The ability to predict actions of others from distributed cues is still developing in children

Daniel Kim[1], Emalie McMahon[2], Samuel A. Mehr[3,4], Ken Nakayama[3], Elizabeth S. Spelke[3], Maryam Vaziri-Pashkam[5]

[1] Department of Hearing and Speech Sciences, Vanderbilt University.

[2] Department of Cognitive Science, Johns Hopkins University

[3] Department of Psychology, Harvard University

[4] Data Science Initiative, Harvard University

[5] Laboratory of Brain and Cognition, National Institute of Mental Health

Acknowledgements: This research was supported by NSF STC award CCF-1231216.

ABSTRACT

Adults use distributed cues in the bodies of others to predict and counter their actions. To investigate the development of this ability, adults and 6- to 8-year-old children played a competitive game with a confederate who reached toward one of two targets. Child and adult participants, who sat across from the confederate, attempted to beat the confederate to the target by touching it before the confederate did. Adults used cues distributed through the head, shoulders, and body to predict the reaching actions. Children, in contrast, used cues in the arms and torso but not in the head, face or shoulders to predict the actions. These results provide evidence for a qualitative change in the ability to respond rapidly to predictive cues to others' actions develops slowly over childhood. Despite children's sensitivity to eye gaze even in infancy, cues from the head and body do not influence their action predictions as late as 8 years of age.

Keywords: Action prediction, development, action understanding, social interaction, biological motion

Walking down a narrow hallway as another person approaches, you have probably encountered the comedy of being unable to anticipate the passerby's direction — you go left, she also goes left; you switch direction only to realize that she has made the same choice; this continues until one of you steps aside. This situation is funny because it has happened to everyone, but nonetheless happens rarely: typically, we are reliable predictors of other people's actions.

How do humans succeed at the complex task of anticipating others' actions? Previous studies have shown that adults predict the target of an action and make anticipatory eye movements to that location (Flanagan & Johansson, 2003). These predictions are likely based on kinematic cues (Cavallo et al., 2016; Diaz, Fajen, & Phillips, 2012) that are widely distributed across body of the actor (McMahon et al, 2019; Pesquita, Chapman, & Enns, 2016; Vaziri-Pashkam, Cormiea, & Nakayama, 2017). Adults can use this distributed information to make predictions even when the locus of the information is far from the body part performing the action. For example, when only viewing the head, neck, and shoulders, adults can predict where someone will reach with their finger (Pesquita, Chapman, & Enns, 2016; Vaziri-Pashkam, Cormiea, & Nakayama, 2017).

These cues begin early in the actor's movement. For example, when asked to predict the target of the reach, participants are able to predict the target of the reach before the actor's finger had even lifted-off from the table (McMahon et al., 2019). When the movements prior to the finger's lift-off are occluded, participants are much slower at predicting the target of the reach (Vaziri-Pashkam et al., 2017). These movements that occur prior to the explicit reach are visually subtle and may be the result of postural adjustments preparing the body for a large limb movement (Hodges, Cresswell, Daggfeldt, & Thorstensson, 2000; Hodges, Cresswell, &

Thorstensson, 1999). Moreover, adults do not require training to use these subtle preparatory movements for action prediction: naïve adult participants are already experts at predicting the target of another's reach (Vaziri-Pashkam et al., 2017).

While adults do not seem to improve their action prediction abilities on the timescale of a typical experiment (Vaziri-Pashkam et al., 2017), they may have acquired these abilities through a lifetime of experience predicting the actions of others.

Yet, it has been shown that infants as young as 5 months of age encode action goals (Woodard, 1998). By 11 months old, after familiarization with a reach movement, infants look at the target of an incomplete reach (Cannon & Woodward, 2012). Also, infants make anticipatory eye movements to the target of an action (Falck-Ytter; Gredebäck, & von Hofsten, 2006, Gredebäck & Kochukhova, 2010; Rosander, & von Hofsten, 2011; Ambrosini et al., 2013; Brandone, Harwitx, Aslin, & Wellman, 2014) indicating that they predict action goals. Extending this finding, Geangu and colleagues (2015) found that 6-month-old infants' predictive eye movements were limited to biomechanically plausible actions. Cumulatively, these studies demonstrate that even young infants are able to predict the actions of others and are sensitive to the kinematics of people's movements.

