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Development of Social Working Memory in Preschoolers and Its Relation to Theory of Mind

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Social working memory (WM) has distinct neural substrates from canonical cognitive WM (e.g., color). However, no study, to the best of our knowledge, has yet explored how social WM develops. The current study explored the development of social WM capacity and its relation to theory of mind (ToM). Experiment 1 had sixty-four 3- to 6-year-olds memorize 1–5 biological motion stimuli, the processing of which is considered a hallmark of social cognition. The social WM capacity steadily increased between 3- and 6-year-olds, with the increase between 4 and 5 years being sharp. Furthermore, social WM capacity positively predicted preschoolers' ToM scores, while nonsocial WM capacity did not; this positive correlation was particularly strong among 4-year-olds (Experiment 2, N = 144).

Human beings are, by nature, an intensively social species (Allison, Puce, & McCarthy, 2000; Herrmann, Call, Hernández-Lloreda, Hare, & Tomasello, 2007; Meyer & Lieberman, 2012). Indeed, the "social brain hypothesis," a perspective on how the brain supports social-cognitive reasoning (Dunbar, 1998), even suggests that the need to keep track of an increasingly large number of social relationships functions as a key evolutionary constraint for our uniquely large brain size. In our daily lives, the capability to maintain and manipulate a limited set of social information (e.g., people's identity, mental states, traits, and relationships among people) in an online manner, also called "social working memory" (WM), is of paramount importance for navigating our social environment (e.g., Meyer & Lieberman, 2012, 2016; Meyer, Spunt, Berkman, Taylor, & Lieberman, 2012; Meyer, Taylor, & Lieberman, 2015; Thornton & Conway, 2013; Xin & Lei, 2015). Consequently, our brain has evolved neural substrates dedicated to social WM. For instance, Meyer et al. revealed that social WM for personality traits recruits the mentalizing network (e.g., dorsomedial prefrontal cortex, ventromedial prefrontal cortex, right temporoparietal junction; Meyer & Lieberman, 2012; Meyer et al., 2012, 2015), which is deactivated during canonical cognitive WM tasks (e.g., memorizing colors, locations, letters). Moreover, the behavioral performance and neural activation related to social WM were found to correlate with critical social abilities, including empathy (Gao, Ye, Shen, & Perry, 2016; Xin & Lei, 2015), and perspective taking (Meyer et al., 2012, 2015), whereas canonical WM did not.

So far, researchers have explored the capacity (Gao, Bentin, & Shen, 2015; Shen, Gao, Ding, Zhou, & Huang, 2014), storage manner (Thornton & Conway, 2013), function (Gao et al., 2016; Meyer et al., 2012, 2015; Xin & Lei, 2015), and neural substrates of social WM (Lieberman, 2007; Lu et al., 2016; Meyer & Lieberman, 2012, 2016; Meyer et al., 2012, 2015; Thornton & Conway, 2013; Xin & Lei, 2015). However, no study, to the best of our knowledge, has yet explored the development of social WM. This is in sharp contrast to the considerable amount of developmental research on canonical WM (e.g., Hitch, Woodin, & Baker, 1989; Riggs, McTaggart, Simpson, & Freeman, 2006; Simmering, 2012; see Cowan, 2016 for a review). Exploring social WM development would not only add to our comprehensive understanding of the functional development of our social-cognitive system, but also would

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shed light on the mechanisms by which children show improvements in social cognition through some treatments of social dysfunctions (e.g., autism). To this end, we investigated the development of social WM, focusing on 3-, 4-, 5-, and 6-year-olds, since early childhood is regarded as a critical period for the development of social cognition and WM (e.g., Carpendale & Lewis, 2010; Cowan, 2016).

A key perquisite to understanding the developmental trajectory of social WM is to choose representative social stimuli enabling us to test the four age groups using the same parameters. Researchers have thus far predominately employed three categories of stimuli in exploring adults' social WM: people's names (together with trait words), emotional human faces, and biological motion (BM). For instance, Meyer and Lieberman (2012, 2016) and Meyer et al. (2012, 2015) elegantly designed a social WM paradigm using people's names: They first required participants to rate their friends on multiple trait dimensions (e.g., funny); 2 weeks later, they presented participants with 2–4 of their friends' names, followed by a trait word. Participants had to consider to what extent each of these friends possessed the given trait and to mentally rank them. This paradigm has proven to be very sensitive to the mechanisms of social WM, such as the involvement of the mentalizing system. However, this task would be too cognitively challenging for preschoolers, considering that 3- to 6-year-olds have not yet obtained sufficient language ability to recognize and comprehend trait words (for Chinese preschoolers, see Kong, 2004).

Similarly, we thought that human faces would not be ideal stimuli for the current study. Although human faces are frequently encountered stimuli conveying rich social information and have been extensively used in studies of social cognition (see Freiwald, Yovel, & Duchaine, 2016 for a review), researchers have found that WM processes human faces as a type of complex stimuli with detailed information; as such, even adults can hold, at most, two faces (e.g., Gao & Bentin, 2011). Therefore, using human faces might prevent us from determining the development of social WM because of the possible floor effect of performance when retaining faces in WM. Indeed, studies measuring the capacity of canonical WM (particularly for preschoolers) have routinely used simple stimuli (e.g., color), which generally exhibit a capacity of 3–4 visual objects for adults (see Mance & Vogel, 2013 for a review).

Here, we suggest that BM—namely, the movement of animate entities (Johansson, 1973; Troje, 2013)—provides compelling social information and would be appropriate for the exploration of social WM development. BM is one of the most salient and biologically significant events in our daily lives (for reviews, see Blake & Shiffrar, 2007; Troje, 2013), and processing human BM has immense value for successful social interaction, including prosocial behaviors and nonverbal communication (for reviews, see Blake & Shiffrar, 2007; Pavlova, 2012). The neural substrates of BM have been shown to lie within the superior temporal sulcus and ventral premotor cortex (e.g., Puce & Perrett, 2003; Saygin, 2007), which are also related to various aspects of social cognition (for reviews, see Blakemore, 2008; Puce & Perrett, 2003). Impairment in BM perception correlates with social functioning (e.g., theory of mind [ToM]) in schizophrenia (e.g., Kim, Norton, McBain, Ongur, & Chen, 2013), and children with autism spectrum disorders, who have severe impairment on social cognition, tend to also show profound deficits in BM processing (e.g., Annaz et al., 2010). BM processing, therefore, can be considered one of the most fundamental aspects of social-cognitive processes (Troje & Westhoff, 2006), and has even been considered a hallmark of social cognition (Pavlova, 2012).

