



ELSEVIER

Contents lists available at ScienceDirect

Journal of Experimental Child Psychology

journal homepage: www.elsevier.com/locate/jecp

Brief Report

Biological motion perception links diverse facets of theory of mind during middle childhood

Katherine Rice^{a,*}, Laura C. Anderson^a, Kayla Velnoskey^a, James C. Thompson^b, Elizabeth Redcay^a

^a Department of Psychology, University of Maryland, College Park, MD 20742, USA

^b Department of Psychology, George Mason University, Fairfax, VA 22030, USA

ARTICLE INFO

Article history:

Available online xxx

Keywords:

Social perception
Social cognition
Development
Individual differences
Mental state inference
Action perception

ABSTRACT

Two cornerstones of social development—social perception and theory of mind—undergo brain and behavioral changes during middle childhood, but the link between these developing domains is unclear. One theoretical perspective argues that these skills represent domain-specific areas of social development, whereas other perspectives suggest that both skills may reflect a more integrated social system. Given recent evidence from adults that these superficially different domains may be related, the current study examined the developmental relation between these social processes in 52 children aged 7 to 12 years. Controlling for age and IQ, social perception (perception of biological motion in noise) was significantly correlated with two measures of theory of mind: one in which children made mental state inferences based on photographs of the eye region of the face and another in which children made mental state inferences based on stories. Social perception, however, was not correlated with children's ability to make physical inferences from stories about people. Furthermore, the mental state inference tasks were not correlated with each other, suggesting a role for social perception in linking various facets of theory of mind.

© 2015 Elsevier Inc. All rights reserved.

* Corresponding author. Fax: +1 301 314 9566.

E-mail address: krice@umd.edu (K. Rice).

Introduction

Preferential attention to biological motion—most often assessed via point-light displays in which dots are placed on the joints of a moving human figure (Johansson, 1973)—is an evolutionarily conserved and early emerging ability hypothesized to serve as an ontogenetic and phylogenetic foundation for humans' higher order social cognition (Frith & Frith, 1999; Klin, Lin, Gorrindo, Ramsay, & Jones, 2009; Pavlova, 2012). In evaluating this claim of a broader role for biological motion perception, determining the relation between this basic perceptual capacity and theory of mind (ToM) is of particular interest. ToM, or inferring and reasoning about the mental states of others, is a complex instantiation of social cognition hypothesized to rely on separate behavioral and neural systems than biological motion perception (Gweon & Saxe, 2013; but see Yang, Rosenblau, Keifer, & Pelphrey, 2015). Finding that variability in biological motion perception can explain variance in ToM would provide evidence that these two distinct tasks may rely on a common social processing system.

Two recent studies have found a relation between biological motion perception and ToM. Phillips et al. (2011) sampled a wide age range of adults and found that the ability to make social judgments (e.g., emotional inference) about a point-light display correlated with false belief reasoning. However, because the biological motion task required emotional inference, the relation may have been driven by common variance in higher order social abilities. In contrast, Miller and Saygin (2013) employed a biological motion task that presented a point-light figure walking in place and required no mental state inference. Adults who were better able to detect the direction that the walking point-light figure was facing (i.e., right or left) while the figure was embedded in increasing levels of noise were better able to infer mental states from a photograph of someone's eyes (i.e., face-based ToM). Interestingly, participants' ability to determine whether the biological figure was walking backward (i.e., "moonwalking") or forward (regardless of whether the figure was facing left or right) was not correlated with face-based ToM. The differential behavioral correlates of facing versus walking direction judgments may be explained by adult research indicating that these judgments differentially rely on form information (used to determine facing direction) versus motion information (used to determine walking direction) (Thompson, Clarke, Stewart, & Puce, 2005). These findings suggest that, at least during adulthood, face-based ToM is related to form-based biological motion perception.

In addition to research with typical adults, clinical evidence has suggested a possible link between biological motion perception and social cognition. For example, individuals with autism spectrum disorders have deficits in both biological motion perception (e.g., Blake, Turner, Smoski, Pozdol, & Stone, 2003; Klin et al., 2009) and ToM (reviewed in Tager-Flusberg, 2007), and these impairments correlate with symptomatology (Blake et al., 2003). Similar patterns have been found in schizophrenia, a disorder that includes deficits in both ToM (Bora, Yucel, & Pantelis, 2009) and biological motion perception (Kim, Park, & Blake, 2011). Furthermore, biological motion processing also tends to be less typical in disorders with larger social impairments (e.g., fragile X syndrome) versus disorders with more preserved social skills (e.g., Williams syndrome) (reviewed in Pavlova, 2012). Most clinical studies, however, have not examined higher order social cognition and biological motion processing in the same sample, leaving open the question of whether these domains are linked on an individual level.

