ToM: Belief-based emotion	1.05	.62	72	$1.68^{\dagger}$	.098
Expressive vocabulary	.13	.03	72	4.85^{***}	< .001
Random effects				Variance	*SD*
Participant (Intercept)				1.38	1.17

Number of observations = 72, Participants = 72

$^{***}p<.001$; $^{**}p<.01$; $^{*}p<.05$; $^{\dagger}p<.1$

the null model to identify the best fit model. The final model for inferential reading comprehension included the mixed condition of the Hearts and Flowers EF task, the *line-of-sight* and *belief-based emotion* subtasks from ToM, and Cantonese expressive vocabulary as the fixed effects in addition to group and participant (see Table 7). The LRT statistics showed that this alternate model significantly improved the fit of model, $\chi2$ (4) = 37.97, $p<0.001$. In the final model, a significant main effect of group ($p<0.01$) indicated that children with autism (M = 10.9, *95% CI* [10.1, 11.7]) scored significantly lower than their TD peers (M = 12.8, *95% CI* [12.0, 13.6]). Significant contributions were observed for the mixed condition of the Hearts and Flowers EF task ($p<0.01$), the *line-of-sight* subtask from ToM ($p<0.05$), and Cantonese expressive vocabulary ($p<0.001$). However, the *belief-based emotion* subtask from ToM was not a significant predictor in the full model ($p=0.098$).

Discussion

The present study investigated how reading comprehension deficits are associated with specific impairments in EF, ToM, and language abilities in Chinese school-aged children with autism. Our results demonstrated that although Chinese children with autism were comparable to their TD peers on all basic EF skills (inhibition and shifting), most basic ToM skills, non-verbal intelligence, working memory, receptive vocabulary, and word reading, they exhibited significant difficulties in EF planning skills, advanced ToM subtasks, expressive vocabulary skill, and reading comprehension. Moreover, these multiple but specific impairments in EF, ToM, and language were significantly associated with reading comprehension difficulties. These results are discussed in terms of heterogeneity of autism and reading comprehension difficulties.

Expressive language-related reading difficulties in children with autism

By distinguishing between literal and inferential questions, the present study showed that despite their intact word reading abilities, Chinese children with autism exhibited deficits in both literal and inferential reading comprehension. This finding not only extends previous research showing the hyperlexic reading profile (i.e., exceptional word reading but impaired reading comprehension) in children with autism in alphabetic languages but also corroborates recent evidence showing universal difficulties in literal and inferential comprehension among Chinese school-age children with autism (Tong et al., 2019).

More importantly, this study demonstrated for the first time that literal and inferential reading comprehension rely on some common but also distinct cognitive and language skills. Specifically, nonverbal intelligence and cognitive shifting are both involved in the two reading comprehension types, but inferential questions demand more on expressive vocabulary and some perspective-taking ToM skills. The significant contribution of expressive vocabulary to inferential reading comprehension can be explained by their shared conceptually driven processes, whereby either the production of a two-character Chinese word initiated by a picture or the inference of the meaning between associated words involves the activation of its respective lemmas or the abstract lexical representations that correspond to the words (Levelt et al., 1999). This explanation is supported by McIntyre et al. (2017)'s study showing that children with high-functioning autism experienced difficulties with story recall, and that the relationship between their reading comprehension difficulties and autistic features was mediated by the higher-order language and cognitive processing, which were related to the inferential and organization skills. Additionally, our finding is partly in line with a previous study reporting that children and adolescents with autism struggled with inferential but not literal comprehension questions (Myles et al., 2002).

Furthermore, the association between expressive vocabulary difficulty and inferential reading comprehension deficits observed in the present study reinforces the notion that oral language plays a critical role in reading comprehension, which is one of key premises of the SVR model (Gough & Tunmer, 1986). However, different from the SVR model which assumes the connection between word reading and reading comprehension, word reading did not emerge as a significant predictor of Chinese reading comprehension. This result is not surprising as the evidence has shown that oral language was a stronger predictor of reading comprehension than word reading in later reading development, which was demonstrated by the disappearance of the unique contribution of word reading after vocabulary was considered (Davidson et al., 2018).