Befitting the importance of BM processing, our vision system has evolved incredible BM processing ability. This can be conspicuously demonstrated by the point-light display (PLD) technique. PLDs depict human BM using a simple set of light points (e.g., 12 points) placed at the joints of a moving human body (Johansson, 1973). Although highly impoverished (e.g., texture, clothes, and hair style are absent), once in motion, the PLDs are rapidly recognized as meaningful movement. Furthermore, an abundance of social information, such as identity, gender, emotion, trait, and intention, can be extracted (see Puce & Perrett, 2003; Troje, 2013 for reviews), whereas the social perception of BM is dramatically impaired when the BM is inverted (Blake & Shiffrar, 2007). Researchers have conducted numerous studies to uncover the development of BM perception using PLD as the stimuli of interest. For instance, it was found that infants are highly sensitive to BM, with even 2-day-old babies demonstrating a preferential attention toward BM (e.g., Bardi, Regolin, & Simion, 2011). Furthermore, 3-month-olds can categorize the BM of animals (Arterberry & Bornstein, 2001), and 4-month-olds can further differentiate upright from inverted BM and exhibit a preference for the former (e.g., Fox & McDaniel, 1982). Critically, 3-year-olds can reliably recognize PLD BM (Pavlova, Krägeloh-Mann, Sokolov, & Birbaumer, 2001). Therefore, having 3- to 6-year-olds memorize a set of BM stimuli would enable us to understand preschoolers' development of social WM without the limitations of using names or human faces.

Recent WM studies offer further support for the feasibility of using PLDs of BM as representative stimuli for exploring social WM in preschoolers. Gao and colleagues used PLDs and found that 18- to 25-year-olds can retain 3–4 human BM stimuli in WM (Gao et al., 2015; Shen et al., 2014), which is in line with typical estimates of WM capacity (Cowan, 2001). Therefore, BM stimuli would enable us to explore social WM without the risk of a floor effect. Moreover, two lines of evidence imply that social information is indeed processed when retaining BM in WM. First, neuroimaging studies have shown that the neural substrates for WM storage of BM include the mirror neuron system (Gao et al., 2015; Lu et al., 2016), which is suggested to have a close link with social cognition (e.g., Rizzolatti & Fabbri-Destro, 2008; but see Cook, Bird, Catmur, Press, & Heyes, 2014 for a different view). Second, Gao et al. (2016) found that the WM capacity of BM, but not canonical WM capacity (e.g., color), is a predictor of empathy, which is a key aspect of social functioning. However, to the best of our knowledge, no study has yet explored the development of WM for BM. To this end, we investigated the development of social WM by presenting PLDs of BM to 3- to 6-year-olds.

Given that WM is considered a fundamental process underlying the development of higher level cognitive abilities (e.g., language comprehension, reading, intelligence, visual search; see Cowan, 2014, 2016 for reviews), we further examined whether social WM capacity is similarly related to the development of higher level social-cognitive abilities in preschoolers by focusing on ToM (Schaafsma, Pfaff, Spunt, & Adolphs, 2015). ToM refers to the ability to understand other people's desires, emotions, beliefs, intentions, and other inner experiences that result in and are manifested in human action (Wellman, Cross, & Watson, 2001), and is considered a crucial development of the preschool years (e.g., Duh et al., 2016; Liu, Wellman, Tardif, & Sabbagh, 2008; Wellman et al., 2001). Extensive research has demonstrated that ToM predicts children's social competence in such domains as prosocial behaviors, interpersonal interaction, and popularity with peers (e.g., Astington & Jenkins, 1995; Slaughter, Imuta, Peterson, & Henry, 2015). Impairments in ToM are associated with debilitating social-cognitive deficits such as autism and psychopathy (e.g., Baron-Cohen, Tager-Flusberg, & Cohen, 1994; Blair et al., 1996). Previous WM studies have predominately explored the relation between executive functions and ToM (e.g., Duh et al., 2016; see Devine & Hughes, 2014 for a meta-analysis), and have consistently demonstrated a moderate positive correlation between these two constructs (e.g., r = .33 for Chinese preschoolers; Duh et al., 2016). However, few studies have explored the relation between social WM and core social capabilities (e.g., empathy, perspective taking; cf. Gao et al., 2016; Meyer et al., 2012, 2015; Xin & Lei, 2015), and none have explored the correlation between social WM and ToM. Thus, the current study fills this gap by requiring 3- to 5-year-olds to complete a scale of five ToM tasks developed by Wellman, Fang, Liu, Zhu, and Liu (2006) and Wellman and Liu (2004) after they completed a social WM (i.e., BM) task. To understand the unique function of social WM in the maturation of social-cognitive ability, we required participants to memorize either BM or movements that had poor biological information (i.e., inverted BM). We predicted that only the social WM capacity (i.e., capacity for BM) would predict ToM.

To overview the current study, we adopted a change detection task, which is commonly used for estimating the WM capacity of both adults and preschoolers (Mance & Vogel, 2013). Experiment 1 addressed the development of social WM for 3- to 6-year-olds. Experiment 2 further determined the correlation between social WM capacity and ToM.

Experiment 1: The Development of Social WM

Experiment 1 examined the development of social WM by requiring 3- to 6-year-olds to memorize 1–5 BM stimuli.

Method

Participants

In total, 64 children aged between 3 and 6 years old who were recruited from kindergartens in Hangzhou, a large-size city located in the southeast of China, participated in the study. There were 16 each of 3-year-olds (M = 3 years 7.61 months, SD = 1.83 months; 7 female), 4-year-olds (M = 4 years 6.33 months, SD = 3.21 months; 9 female), 5-year-olds (M = 5 years 7.02 months, SD = 4.14 months; 9 female), and 6-year-olds (M = 6 years 3.48 months, SD = 2.81 months; 8 female), collected between September 2014 and February 2015. All participants reported normal or corrected-to-normal vision and had no history of neurological damage, psychiatric disorders, head trauma, or psychological medications. All children's ethnicity was Han. Informed consent was obtained from preschoolers' parents. The study was approved by the Institutional Review Board at the Department of Psychology and Behavioral Sciences, Zhejiang University.