Middle childhood (roughly 7–12 years of age) is an important time to examine the relation between biological motion and ToM. Children's ability to detect biological motion in visually noisy displays increases throughout middle childhood (Hadad, Maurer, & Lewis, 2011), and these behavioral changes coincide with increased neural specialization for processing biological motion (Carter & Pelphrey, 2006). During this same developmental window, children's ToM improves across a variety of different tasks (Apperly, Warren, Andrews, Grant, & Todd, 2011; Banerjee, Watling, & Caputi, 2011; Devine & Hughes, 2013; Dumontheil, Apperly, & Blakemore, 2010; Miller, 2012) and demonstrates increased neural specialization (Gweon, Dodell-Feder, Bedny, & Saxe, 2012). No existing studies, however, have examined the relation between these two domains during middle childhood.

Investigating the relation between ToM and biological motion processing during this time of specialization will provide clearer insight into whether both tasks rely on an integrated social processing system. A first possibility is that children will show the same pattern as adults (i.e., relation between ToM and judging the facing direction of a point-light display), providing evidence for a developmentally

constant relation between these two domains. In contrast, if social cognition and social perception are not related in children despite evidence of their relation in adults, it would suggest that such abilities initially develop separately, supporting theories that these two systems are domain specific and distinct. A third possibility is that during this period of developmental change and specialization, the relations between different social domains may be less specific than those relations during adulthood, such that multiple facets of biological motion perception (e.g., facing direction, walking direction) relate to social cognition during middle childhood.

Thus, we conducted the current study to examine the link between the ability to perceive biological motion and ToM in a sample of children aged 7 to 12 years. Adapting the biological motion paradigm of Miller and Saygin (2013), we assessed the ability of children to determine whether a figure was facing left or right (Facing Direction) and whether a figure was walking forward or backward (Walking Direction) in increasing levels of noise. We included two ToM measures: one requiring mental state inferences from photographs of the eye region (Reading the Mind in the Eyes; Baron-Cohen, Wheelwright, Spong, Scahill, & Lawson, 2001), which measures face-based ToM, and one requiring mental state inferences from verbal information alone (Strange Stories; White, Hill, Happé, & Frith, 2009), which measures story-based ToM. Specifically, in the Reading the Mind in the Eyes task (hereafter referred to as Mind in the Eyes for brevity) children match an emotional or cognitive state to a picture of a person's eyes, and in the Strange Stories task children infer a character's mental state in order to explain that character's behavior. Previous findings demonstrating a relation between face-based ToM and biological motion perception may be driven by common variance in visual processing. Thus, the use of story-based ToM provides a stronger test case that biological motion and ToM tap into a common system. We first examined age-related changes across social cognition and social perception. We next examined, controlling for age and general cognitive ability, whether Facing Direction or Walking Direction biological motion perception correlated with performance on both ToM measures as well as performance on a control measure examining physical inference ability for stories about people.

Method

Participants

A total of 52 children (25 boys) aged 7 to 12 years (mean = 10.07 years, $SD = 1.71$) were recruited from a database of local families and participated with the consent of their parents or guardians. All recruited children were included in the final sample. All children were full-term native English speakers with no history of neurological damage, psychiatric disorders, head trauma, or psychological medications, and none had first-degree relatives with autism or schizophrenia, as assessed via parent report.

Procedure and experimental tasks

All procedures were approved by the university institutional review board. Children completed a battery of measures, including the specific measures of social perception and ToM detailed below and the Kaufman Brief Intelligence Battery (KBIT-2; Kaufman & Kaufman, 2004), which measured non-verbal IQ (via matrix reasoning) and verbal IQ (via vocabulary and verbal riddles), resulting in a composite full-scale IQ (FSIQ). Children's nonverbal IQ ranged from 80 to 142 (mean = 112.6, $SD = 13.9$), verbal IQ ranged from 82 to 141 (mean = 117.3, $SD = 12.4$), and FSIQ ranged from 84 to 141 (mean = 117.5, $SD = 13.2$).