Theory of mind-related reading comprehension difficulties in children with autism

In this study, Chinese children with autism exhibited significantly lower performance than their TD peers in advanced ToM but not basic ToM tasks. This result is consistent with previous research showing that deficits in the advanced or implicit level of ToM were more pervasive than the basic or explicit level of ToM in autism (Frith, 2012; Tong et al., 2019). Moreover, based on the comparison of individual ToM subtasks, we found that group differences depended on the level of perspective-taking. For example, the two groups were comparable in the *first-order false-belief* subtask (basic ToM) but significantly different in the *second-order false-belief* subtask (advanced ToM). This may, in part, explain the mixed patterns reported in the previous literature using false-belief tasks and therefore justify why ToM needs to be examined as specific skills instead of as a holistic set of skills. Additionally, consistent with our prediction, the children with autism in this sample were impaired in all subtasks of advanced ToM, which can be attributed to their poor interpersonal interactions (Hughes & Leekam, 2004).

However, we noticed that the children with autism performed worse than their TD peers on one basic ToM subtask, namely, *perception-based action*. One explanation is that unlike other basic ToM subtasks, this task involved inference-making in determining the whereabouts of an object based on the character's understanding of the situation, which posed a special challenge to the children with autism. Another explanation comes from the mental files theory (Doherty & Perner, 2020) which suggests that despite their ability to construct the mental files for different perspectives, children with autism have deficiencies in registering these coreferential files to represent the same entity. As demonstrated in the s*eeing-leads-to-knowing* and the *line-of-sight* subtasks, the two groups were comparable in the ability to identify others' perspectives. Thus, the group difference in the *perception-based action* subtask indicate that these children's impairment arises from linking the coreferential information.

More importantly, our study demonstrated the associations between specific aspects of ToM skills and reading comprehension impairments. In particular, two emotion-related advanced ToM skills that required perspective-taking of a character's emotional state (i.e., the *reality-based emotion* and the *second-order belief-based emotion*) were found to be significant predictors of literal reading comprehension. On the one hand, this finding indicates the critical role of affective components of ToM in localizing the information available during text reading (Sebastian et al., 2012; Shamay-Tsoory et al., 2010). On the other hand, although children with autism have similar emotion recognition ability with their TD peers (Jones et al., 2010; Schwenck et al. 2011), our findings suggest that their lack of understanding of the emotional states of others or empathic abilities may hinder these children's processing of explicit information stated in the text, and thus impedes their performance in literal comprehension questions.

In contrast, a perspective-taking basic ToM skill (i.e., *line-of-sight*) appeared to be a significant contributor to inferential reading comprehension although the two groups exhibited comparable performance. This can be explained by the close link between the perceptual role-taking skill assessed by the *line-of-sight* of ToM and joint attention (Chawarska et al., 2007; Mundy, 1995). Joint attention is one of the precursor skills of ToM (Charman et al., 2000) that predicts language development and social cognition (Mundy et al., 2016). We speculate the association between the *line-of-sight* of ToM and inferential reading comprehension may be mediated by joint attention which enables children to coordinate limited cognitive resource to comprehend contextual information. Thus, this finding may suggest that inferential reading comprehension is more likely to be associated with cognitive ToM. Additionally, the finding that inferential reading comprehension was best predicted by group status, Cantonese expressive vocabulary, shifting-specific EF, and a perspective-taking basic ToM skill reflects that reading comprehension is a complex cognitive processes that involves the coordination of multiple cognitive factors.

Executive function-related reading difficulties in children with autism

Consistent with previous research (for reviews, see Geurts et al., 2014; Hill, 2004), we found that executive dysfunction in Chinese children with autism was manifested in higher-order planning skills but not in lower-order working memory and shifting skills. However, given the evidence showing the heterogenous EF difficulties in children with autism (Van Eylen et al., 2015) and the task-dependent EF deficits (Ellis Weismer et al., 2018), the absence of group difference in lower-order EF skills in the present study needs to be verified in other EF tasks in the future research.