Stimuli

The PLDs of BM were selected from the database created by Vanrie and Verfaillie (2004), and comprised the BMs of cycling, jumping, painting, spading, walking, waving, and chopping (see Figure 1). Each stimulus contained 12 dots and has been used for estimating the social WM capacity of adults (e.g., Gao et al., 2015; Lu et al., 2016; Shen et al., 2014). The PLD animations each comprised 30 distinct frames, with each frame being displayed twice in succession; together, this led to a 1-s animation (with a 60-Hz refresh rate). The displays subtended a visual angle of approximately 1.64° × 1.64° from a viewing distance of 60 cm. One to five distinct stimuli were presented during each trial (cf. Shen et al., 2014). The spatial locations of the stimuli were evenly distributed along the periphery of an invisible circle with a radius of 4.88° from the center of the screen center. The PLDs were presented to children on a black background on a 14-in. Lenovo Y400 laptop.

Design and Procedure

Participants were required to memorize 1, 2, 3, 4, or 5 BM, which were presented in different blocks. There were 12 trials for each memory load, which resulted in a total of 60 trials. To help the preschoolers become engaged with the memory task, we followed the procedure of previous WM studies (e.g., Case, Kurland, & Goldberg, 1982) by requiring participants to complete the experimental blocks in a fixed ascending manner. Specifically, preschoolers were told that they would play a game and that each memory load served as one game level; only by passing their current level could they advance to the next. The 3-year-olds only had to memorize 1–3 BM; however, they were given the opportunity to try for higher memory loads if they wanted. The other three age groups had to complete all five memory load conditions. When experimenters explained the procedure to participants, they were not allowed to use words such as "cycling" and "jumping" to describe the stimuli, to ensure that participants did not verbally encode the BM.

Each trial began with a red fixation appearing for 300 ms to inform participants of the upcoming memory task (see Figure 2). After a blank interval of 150–350 ms, the memory array was presented on the screen for *N*s (according to the number of to-be-memorized stimuli, e.g., 3 s for three stimuli) to ensure that participants had sufficient encoding time (cf. Gao et al., 2015; Lu et al., 2016; Shen et al., 2014). After a 1-s blank interval, a red probe was presented until a response was given. Participants were asked to judge whether the probed movement had appeared within the memorized set. The experimenter instructed participants to make a verbal response (yes or no) and recorded it on an external keyboard. The task emphasized accuracy, and participants were given as much time as they needed to make a judgment. A smiling cartoon face appeared at the screen center for 300 ms when a response was correct, whereas a frowning cartoon face was presented for incorrect responses. The probed BM was a new one in 50% of the trials. Once a response had been recorded, the experimenter pressed the space bar to begin the next trial. If the child could not focus on a trial because of unexpected issues, experimenter presented the same trial again by pressing the space bar on the keyboard. Note that previous studies added a digit rehearsal task to the memory task to prevent participants from verbally encoding BM stimuli (e.g., Gao et al., 2015; Lu et al., 2016; Shen et al., 2014).

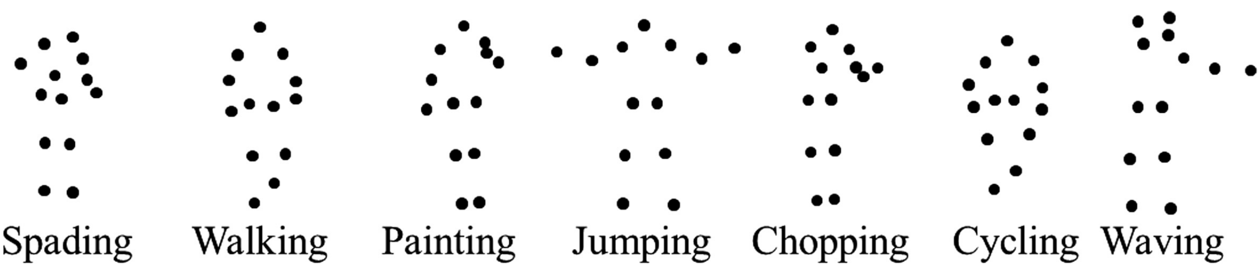

Figure 1. Example frames for the biological motion stimuli used in Experiments 1 and 2.

However, we did not do this because children do not develop verbal rehearsal strategies until around 7 years old (Hitch et al., 1989).

Before the formal experiment, participants completed eight practice trials of set size 1 and four trials of set size 2. Only when participants sufficiently understood the task did the experiment move to the next stage; otherwise, the participants had to redo the practice trials. The whole experiment lasted for about 25 min.

Data Analysis

To estimate the WM capacity, we employed Cowan's formula (Cowan, Blume, & Saults, 2013): $K = S \times (H - F)/H$, where K is the WM capacity, S is the number of to-be-memorized stimuli, H is the hit rate (i.e., the successful detection of a new stimulus), and F is the false alarm rate (i.e., incorrectly indicated a stimulus as new). We calculated the K for each set size of each participant. To obtain a more accurate estimate, we considered the maximum K (K-max) among all load conditions as a participant's WM capacity (e.g., Shen et al., 2014). A Pearson's correlation was calculated between K-max and the participants' age (by treating age as a continuous variable). Finally, a one-way analysis of variance (ANOVA) with age group (ages 3, 4, 5, and 6) as the between-subjects factor was performed on the K-max to determine how social WM capacity develops. Note we did not find any significant effect of gender in Experiments 1 or 2 (for either the ANOVA or Pearson's correlation analysis), and these results were not the main interest of the current study. Hence, we have not reported them here.

Results

Pearson's correlation revealed a significantly positive correlation between age and K-max (Figure 3a), $r(64) = .57$, $p < .01$, indicating that the WM capacity of BM increases with age. Corroborating this finding, the one-way ANOVA on K-max (Figure 3b) revealed a significant main effect of age group, $F(3, 60) = 10.88$, $p < .01$, $\eta_p^2 = .89$. Post hoc analysis (Bonferroni-corrected) showed that 3-year-olds (K-max = 1.54) and 4-year-olds (K-max = 1.97) had a significantly lower social WM capacity than did 5-year-olds (K-max = 2.85) and 6-year-olds (K-max = 3.08), $ps < .05$; the 3- and 4-year-olds did not significantly differ from each other, and neither did the 5- and 6-year-olds, $ps > .10$. These results indicated that social WM capacity developed dramatically from between the 3rd and 4th years to between the 5th and 6th years.