Biological motion perception

The biological motion perception task presented children with point-light walkers embedded in increasing levels of noise (Fig. 1). The point-light walkers, consisting of 13 white dots presented on a black background, were based on standard validated stimuli (Vanrie & Verfaillie, 2004). The figure did not move across the screen, but the illusion of movement was created based on point movement.

Please cite this article in press as: Rice, K., et al. Biological motion perception links diverse facets of theory of mind during middle childhood. *Journal of Experimental Child Psychology* (2015), <http://dx.doi.org/10.1016/j.jecp.2015.09.003>

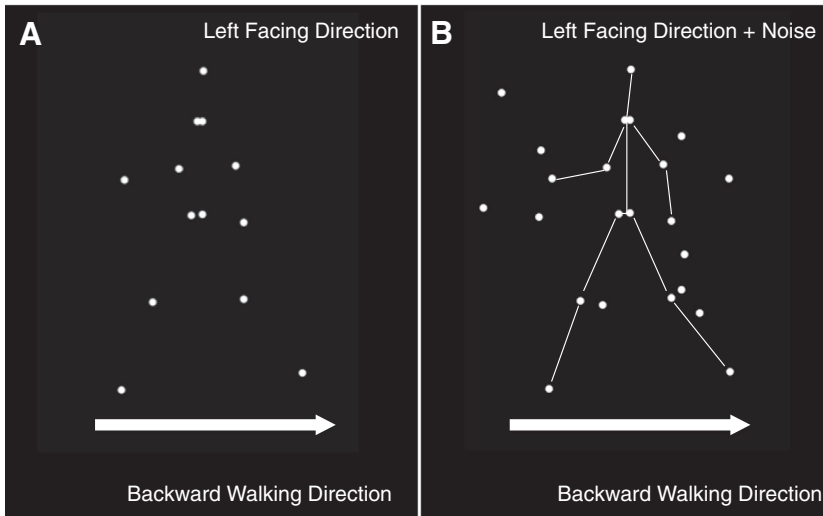


Fig. 1. Biological motion stimuli. Example stills from biological motion stimuli show a figure in no noise facing left and walking backward (A) and the same figure embedded in noise (B) (the white lines are superimposed in the figure to indicate the point-light walker but were not present in the experiment). Participants were also shown figures that faced right and walked backward, figures that faced left and walked forward, and figures that faced right and walked forward. Depending on the experimental block, children labeled either the facing direction or walking direction of the point-light figure. Figures did not translate across the screen, but an illusion of movement was created based on the movement of the points.

On each trial, the figure was presented for 2000 ms, facing either left or right and walking either forward or backward (i.e., moonwalking) (Miller & Saygin, 2013). Children sat approximately 50 cm from a computer monitor, such that the figure subtended approximately 9.9 degrees of visual angle. Images were presented at 30 frames per second. All stimuli were programmed and presented using MATLAB Psychophysics Toolbox Version 3 (PTB-3).

Children completed a task identical to one previously completed by adults (Miller & Saygin, 2013). Specifically, children completed two blocks of trials (counterbalanced across participants). In the Facing Direction block children identified whether the walker was facing right or left, and in the Walking Direction block children identified whether the walker was walking forward or backward. Before the experiment, children received feedback on 10 practice trials of each motion judgment type (embedded in minimal levels of noise), ensuring that all children were able to perform the task.

Each experimental block determined children's performance threshold in identifying biological motion along that particular dimension (i.e., Facing Direction or Walking Direction) by adaptively adding noise dots to the display. All noise dots were the same size, color, and luminance as the point-light walker dots and were programmed to follow the same motion trajectory as walker dots after starting from a random point within the stimulus window. All children began each block at Level 1, in which the point-light figure was accompanied by two noise dots. Each time children responded correctly to three items in a row, two additional noise dots were added to the display (e.g., Level 2 had four noise dots). When children responded incorrectly, the task difficulty moved back a level (e.g., answering a Level 2 item incorrectly would result in a Level 1 item being presented on the next trial). Reversals were defined as trials in which there was a change (either positive or negative) in noise adaptation, such that any time the noise level had been increasing and then decreased, or had been decreasing and then increased, a reversal was recorded. After 12 reversals, or after a maximum of 80 trials, the experimental block terminated. By averaging together noise levels across all reversal trials, we determined the noise dot threshold at which children achieved 79% accuracy (i.e., via a 3-up, 1-down staircase; Levitt, 1971). Higher thresholds indicated that children were able to detect information from the point-light walker while the walker was embedded in higher levels of noise.