However, it is an open question whether children read the kinematic information in the body of others comparably to adults. Are children also sensitive to subtle preparatory movements, or do they rely on more explicit kinematic cues? Can children use distributed information present through the body of an actor to predict her actions, or do their action predictions depend on attention to the parts of the actor's body that are directly engaged in preforming the action? Differences in the abilities of children and adults would suggest that expertise in action prediction may develop slowly.

To address these open questions, we compared the predictive abilities of 6- to 8-year-old children and adults for the same action task. We used a two-person action paradigm (after Vaziri-Pashkam et al., 2017) in a realistic setting to investigate how children and adults use the kinematics of others' actions to make predictions. Adults and children played a competitive reaching game. In the game, a confederate (the "Attacker") sat across from the participant (the "Blocker") behind a transparent barrier with two targets marked on it. As the Attacker reached as quickly as possible for one of the targets (chosen at random and signaled to the Attacker by a computer via headphones), the Blocker's task was to beat the Attacker to the target, touching the target before the Attacker did.

To ask whether children are able to use distributed information in the body of the Attacker, we occluded different parts of the Attacker's body during the game in different visual conditions. We also created a control condition in which all preparatory information was removed. In this condition, the participants played against a dot on a screen rather than an Attacker who was not present. The dot moved on the screen based on the kinematics of the Attacker's finger from the game. By comparing the reaction times of adults and children in each condition with the Attacker to the Moving Dot control condition, we assessed how children and adults utilized their opponent's preparatory movements during action prediction.

METHOD

Participants

Thirteen children between 6 and 8 years old (*M* = 7.57 years old, *SD* = 0.92 years, 8 females) were recruited through the Harvard Lab for Developmental Studies database. Thirteen adults between 18 and 35 years old (*M* = 24 years old, *SD* = 5 years, 8 females) were recruited through the Harvard Psychology Study Pool. All participants were right-handed and had normal or corrected-to-normal vision. Participants or participants' legal guardians gave informed consent prior to participation. Children were rewarded with stickers, and parents were given $5 for travel expenses, Adult participants were compensated $10 for their time. All experiments were approved by the Committee on the Use of Human Subjects in Research at Harvard University.

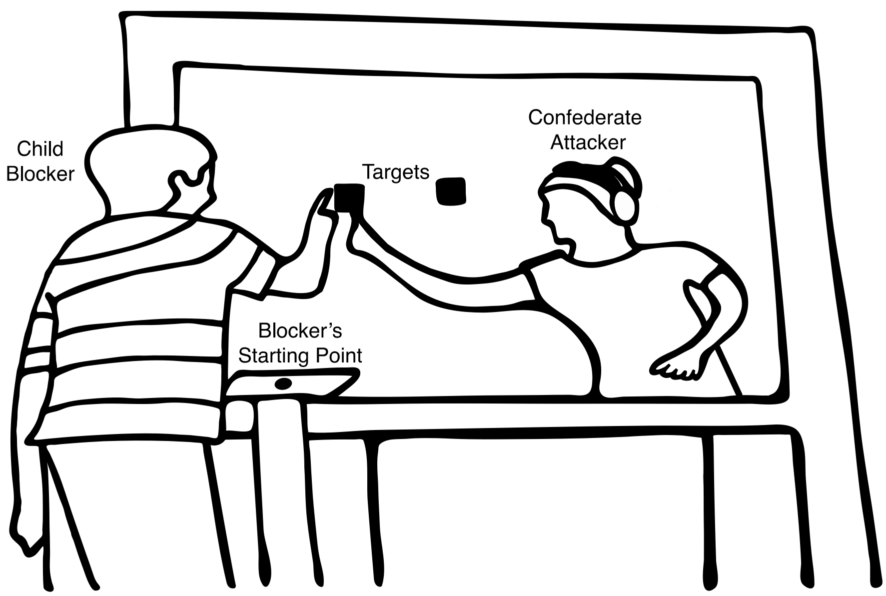

Figure 1: An example illustration of the experimental setup with a child participant in the "full-body" condition. The child is acting as a Blocker and standing across from a confederate Attacker. The Attacker is signaled through her headphones on each trial to contact either the left or the right target on the Plexiglas screen. The child is told that he should try to beat her to the target. The winner of the trial is the first person to contact the target on that trial. To match height across participants and the confederate, adult participants were seated, while child participants were standing on a platform adjusted to the height of the child.