Discussion

Experiment 1 indicated that there was a significant increase in social WM capacity from 3 to 6 years of age, from 1.54 BM stimuli at 3 years old to 3.08 at 6 years old. The value of the latter group is close to that of adults (cf. Shen et al., 2014). We in particular found a rapid increase from 4 to 5 years old. We speculate that this rapid increase links with the development of social cognition, which exhibits a similar trend during this period. For instance, several studies have documented that 4 to 5 years after birth is a key stage for maturation of ToM (at least in the false belief tasks; e.g., Wellman, 2014). In Experiment 2, we tested this hypothesis by examining whether preschoolers' social WM capacity is positively associated with their ToM capability.

Experiment 2: Social WM Capacity Predicts Preschoolers' ToM

To comprehensively measure preschoolers' ToM, in Experiment 2, we used a Mandarin version of the ToM scale developed by Wellman et al. (2006). This scale contains five core tasks for measuring ToM

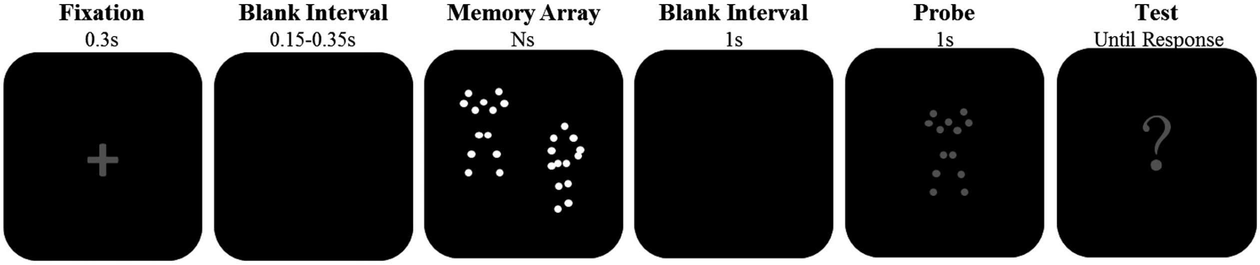

Figure 2. A schematic representation of a single trial in biological motion working memory tasks. The gray color in fixation, probe, and test was red in real experiment.

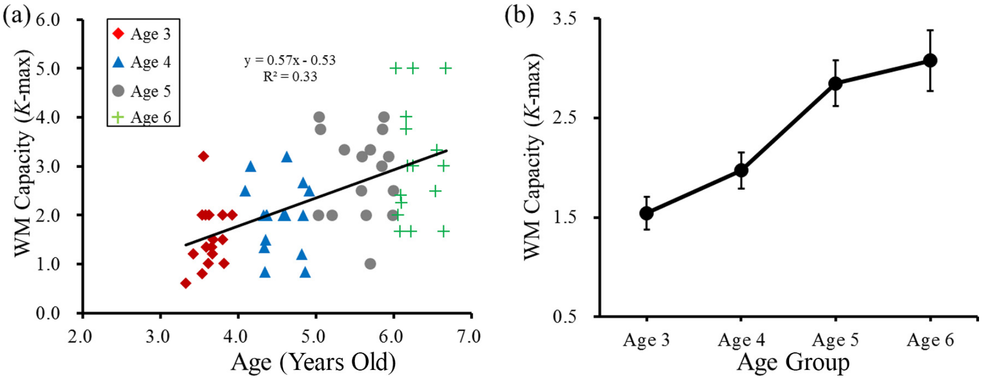

Figure 3. (a) The correlation between estimates (*K*-max) of working memory (WM) capacity and the age of the preschoolers. (b) The estimates (*K*-max) of WM capacity for 3- to 6-year-olds. The error bars indicate the standard errors.

understanding (Wellman & Liu, 2004; Wellman et al., 2006). Additionally, because it has been consistently shown that there was a considerable increase in ToM from 3 to 5 years old (e.g., Duh et al., 2016; Wellman et al., 2006), we decided to test preschoolers within this age range.

Furthermore, we had participants memorize either BM or inverted BM. Researchers have consistently shown that inverting BM dramatically impairs the social perception of BM, even when the same physical information is displayed (Blake & Shiffrar, 2007). We hypothesized that only social WM capacity (i.e., BM) would predict ToM.

Method

Participants

To minimize the participants' fatigue, each participant memorized only one type of stimuli. Thus, for the BM condition, we recruited 24 children each of 3-year-olds (M = 3 years 7.99 months, SD = 1.48 months; 13 female), 4-year-olds (M = 4 years 7.46 months, SD = 2.86 months; 11 female), and 5-year-olds (M = 5 years 6 months, SD = 2.49 months; 13 female), which were collected between March 2015 and January 2016. For the inverted BM condition, we also recruited 24 children each of 3-year-olds (M = 3 years 6.39 months, SD = 2.82 months; 10 female), 4-year-olds (M = 4 years 5.33 months, SD = 2.16 months; 14 female), and 5-year-olds (M = 5 years 5.74 months, SD = 9.59 months; 13 female), which were collected between June 2017 and July 2017. The data of six 3-year-olds and two 4-year-olds were replaced, because these children did not understand the task or were disturbed during the tasks. None had participated in Experiment 1. The other aspects were the same as in Experiment 1.

Stimuli

In addition to the BM stimuli used in Experiment 1, we inverted the BM used in Experiment 1 and required the participants to memorize them in the control condition. The other aspects of the stimuli and their presentation were the same as in Experiment 1.