Mind in the Eyes

Children viewed a series of 28 black and white photographs depicting the eye region of a series of adults (Baron-Cohen et al., 2001). Children were presented with four potential words describing an adult's mental state (e.g., not believing, sad, kind, shy) and were asked to choose the word that best described how that person was feeling. The experimenter read the words out loud and let the child know to ask if they were confused about the meanings of any words. Children received 1 point for each correct answer.

Strange Stories

Children listened to a subset of eight different recorded vignettes from the original Strange Stories (White et al., 2009). Each vignette presented a scenario involving mental states (e.g., white lie, double crossing), and after each vignette children were asked one question that required an understanding of a character's mental state. Children responded verbally, and their responses were transcribed and coded. Children could score 0 to 2 points for each answer, with higher scores corresponding to increased mental state understanding (e.g., he lied so he wouldn't hurt his aunt's feelings). This scoring scheme resulted in a final possible score of 0 to 16 (White et al., 2009).

Children also listened to three Control Stories developed by White et al. (2009) in which children made physical inferences from a story involving people (e.g., someone getting wet because a bush poked holes in his umbrella). Children could score 0 to 2 points for each answer, with higher scores corresponding to more sophisticated physical inference ability, resulting in a final possible score of 0 to 6 points. Two coders scored children's responses. Based on a subset of 23 participants, interrater reliability was high for both story types (Strange Stories Krippendorff's $\alpha = .77$; Control Stories Krippendorff's $\alpha = .81$) (Fleiss, 1981; Hayes & Krippendorff, 2007). All disagreements were resolved by the first author.

Statistical analyses were conducted using SPSS 21, and correlation confidence intervals were derived in MATLAB 8.1 using the built-in "bootCI" bootstrap resampling function with 5000 iterations.

Results

Descriptive statistics

Both the ToM assessments (Mind in the Eyes: mean = 67.7%, $SD = 11.9$, range = 46.4–89.3, skew = $-.20$; Strange Stories: mean = 75.2%, $SD = 16.8$, range = 50–100, skew = $-.03$; Control Stories: mean = 72.1%, $SD = 22.6$, range = 33.3–100, skew = $-.23$) and the biological perception assessments (Facing Direction: mean noise dots = 9.9, $SD = 5.8$, range = 2.4–24.3, skew = $.74$; Walking Direction: mean = 8.4, $SD = 5.3$, range = 2.5–20.7, skew = $.86$) captured variability during middle childhood. In the biological motion perception task, children performed significantly better on Facing Direction than Walking Direction, $t(51) = 2.16$, $p = .035$.

Children's performance on all four measures improved with age, although the relation was weakest for Strange Stories (Mind in the Eyes: $r(50) = .28$, 95% confidence interval (CI) [.006, .51], $p = .044$; Strange Stories: $r(50) = .21$, 95% CI [-.08, .47], $p = .14$; Facing Direction: $r(50) = .52$, 95% CI [.24, .69], $p < .001$; Walking Direction: $r(50) = .40$, 95% CI [.13, .61], $p = .003$). Both ToM measures were correlated with FSIQ (Mind in the Eyes: $r(50) = .29$, 95% CI [.003, .57]; Strange Stories: $r(50) = .44$, 95% CI [.20, .64]; $ps < .05$) and nonverbal IQ (Mind in the Eyes: $r(50) = .28$, 95% CI [.01, .53]; Strange Stories: $r(50) = .52$, 95% CI [.30, .69]; $ps < .05$). Correlations with verbal IQ were positive but smaller (Mind in the Eyes: $r(50) = .22$, 95% CI [-.07, .50], $p = .12$; Strange Stories: $r(50) = .24$, 95% CI [-.02, .49], $p = .085$). In contrast, neither biological motion perception measure was correlated with any IQ scale ($ps > .10$).

Given the relations among task performance, age, and FSIQ, subsequent correlations controlled for age in months and FSIQ. Patterns of correlations were unchanged when a nonparametric statistical test was used (i.e., Spearman's rho) and were unchanged when nonverbal or verbal IQ was entered as a covariate instead of FSIQ. Because there were no significant differences between boys and girls on any measures ($ps > .05$), gender was not included in subsequent analyses.