Moreover, shifting but not other EF skills emerged to be a significant contributor to both literal and inferential reading comprehension. This result reflects the cognitive uniqueness of shifting as compared with other EF componential skills. According to an integrative framework of EF (Miyake et al., 2000), shifting is a higher-level EF skill that involves the coordination of two lower-level components, i.e., inhibition and updating. Similarly, Ellis Weismer et al. (2018) suggested that among six EF measures tapping inhibition, shifting, and updating of working memory, shifting may be most closely aligned with the broad construct of EF. This finding also aligns with previous studies showing that reading comprehension is a complex task that requires shifting among various tasks (e.g., decoding, vocabulary, and syntactics) (Cartwright et al., 2017). Additionally, given the evidence showing that shifting is involved in syntactic processing (Woodard et al., 2016) and lexical-semantic processing (Haebig et al., 2015) that are critical components of text reading comprehension, it is not surprising that shifting is involved in both literal and inferential reading comprehension.

Nevertheless, despite its involvement, shifting may play a different role in literal and inferential reading comprehension. As literal reading comprehension is less dependent on language skills and shifting is more influenced by children's general cognitive capacity and autism severity (Akbar et al, 2013), the influence of shifting on literal reading comprehension may be mediated by non-verbal intelligence. In contrast, inferential reading comprehension places high demands on expressive language skills, and thus, shifting may exert impacts on inferential reading comprehension via its service to language (Joseph et al., 2005). Due to the limitation of the present study, these speculations need to be further examined in the future research.

Implications, limitations and future directions

By assessing different aspects of ToM, EF, and reading comprehension skills, this study demonstrated for the first time that Chinese school-aged children with autism exhibited deficits in advanced ToM, higher-order EF skills, and expressive language and some of these deficits contributed to impaired literal and inferential reading comprehension. These findings, on the one hand, extend the SVR model to Chinese children with autism by confirming the critical role of oral language skills (i.e., expressive vocabulary) in reading comprehension (Gough & Tunmer, 1986). On the other hand, our findings indicate that in addition to oral language skills, other factors including ToM and EF also contribute to reading comprehension, suggesting multiple and heterogeneous sources of reading comprehension difficulties.

Despite their implications, our findings need to be interpreted with the consideration of the following limitations. One is that the participant inclusion was based on professional diagnosis but not confirmed with our own measures. It would be ideal to have the children's autism severity assessed and include this measure in the reading comprehension deficit models. Also, the reliabilities of some measures were relatively lower than others (i.e., WASI Matrix Reasoning alpha = 0.70; Cantonese PPVT alpha = 0.62) despite being at acceptable range (Hair et al., 2010). Moreover, our EF and ToM tasks were limited in tackling the complex cognitive and social functioning skills, which may be one of possible reasons for the lack of significant associations between higher-order EF and advanced ToM with inferential reading comprehension. Thus, future research may consider using more advanced EF tasks (e.g., organization and self-monitoring) and an extended version of the ToM battery that includes a broader range of ToM skills (e.g., irony, deception, and faux pas) in order to further investigate the associations among the deficits in higher-order EF, advanced ToM, and inferential reading comprehension.

Conclusions

The present study demonstrated that Hong Kong Chinese school-age children with autism exhibited heterogeneous and specific impairments in ToM, EF, and oral language impairments, and some of these deficits were uniquely associated with their literal and inferential reading comprehension deficits. Specifically, shifting-specific EF was significantly associated with both types of reading comprehension whereas different ToM and language skills exhibited unique associations with literal and inferential reading comprehension. Our results indicate multiple atypicalities across cognitive, social, and academic domains in autism, and suggest that cognitive flexibility and social cognition should be taken into account in understanding the heterogeneity of reading comprehension deficits in children with autism.

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