ToM Understanding Task

A Mandarin version of the ToM scale developed by Wellman et al. (2006) was used. This scale comprises five subtasks, which were used to measure whether children could understand the following five aspects of ToM: that two people (the child and another person) might have different desires (*diverse desires* task), beliefs (*diverse beliefs* task), or knowledge about the same thing (*knowledge access* task); that another person might have a false belief (*contents false belief* task); and that a person can feel one thing but display a different emotion (*real–apparent emotion* task). To make these subtasks more suitable for our sample, we made slight modifications to the materials: namely, by using an apple and a pear (rather than ice cream and egg) in the diverse desires task, a schoolbag and a drawer (rather than a bed and cupboard) in the diverse beliefs task, and a cracker box (rather than a potato chip tube) in the contents false belief task (cf. Wu & Su, 2014). In our study, the experimenter first told the participants five stories using toys and pictures. A cartoon character with a Chinese visage and black hair, whose name was "Feifei," served as the protagonist in the tasks. The experimenter then asked the preschoolers certain questions, and wrote down the answers on paper. After completing all ToM subtasks, the preschoolers received a sticker as a reward.

The task order was fixed, following Wellman et al.'s (2006) procedure: diverse desires, diverse beliefs, knowledge access, contents false belief, and real–apparent emotion. For each subtask completed, preschoolers received one point. Children received no feedback on their answers for this task. The overall ToM score ranged from 0 to 5.

Procedure

Participants were initially allocated to either the BM or inverted BM group randomly. In each group, children completed the WM task with the corresponding stimuli, and then completed the ToM understanding tasks within 1 week of their completion of the WM task to minimize preschoolers' fatigue. The experiment was conducted in a quiet room in the kindergarten that the preschoolers attended. The other aspects were the same as in Experiment 1.

Data Analysis

In addition to estimating the WM capacity of BM and inverted BM using the formula described in Experiment 1, we calculated the Pearson's correlations between *K*-max and ToM scores. Furthermore, we performed separate two-way analyses of variance on *K*-max and ToM score, with age group (3-, 4-, and 5-year-olds) and stimulus type (BM vs. inverted BM) as the between-subjects factors.

Results

Development of WM Capacity of BM and Inverted BM

Pearson's correlation revealed that the WM capacity of both BM (Figure 4a) and inverted BM (Figure 4b) increased with age, $r(72) > .44$, $ps < .01$. The two-way (age group and stimulus type) ANOVA on the *K*-max (see Figure 4c) revealed a significant main effect of age group, $F(2, 138) = 32.82$,

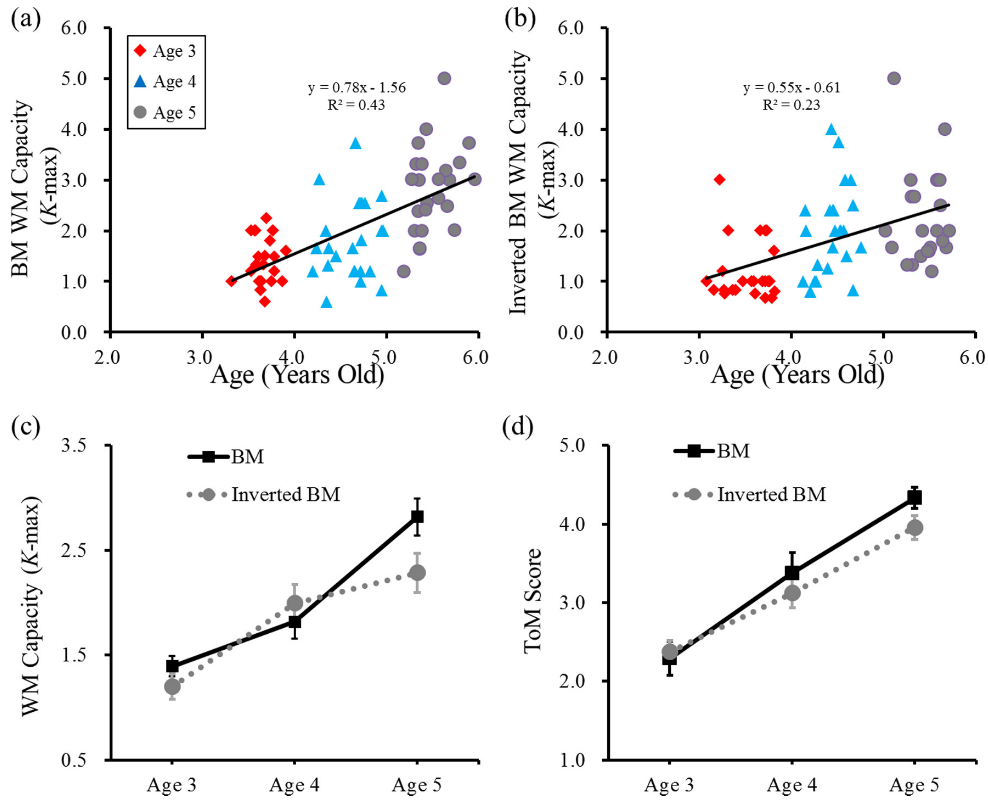

Figure 4. (a, b) The correlation between estimates (*K*-max) of working memory (WM) capacity and the age of the preschoolers for biological motion (BM) and inverted BM, respectively. (c, d) The estimates (*K*-max) of WM capacity and theory-of-mind (ToM) scores, respectively, for 3- to 5-year-olds. Error bars indicate the standard errors.

$p < .01$, $\eta_p^2 = .32$. Post hoc analysis (Bonferroni-corrected) further showed that 3- and 4-year-olds had significantly lower WM capacity than did 5-year-olds ($ps < .01$). Furthermore, 3-year-olds had a significantly lower WM capacity than did 4-year-olds ($p = .001$). The main effect of stimulus type was not significant, $F(1, 138) = 2.07$, $p = .15$, $\eta_p^2 = .015$. The Age Group × Stimulus Type interaction was marginally significant, $F(2, 138) = 2.63$, $p = .076$, $\eta_p^2 = .04$. Further independent t tests revealed that 5-year-olds had a higher WM capacity of BM (K-max = 2.82) than of inverted BM (K-max = 2.29), $t(46) = 2.08$, $p = .04$, Cohen's $d = .62$. However, such a difference vanished in 3- and 4-year-olds.