Please cite this article in press as: Rice, K., et al. Biological motion perception links diverse facets of theory of mind during middle childhood. *Journal of Experimental Child Psychology* (2015), <http://dx.doi.org/10.1016/j.jecp.2015.09.003>

Relations among tasks

Facing Direction performance and Walking Direction performance were significantly correlated, $r(50) = .63$, 95% CI [.35, .78], $p < .0001$, and this correlation remained significant after controlling for effects of age and FSIQ, $r(48) = .54$, 95% CI [.22, .74], $p < .0001$. In contrast, the correlation between the two ToM measures was significant in the uncorrected model, $r(50) = .34$, 95% CI [.12, .55], $p = .014$, but was not significant after controlling for age and FSIQ, $r(48) = .18$, 95% CI [-.06, .41], $p = .21$.

Controlling for age and FSIQ, both Facing Direction performance and Walking Direction performance were significantly correlated with Mind in the Eyes scores (Facing Direction: $r(48) = .42$, 95% CI [.17, .62], $p = .003$; Walking Direction: $r(48) = .35$, 95% CI [.11, .53], $p = .012$). Facing Direction performance was also significantly associated with Strange Stories performance, $r(48) = .43$, 95% CI [.19, .61], $p = .002$. Although the Walking Direction correlation with Strange Stories was only marginally significant, $r(48) = .24$, 95% CI [-.02, .50], $p = .089$, the Walking Direction and Facing Direction correlations with Strange Stories were not significantly different from each other ($z = -1.44$, $p = .15$).

Given that Facing Direction and Walking Direction did not differentially predict either ToM measure, we calculated correlations between ToM performance and the average of Facing Direction and Walking Direction, controlling for age and FSIQ. Both correlations were significant (Mind in the Eyes: $r(48) = .44$, 95% CI [.21, .62], $p = .001$; Strange Stories: $r(48) = .38$, 95% CI [.15, .57], $p = .006$) (Fig. 2). Furthermore, adding biological motion perception to a model that already included FSIQ and age

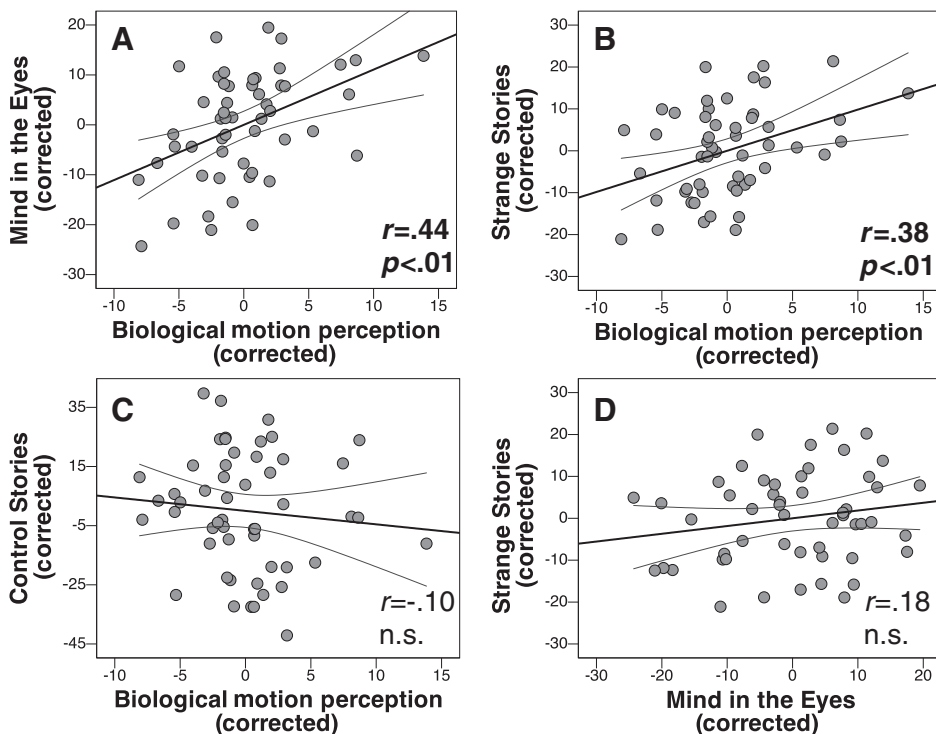


Fig. 2. Partial correlations among social perception and theory of mind tasks. (A,B) Children's ability to perceive the facing and walking directions of point-light displays of biological motion embedded in noise was significantly correlated with their ability to infer mental states from photographs of the eye regions (A) and their ability to make mental state inferences about characters in stories (B). (C) In contrast, social perception was not related to children's ability to make physical inferences from stories about people. (D) The two theory of mind measures were not significantly related to each other. All plotted points are the residual values after correcting for age in months and full scale IQ. Mind in the Eyes, Strange Stories, and Control Stories residual values were derived from percentage accuracy.