Stimuli and Procedure

Participants in this study performed a competitive reaching task similar to our previous studies (Vaziri-Pashkam et al., 2017; McMahon et al., 2019). The participants were always assigned the role of the "Blocker." They were positioned across from a confederate "Attacker"

(~1.2 m apart) and separated by a Plexiglas screen (1.2 m x 1.5 m) on which two foam squares (5 cm) were placed ~26 cm apart. Adults sat, while children stood on a platform. The platform was raised as needed so that the standing height of each child roughly matched the seated height of the adult confederate (Figure 1).

The Attacker and the Blocker began each trial with their finger on a fixed starting point. The Attacker was then signaled through headphones to reach to either the left or the right target. The Blocker could not hear the instructions. The Blocker was told at the beginning of the session that the goal of the game was to beat the Attacker (i.e., to touch the correct target before the Attacker did). The confederate Attacker reached to the target immediately after hearing the signal.

The confederate and the participant each wore a magnetic sensor on their index finger. These sensors recorded the difference in time between when the Attacker and the Blocker contacted the target. Based on a threshold, the difference in contact time for a given trial determined whether the Attacker or the Blocker won on that trial. Because the Attacker usually won, a threshold was set so that the Attacker and Blocker each won on approximately half of the trials. If the difference was smaller than the threshold, the Blocker won, otherwise, the Attacker won. The threshold for the first 5 trials was set at a fixed value of 150 ms. After the first 5 trials, the threshold was set to the median time difference between the Attacker and Blocker’s contact on all previous trials to ensure an approximately balanced number of wins and losses in each block.

Participants performed the task over 5 blocks of 20 trials. The first block was a practice block in which the full body of the Attacker was visible to the Blocker. The next 3 blocks

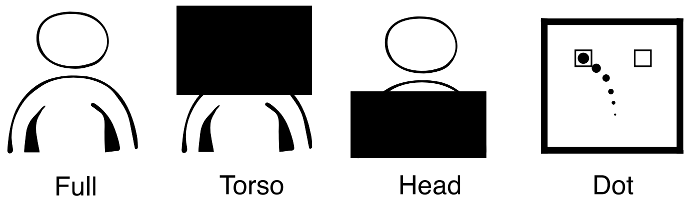

Figure 2: An illustration of the four experimental conditions. In the Full condition, the participants had a full view of the Attacker's body. In the Torso condition, only the torso was visible, while the head and shoulders were occluded by attaching black cardboard to the plexiglass screen. For the Head condition, the head and shoulders were visible, but the torso was occluded. In the Moving Dot condition, the Attacker was replaced with a dot that mapped to the movement of an Attacker's finger.

(counter-balanced across participants) varied between one of 3 conditions: Full, Torso, or Head (Figure 2). As with the practice trials, in the Full condition, the full body of the Attacker was visible to the Blocker. In the Torso condition, the torso and part of the upper limb of the Attacker was visible to the Blocker, while the head, neck and shoulders were occluded by attaching a large piece of black cardboard to the plexiglass screen. In the Head condition, the head, neck and shoulders of the Attacker were visible to the Blocker and the torso of the Attacker was occluded by the black cardboard.

A computer monitor (53 cm wide and positioned ~28 cm behind the plexiglass screen) replaced the Attacker in the final block for a control condition termed the Moving Dot condition. In this condition, instead of watching the Attacker, participants watched a video of a moving dot, which followed the trajectory from a human Attacker in a previous study. This way, the participants only saw the kinematics of an Attacker's finger that was used to control the movements of the dot on the screen and information from all other parts of the body was removed. The same sensors that recorded the difference in target contact time also recorded the kinematics of the Attacker's finger throughout her movement. Selecting the kinematics from twenty random trials from a previous study, the dot's movement mapped to the finger kinematics so that the dot moved as the Attacker's finger would move during the typical blocks. The x- and y-positions (left-right and up-down) of the dot on the screen mapped to the x- and y-positions of the Attacker's finger. Finally, the diameter of the dot mapped to the z-position of the finger (distance to the target) such that the dot became larger as the finger moved toward the target. As in the previous blocks, Blocker's task was to reach as quickly as possible to the target of the dot's movement.