To further examine whether there was rapid development of WM capacity for BM from 4 to 5 years old (cf. Experiment 1) relative to inverted BM, we conducted a two-way ANOVA on K-max with age group (4- vs. 5-year-olds) and stimulus type (BM vs. inverted BM) as the between-subjects factors. The ANOVA revealed a significant main effect of age group, $F(1, 92) = 13.83$, $p < .01$, $\eta_p^2 = .13$, and a nonsignificant main effect of stimulus type, $F(1, 92) = 1.03$, $p = .31$, $\eta_p^2 = .01$. Critically, the Age Group × Stimulus Type interaction was significant, $F(1, 92) = 4.18$, $p = .04$, $\eta_p^2 = .04$, suggesting that the development of WM capacity of BM (the difference of K-max = 1.00) is indeed quicker than that of inverted BM capacity (the difference of K-max = 0.29) from 4 to 5 years old. Corroborating this finding, we calculated the slope of WM development from 4 to 5 years old by constructing a linear regression between K-max (dependent variable) and participants' age. We found that the slope (standardized beta coefficient) was .57 ($p < .01$) and .19 ($p = .19$) for BM and inverted BM capacity, respectively.

Development of ToM

Pooling the ToM scores under the two stimulus conditions together, we found a significantly positive correlation between age and ToM score, $r(144) = .63$, $p < .01$. Consistent with this finding, a two-way (age group and stimulus type) ANOVA on ToM score (see Figure 4d) revealed a significant main effect of age group, $F(2, 138) = 46.45$, $p < .01$, $\eta_p^2 = .40$. Post hoc analysis (Bonferroni-corrected) showed that the ToM score increased with age ($ps < .001$), which replicates previous findings (e.g., Duh et al., 2016; Wellman et al., 2006). Neither the main effect of stimulus type, $F(1, 138) = 1.38$, $p = .24$, $\eta_p^2 = .01$, nor the Age Group × Stimulus Type interaction, $F(2, 138) = 0.79$, $p = .45$, $\eta_p^2 = .01$, reached significance.

Correlation Between WM Capacity and ToM

Pearson's correlation analyses (see Figure 5) revealed a significant positive correlation between K-max and ToM score for BM, $r(72) = .61$, $p < .01$, but not for inverted BM, $r(72) = .21$, $p > .05$. These results held even after controlling for participants' age (partial $r = .32$, $p = .007$ for BM; partial $r = -.117$, $p = .33$ for inverted BM).

We further examined the correlations between K-max and ToM score within each age group. In the BM group, we found a significant positive correlation among 4-year-olds, $r(24) = .61$, $p = .002$; however, there was no significant correlation among 3-year-olds because of the limited BM capacity range, $r(24) = .27$, $p = .21$, or among 5-year-olds because of the ceiling effects of ToM performance, $r(24) = .14$, $p = .52$. In the inverted BM group, there was no significant correlation in each age at all ($ps > .15$).

Discussion

Experiment 2 showed two main findings. First, we replicated the findings of Experiment 1—namely, that there is rapid development of WM capacity for BM from 4 to 5 years old. We extended these results by showing that, while there is a similar developmental pattern between BM and inverted BM (increased WM capacity with aging), the development of WM capacity is quicker for BM than for inverted BM. Second, as predicted, we observed a positive correlation only between ToM and WM capacity of BM. However, this correlation vanished for inverted BM. It is worth noting that we replicated the nonsignificant correlations revealed in the inverted BM condition by requiring 72 preschoolers (24 participants for each age group) to memorize a set of rectangular movements (see Gao et al., 2015, 2016 for descriptions of the stimuli). Therefore, the nonsignificant correlations were not limited to the current stimulus set. Furthermore, paralleling the rapid development of social WM capacity between 4 and 5 years of age, we found a significant correlation between WM capacity of BM and ToM score among 4-year-olds. This further implies that 4–5 years of age is a pivotal stage for the development of social WM. Meanwhile, one should be cautious in interpreting the unique correlation among 4 years olds: It is possible that the nonsignificant correlation in 3- and 5-year-olds for BM is due to the specific ToM scale we used (i.e., that developed by Wellman et al.,