explained an additional 12% of the variance in Strange Stories performance and 16% of the variance in Mind in the Eyes performance.

Controlling for age and FSIQ, neither measure of biological motion perception, including the average composite, nor the ToM measures were correlated with performance on the Control Stories ($r_s < .10$).

Discussion

The current study provides the first developmental evidence for a relation between ToM and biological motion perception in a single sample. Throughout middle childhood, performance on both social perception and social cognition measures improved. Controlling for age and IQ, children's ability to determine the direction that a point-light human figure embedded in noise was facing or walking was correlated with well-established measures of face-based ToM (Mind in the Eyes) and story-based ToM (Strange Stories), but not with a measure of children's ability to make physical inferences from stories about people. Such findings suggest that, rather than biological motion processing and ToM representing distinct skills with separate developmental trajectories, a common mechanism may connect these domains.

The precise mechanism linking these tasks, however, is unknown. One possibility is that a single skill is involved across domains. For example, each task may involve an element of social simulation (Gallesse & Goldman, 1998), perspective taking (Yang et al., 2015), understanding intentionality (cf. Wellman, Lopez-Duran, LaBounty, & Hamilton, 2008), or interpreting social cues such as agency (Miller & Saygin, 2013; Phillips et al., 2011). Alternatively, rather than children actively using the same skill set during all three tasks, task performance may be indirectly related. For example, early orientation to biological motion may lead to increased social interaction in which children gain the skills necessary to navigate social cognitive problems (see Dziura & Thompson, 2014). In this way, early differences in social perception create a developmental cascade, resulting in increased performance on ToM tasks during middle childhood. Future longitudinal research could clarify the temporal dynamics of the relations between social perception and social cognition. For example, longitudinal research has linked infant social perception to preschool ToM (e.g., Brooks & Meltzoff, 2015; Wellman et al., 2008), although such research has not examined biological motion.

Although biological motion perception related to both ToM measures, story-based ToM and face-based ToM were not significantly related to each other. This finding dovetails with recent behavioral and neural evidence suggesting a dissociation between different measures of ToM (reviewed in Schaafsma, Pfaff, Spunt, & Adolphs, 2015). One possible explanation for this pattern of correlations is that performance on different ToM tasks relies on a variety of different domains (e.g., gaze processing, linguistic understanding), creating high levels of variability in performance across tasks (Schaafsma et al., 2015). Variability across ToM tasks may be especially high when comparing a face-based task involving the labeling of cognitive and emotional mental states (Mind in the Eyes) with a story-based task involving reasoning about mental states based on behaviors (Strange Stories). However, in spite of this variability, if ToM tasks tap into the same basic social perceptual domain measured by biological motion task performance, varied ToM tasks may correlate with biological motion processing but not each other. Investigating the relations between ToM measures and different domains of social processing will offer insight into common and distinct components of ToM.

Interestingly, in contrast to adult research (Miller & Saygin, 2013), children's abilities to determine Facing Direction and Walking Direction were correlated both with each other and with ToM measures. The previous adult study linking Facing Direction, but not Walking Direction, to face-based ToM suggested that judgments of Facing Direction relied on form cues, which may be more salient to social cognition than the motion cues used in the Walking Direction task. Developmental evidence of children's relative reliance on different biological motion cues (e.g., form vs. motion), however, is limited, raising the possibility that children are using a common social perceptual system for both types of discrimination. Notably, and consistent with previous adult research (e.g., Lange & Lappe, 2006), children were significantly more successful at making Facing Direction determinations than Walking Direction determinations. ToM correlations with Facing Direction performance were also numerically, albeit not

significantly, larger than Walking Direction correlations, suggesting that middle childhood may represent the beginning of a shift to adult-like patterns, although the magnitude of this difference did not increase with age in the current sample. Overall, these findings are consistent with the hypothesis that, earlier in development, relations between social perception and social cognition may be less specific than those during adulthood, and future research should examine more varied stimuli to assess different types of biological and nonbiological motion perception across development.