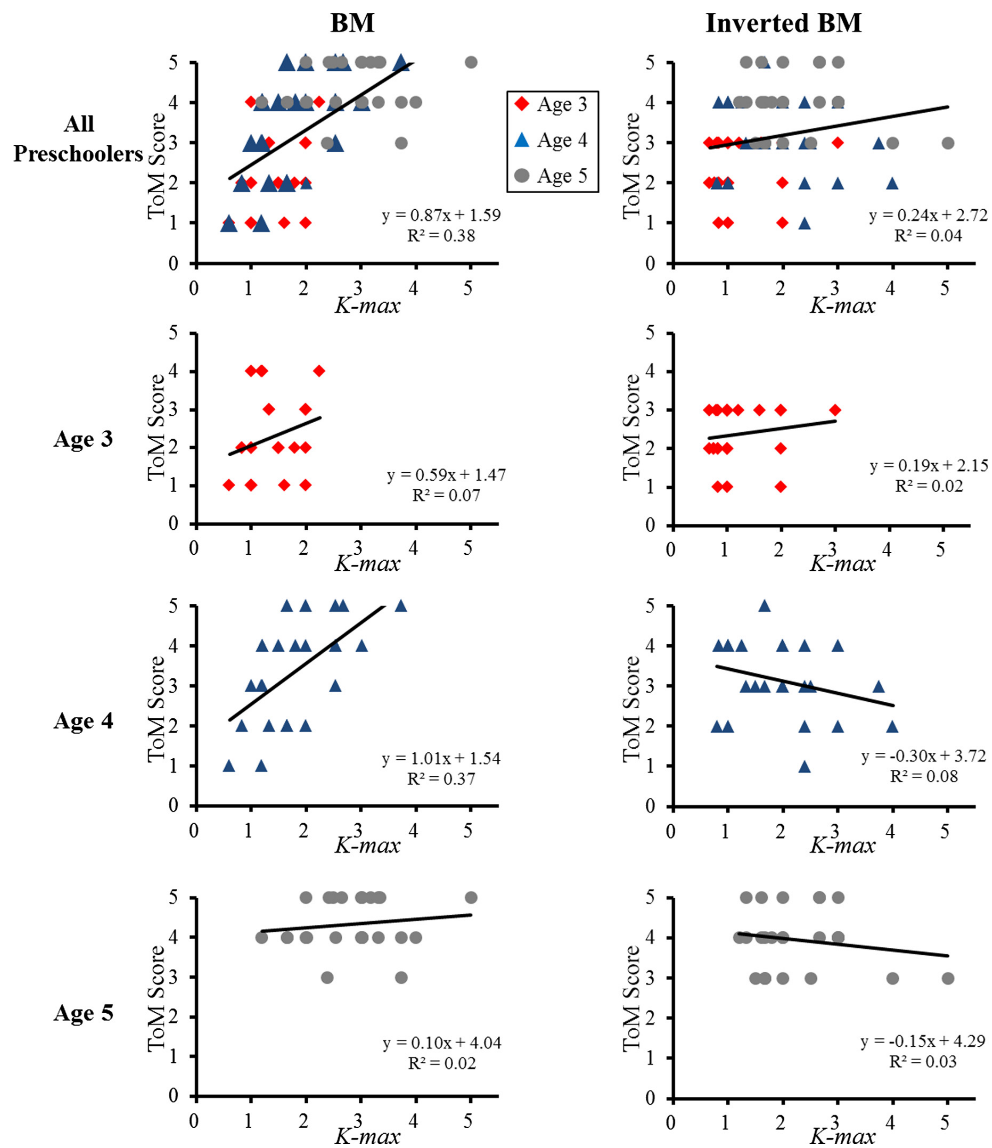

Figure 5. Pearson's correlations between the *K*-max and theory-of-mind (ToM) scale score for all participants (3- to 5-year-olds; the first row), 3-year-olds (the second row), 4-year-olds (the third row), and 5-year-olds (the fourth row). The left column displays the results for the biological motion (BM) condition, while the right column displays the results for the inverted BM condition.

2006). More empirical evidence obtained using other ToM scales (e.g., face-based ToM) is needed to verify this finding.

General Discussion

Adopting BM as target stimuli that convey social information, we, for the first time, have illustrated the development of social WM and its relation to higher level social-cognitive ability (ToM) using two experiments. We found that the capacity for social WM steadily increased between 3 and 6 years of age, with a particularly sharp development occurring between 4 and 5 years of age (Experiments 1 and 2). Furthermore, we found a significant positive relation between social WM capacity and higher level social-cognitive ability—namely, ToM—which was strongest among 4-year-olds (Experiment 2).

Development of Social WM

The development of WM has been extensively studied for decades (e.g., Hitch et al., 1989; Riggs et al., 2006; Simmering, 2012), but has primarily focused on visual and verbal WM; until now, the development of social WM has not been studied. Similarly, extant studies of social cognition studies have predominately explored the development of social perception and higher level social-cognitive abilities (e.g., ToM, empathy; Carpendale & Lewis, 2010; Duh et al., 2016); despite being a core aspect of social cognition, social WM has not been examined from a developmental perspective. The current study closed this gap, showing that there are both common and distinct developmental trajectories between canonical (e.g., visual object, letters) and social WM. Similar to canonical WM capacity (e.g., Riggs et al., 2006; Simmering, 2012), social WM capacity increases with age, with it being able to store around 1 or 2 BM stimuli in 3-year-olds to 3 or 4 stimuli in 6-year-olds. As such, the current study adds new evidence to the notion that WM continues developing from the 1st year of life (e.g., Riggs et al., 2006; Simmering, 2012). It is, however, worth noting that recent visual WM studies have suggested that WM capacity continues developing after 6 years old (e.g., Isbell, Fukuda, Neville, & Vogel, 2015); however, in Experiment 1, we found that the K value (our index of social WM capacity) had reached the level of adults (cf. Gao et al., 2015; Shen et al., 2014) at around 6 years of age. It should be noted that there were certain differences in experimental settings between the current study and previous studies focusing on adults, particularly in the manner of presenting different memory loads. Unlike previous studies, which presented the different memory load conditions randomly (cf. Gao et al., 2015; Shen et al., 2014), we presented the memory load conditions in a fixed ascending order to enhance preschoolers' engagement with the task. This might have overestimated preschoolers' social WM capacity because of practice effects. Therefore, further study would be required to examine whether social WM indeed reaches the adult level at 6 years of age, and whether it continues to develop after that.

A novel finding that clearly separates development of social WM capacity from that of canonical WM capacity is that the former does not appear to increase at a constant rate, but exhibited a speeded development between 4 and 5 years of age. Canonical WM has been implicitly or explicitly assumed to develop linearly between 3 and 5 years of age (Riggs et al., 2006; Simmering, 2012). However, the current Experiment 1 implied a rapid development of WM capacity for BM from 4 to 5 years old, and Experiment 2 further found that the development of WM capacity was quicker for BM than for inverted BM from 4- to 5-years old. This finding is to some extent meaningful because numerous studies have revealed that the 4th to the 5th year after birth is a key period for the development of social abilities, such as ToM (e.g., Liu et al., 2008; Wellman et al., 2001). Corroborating this finding, we found a positive correlation between social WM capacity and ToM in general (even after controlling for age), and for 4-year-olds in particular. These results support the view that there is a close relation between social WM and social ability. However, since we only tested one representative (i.e., BM) of social WM, future studies should consider other stimuli to examine the generality of the rapid development of social WM between 4 and 5 years of age.

Additionally, it is important to note that researchers have suggested that there might be two distinct types of social WM (Lieberman, 2007; Xin & Lei, 2015): One requires participants to internally focus their attention on friends' internal traits and rank them according to a specific dimension (i.e., internally orientated social WM; e.g., Meyer & Lieberman, 2012, 2016; Meyer et al., 2012, 2015); the other requires participants to focus their attention on the external world and their friends' faces or actions (externally orientated social WM; e.g., Gao et al., 2015, 2016; Lu et al., 2016; Shen et al., 2014; Thornton & Conway, 2013; Xin & Lei, 2015). Xin and Lei (2015) elegantly showed that there are certain differences in the neural substrates of these two types of social WM. To ensure that we could use the same parameters among the four tested age groups (3-, 4-, 5-, and 6-year-olds) in this study, we decided that BM stimuli were the best for meeting our aims. Therefore, the current findings might be limited to externally orientated social WM. Future studies might consider the development of internally orientated social WM.