Exploring the links between biological motion processing and social cognition using neuroimaging may also elucidate the relationship between domains. Extant neural evidence does support some potential overlap between domains given that the posterior superior temporal sulcus (pSTS) is consistently activated in both children and adults when processing biological motion as well as in higher order social cognition such as intention processing (reviewed in Yang et al., 2015). Furthermore, the temporoparietal junction (TPJ)—a region consistently implicated in ToM studies and adjacent to the pSTS—is responsive to both biological motion and ToM in the same adult sample (Lee & McCarthy, 2014). In addition, the TPJ continues to specialize into middle childhood, with increasingly focal activation for processing mental states over general social information. Thus, there may be greater spatially overlapping neural activation in the TPJ/pSTS region for both mental state inference and basic social perception earlier in development. Future research should examine the common and distinct developmental neural bases of biological motion perception and ToM in the same sample.

Not only does middle childhood represent a time of change in neural activation and social-cognitive tasks, but at this age children also show widening variability in social skills as their interactions grow more complex (Monahan & Steinberg, 2011). Understanding the mechanisms underlying individual differences in social cognition in this age range, therefore, may offer insight into children's psychosocial outcomes. Exploring the links between these more experimental measures of social cognition and perception and real-world social outcomes is an important direction for future work. Ultimately, understanding the developmental relation between different domains of social processing will help to illuminate whether disparate tasks rely on an integrated system, informing understanding of typical and atypical development.

References

- Apperly, I. A., Warren, F., Andrews, B. J., Grant, J., & Todd, S. (2011). Developmental continuity in theory of mind: Speed and accuracy of belief–desire reasoning in children and adults. *Child Development, 82*, 1691–1703.
- Banerjee, R., Watling, D., & Caputi, M. (2011). Peer relations and the understanding of faux pas: Longitudinal evidence for bidirectional associations. *Child Development, 82*, 1887–1905.
- Baron-Cohen, S., Wheelwright, S., Spong, A., Schill, V., & Lawson, J. (2001). Are intuitive physics and intuitive psychology independent? A test with children with Asperger syndrome. *Journal of Developmental and Learning Disorders, 5*, 47–78.
- Blake, R., Turner, L. M., Smoski, M. J., Pozdol, S. L., & Stone, W. L. (2003). Visual recognition of biological motion is impaired in children with autism. *Psychological Science, 14*, 151–157.
- Bora, E., Yucel, M., & Pantelis, C. (2009). Theory of mind impairment in schizophrenia: Meta-analysis. *Schizophrenia Research, 109*, 1–9.
- Brooks, R., & Meltzoff, A. N. (2015). Connecting the dots from infancy to childhood: A longitudinal study connecting gaze following, language, and explicit theory of mind. *Journal of Experimental Child Psychology, 130*, 67–78.
- Carter, E. J., & Pelphrey, K. A. (2006). School-aged children exhibit domain-specific responses to biological motion. *Social Neuroscience, 1*, 396–411.
- Devine, R. T., & Hughes, C. (2013). Silent films and strange stories: Theory of mind, gender, and social experiences in middle childhood. *Child Development, 84*, 989–1003.
- Dumontheil, I., Apperly, I. A., & Blakemore, S. J. (2010). Online usage of theory of mind continues to develop in late adolescence. *Developmental Science, 13*, 331–338.
- Dziura, S. L., & Thompson, J. C. (2014). Social-network complexity in humans is associated with the neural response to social information. *Psychological Science, 25*, 2095–2101.
- Fleiss, J. L. (1981). *Statistical methods for rates and proportions* (2nd ed.). New York: John Wiley.
- Frith, C. D., & Frith, U. (1999). Interacting minds—A biological basis. *Science, 286*, 1692–1695.
- Gallese, V., & Goldman, A. (1998). Mirror neurons and the simulation theory of mind-reading. *Trends in Cognitive Sciences, 2*, 493–501.
- Gweon, H., Dodell-Feder, D., Bedny, M., & Saxe, R. (2012). Theory of mind performance in children correlates with functional specialization of a brain region for thinking about thoughts. *Child Development, 83*, 1853–1868.
- Gweon, H., & Saxe, R. (2013). Developmental cognitive neuroscience of theory of mind. In J. L. R. Rubenstein & P. Rakic (Eds.), *Neural circuit development and function in the brain* (pp. 367–377). San Diego: Academic Press.
- Hadad, B. S., Maurer, D., & Lewis, T. L. (2011). Long trajectory for the development of sensitivity to global and biological motion. *Developmental Science, 14*, 1330–1339.