Correlations Between Social WM and ToM

The current study adds new evidence to the function of WM in general, as well as the function of social WM in particular. Numerous studies on canonical WM have revealed that it plays a crucial role in higher level cognitive activities, including IQ, learning/reading ability, and information filtering (e.g., Conway, Cowan, Bunting, Therriault, & Minkoff, 2002). However, to date, only four studies have explicitly addressed this issue for social WM. Meyer et al. (2012, 2015) showed that activation of medial prefrontal cortex increases with social WM load, and that this activation was associated with adults' perspective-taking accuracy. Similarly, Xin and Lei (2015) showed that adults' accuracy on an emotional face recognition 2-back task predicted their level of empathy. Using PLDs of BM as stimuli, Gao et al. (2016) demonstrated that social WM capacity could predict adults' cognitive and affective empathy, while canonical WM (color, rectangular movement) could not. The current study has explored, for the first time, whether social WM capacity can predict ToM ability, which is a cornerstone of preschoolers' social ability. Using the same stimuli as Gao et al. (2016), we showed that social WM is not only associated with empathy but also with ToM, and that this association does not appear for canonical WM (i.e., WM capacity for inverted BM and rectangular movement [see discussion in Experiment 2]). The current study has hence offered the first developmental evidence supporting a close relation between social WM and higher level social abilities.

Moreover, our study revealed a potentially important developmental stage for the relation between social WM capacity and ToM—namely, 4 years of age. However, more empirical evidence (see the Discussion in Experiment 2) is required before reaching a solid conclusion on this point. Taking this correlation and the aforementioned rapid development of social WM between 4 and 5 years of age together, we might argue that the rapid development of social WM is due to the development of social abilities (e.g., ToM), which would boost social WM performance. This is essentially in line with the social brain hypothesis: People with higher level social ability are more easily able to extract social information from the external world, and can store that information more precisely and efficiently (cf. Thornton & Conway, 2013). However, currently, we cannot discount the opposite interpretation: namely, that social WM drives the development of social abilities. Indeed, this is an implicit assumption in studies on the development of canonical WM (Cowan, 2016). The extent and quality of children's social interaction have a considerable impact on the development of their social understanding (Carpendale & Lewis, 2010). Preschoolers with higher social WM capacity can comprehend social interactions in a more effective and efficient manner, and hence will be able to engage in social interaction more easily. This might further facilitate the development of ToM. Corroborating this possibility, Meyer and Lieberman (2016) found that 12 days of social WM training could significantly improve perspective-taking accuracy, whereas training in nonsocial, cognitive WM could not. Future studies would be needed to further elucidate the causal relations between social WM and higher level social ability. Finally, since only BM stimuli were tested for social WM, it is necessary in the future to examine whether the correlation between social WM and ToM is constrained to the BM stimuli.

Implications for ToM

The current findings dovetail well with the notion that there is a strong link between BM processing and ToM. To date, three studies have demonstrated such an association, all of which tapped into visual perception of BM by using PLDs of BM (Miller & Saygin, 2013; Phillips et al., 2011; Rice, Anderson, Velnoskey, Thompson, & Redcay, 2015). Moreover, two of them focused on adults and examined the association of BM perception with a key aspect of ToM (false belief reasoning or face-based ToM). Only Rice et al. (2015) explored this relation in middle childhood (roughly 7–12 years of age), and showed that BM perception was significantly correlated with two measures of ToM: face-based ToM (i.e., making mental state inferences from photographs of the eye region) and story-based ToM (i.e., making mental state inferences based on verbal stories). However, the ability to employ ToM by nature requires intact WM, which is necessary for holding and manipulating information for ongoing tasks. The current study has, for the first time, explored the relation between BM processing and ToM, by focusing on WM storage of BM. Moreover, unlike Rice et al. (2015), we examined this topic among children aged 3–5 years, which is a key period for the development of ToM and hence helps us in understanding the dynamics of the BM–ToM association (see Figure 5).

The current study has also shed important light on the development of ToM. Previous studies have predominately focused on the roles of executive function and verbal intelligence in ToM development (e.g., Carlson, Claxton, & Moses, 2015; for meta-analyses, see Devine & Hughes, 2014; Milligan, Astington, & Dack, 2007). However, it has been argued that action processing plays a foundational role in ToM (cf. Meltzoff, 2013); for instance, one can come to understand others' intention through imitation of their actions (Blakemore, 2008; Lieberman, 2007). This claim received certain support from Bowman, Thorpe, Cannon, and Fox (2016), who showed that action representation is critical for ToM development among 3- to 5-year-olds: Action representation has been revealed as the single best predictor of individual differences in preschoolers' ToM, even beyond executive function and verbal intelligence. The current findings confirm and extend those of Bowman et al. (2016). Specifically, unlike Bowman et al. (2016), who presented preschoolers with static two-dimensional images of hand positions/orientations and handles, and then had them choose the hand that could grab the handle, we examined the association between action representation and ToM by directly requiring participants to memorize a set of actions. Furthermore, we found that only the WM capacity of BM, not inverted BM, predicted ToM score. Overall, we argue that in addition to executive function and verbal intelligence, future ToM studies must consider the role of action representation in ToM development.

Before concluding, we must consider two caveats in Experiment 2. First, to avoid mental fatigue, each participant only memorized one type of stimuli. Future studies should consider requiring participants to memorize both BM and inverted BM stimuli (e.g., on different days), in order to explore the relation between social WM and ToM while controlling for both age and inverted WM capacity. Second, we did not assess participants' executive function or verbal intelligence (e.g., Carlson et al., 2015; Devine & Hughes, 2014), which prevents us from understanding the specificity of the relation between social WM and ToM. To address this caveat, future extensions of the current outcome should add these assessments.

Conclusion

The current study explored the development of social WM and its relation to ToM among 3- to 6-year-olds, by having participants memorize a set of BM stimuli. We have for the first time shown that WM capacity of BM increases dramatically between 3 and 6 years of age, with a particularly sharp increase appearing between 4 and 5 years of age. Furthermore, WM capacity for BM, but not inverted BM, was positively associated with preschoolers' ToM scores. This positive correlation was particularly strong among 4-year-olds.

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Supporting Information

Additional supporting information may be found in the online version of this article at the publisher's website:

Table S1. Result Summary of the Logistic Regression Analyses Examining Age, *K*-max in Relation to Subscales of ToM

Data S1. Relation Between Working Memory Capacity and Subtask of ToM