Please cite this article in press as: Rice, K., et al. Biological motion perception links diverse facets of theory of mind during middle childhood. *Journal of Experimental Child Psychology* (2015), <http://dx.doi.org/10.1016/j.jecp.2015.09.003>

- Hayes, A. F., & Krippendorff, K. (2007). Answering the call for a standard reliability measure for coding data. *Communication Methods and Measures*, 1, 77–89.
- Johansson, G. (1973). Visual perception of biological motion and a model for its analysis. *Perception & Psychophysics*, 14, 201–211.
- Kaufman, A. S., & Kaufman, N. I. (2004). *Kaufman Brief Intelligence Test, second edition (KBIT-2)*. Bloomington, MN: Pearson.
- Kim, J., Park, S., & Blake, R. (2011). Perception of biological motion in schizophrenia and healthy individuals: A behavioral and fMRI study. *PLoS One*, 6(5), e19971.
- Klin, A., Lin, D. J., Gorrindo, P., Ramsay, G., & Jones, W. (2009). Two-year-olds with autism orient to non-social contingencies rather than biological motion. *Nature*, 459, 257–261.
- Lange, J., & Lappe, M. (2006). A model of biological motion perception from configural form cues. *Journal of Neuroscience*, 26, 2894–2906.
- Lee, S. M., & McCarthy, G. (2014). Functional heterogeneity and convergence in the right temporoparietal junction. *Cerebral Cortex*. <http://dx.doi.org/10.1093/cercor/bhu292> [Epub ahead of print].
- Levitt, H. C. C. H. (1971). Transformed up-down methods in psychoacoustics. *Journal of the Acoustical Society of America*, 49, 467–477.
- Miller, S. A. (2012). *Theory of mind beyond the preschool years*. New York: Psychology Press.
- Miller, L. E., & Saygin, A. P. (2013). Individual differences in the perception of biological motion: Links to social cognition and motor imagery. *Cognition*, 128, 140–148.
- Monahan, K. C., & Steinberg, L. (2011). Accentuation of individual differences in social competence during the transition to adolescence. *Journal of Research on Adolescence*, 21, 576–585.
- Pavlova, M. A. (2012). Biological motion processing as a hallmark of social cognition. *Cerebral Cortex*, 22, 981–995.
- Phillips, L. H., Bull, R., Allen, R., Inch, P., Burr, K., & Ogg, W. (2011). Lifespan aging and belief reasoning: Influences of executive function and social cue decoding. *Cognition*, 120, 236–247.
- Schaafsma, S. M., Pfaff, D. W., Spunt, R. P., & Adolphs, R. (2015). Deconstructing and reconstructing theory of mind. *Trends in Cognitive Sciences*, 19, 65–72.
- Tager-Flusberg, H. (2007). Evaluating the theory-of-mind hypothesis of autism. *Current Directions in Psychological Science*, 16, 311–315.
- Thompson, J. C., Clarke, M., Stewart, T., & Puce, A. (2005). Configural processing of biological motion in human superior temporal sulcus. *Journal of Neuroscience*, 25, 9059–9066.
- Vanrie, J., & Verfaillie, K. (2004). Perception of biological motion: A stimulus set of human point-light actions. *Behavior Research Methods, Instruments, & Computers*, 36, 625–629.
- Wellman, H. M., Lopez-Duran, S., LaBounty, J., & Hamilton, B. (2008). Infant attention to intentional action predicts preschool theory of mind. *Developmental Psychology*, 44, 618–623.
- White, S., Hill, E., Happé, F., & Frith, U. (2009). Revisiting the Strange Stories: Revealing mentalizing impairments in autism. *Child Development*, 80, 1097–1117.
- Yang, D. Y. J., Rosenblau, G., Keifer, C., & Pelphrey, K. A. (2015). An integrative neural model of social perception, action observation, and theory of mind. *Neuroscience & Biobehavioral Reviews*, 51, 263–275.