Apparatus

Stimulus generation was done on a Windows computer using MATLAB 8.3 (MathWorks) and Psychtoolbox software (Brainard, 1997). A Polhemus Liberty position tracking sensor (1.27 x 2.22 x 1.9 cm) secured to the index fingers of the Attacker and Blocker recorded the three-dimensional position at 240 Hz. For the moving dot condition, a Dell monitor (1280 x 960 spatial resolution at 60 Hz, width 53cm) was used.

Data Analysis and Statistics

Analyses were performed in MATLAB and R (R Core Team, 2019) on the kinematic data from the finger sensor. In addition to the standard tools in R, we utilized the ggplot2 (Wickham, 2016), plyr (Wichkam, 2011), and nlme (Pinheiro et al, 2019) libraries. To find the main effect of age group on accuracy and reaction time, we ran two-way mixed-design ANOVAs. To further investigate the resulting main effects, we ran two-tailed independent or paired-samples *t*-tests (depending on whether the comparison was within or between groups). The resulting *p*-values were controlled for multiple comparison using the false discovery rate method (FDR, Benjamini & Hochberg, 1995). To control for the effect of the velocity of the

Attacker's reaches, we ran a two-way mixed-design ANOVA with movement time added as a factor to determine the main effect of age group and condition after controlling for the reach duration. Finally, in order to compare the performance of adults and children during an experimental block, we using a linear mixed model of reaction time against trial with subject modeled as a random effect.

RESULTS

All data analyses are based on the kinematics obtained from the sensor on the Attacker and Blocker's index finger. Prior to statistical analysis, we calculated the instantaneous velocity at each time point for each trial. The first time point in which the instantaneous velocity of the movement surpassed 15 cm/s was determined to be the starting point of the Attacker and Blocker's movement. The results of the automated analysis for all trials were manually inspected. If the starting point was determined to be erroneous for a given trial, that trial was removed from all subsequent analyses (4.11% of trials were removed in this way). Exceptionally long reaction times over 1s (around 0.24% of all trials) were also removed from the analysis.

Accuracy

A trial was counted as accurate if the Blocker's finger touched the same target as the Attacker. Overall, the accuracy for both children (M = 99.0%, SD = 3.3%) and adults (M = 99.9%, SD = 0.8%) was very high. Comparing the accuracies across all the visibility conditions (Full, Head, Torso, and Moving Dot blocks) and age group (child and adult) using a two-way mixed-design ANOVA, we did not find a main effect of age ($F(1,24) = 0.99$, $p = 0.33$) or condition ($F(3,72) = 1.10$, $p = 0.35$) or an interaction between age group and condition ($F(3,72) = 0.65$, $p = 0.59$). Children's accuracy was no worse than adults' and the performance in the four visibility conditions did not significantly differ in accuracy. Following this analysis, all inaccurate trials were removed from subsequent reaction time analyses (0.65% of trials).

Reaction Time

The reaction time of the Blocker was calculated as the difference between the start of the Attacker's movement and the start of the Blocker's movement. As was done for the accuracies, the reaction times of the Blocker were also compared across conditions and age group using a two-way mixed-design ANOVA (Figure 3). We found a main effect of age group ($F(1,24) = 46.72$, $p < 0.001$), a main effect of condition ($F(3,72) = 71.57$, $p < 0.001$), and a significant interaction between age group and condition ($F(3,72) = 9.731$, $p < 0.001$). Thus, although adults and children did not differ in accuracy, children (M = 0.30 s, SD = 0.07 s) reacted more slowly than adults (M = 0.18 s, SD = 0.05 s). Moreover, while there was no difference in accuracy between the conditions, adults and children reacted more slowly as the conditions varied from full visibility to full occlusion of the body (M = 0.20, 0.22, 0.25, 0.29 s, SD = 0.08, 0.09, 0.10, 0.07 s).

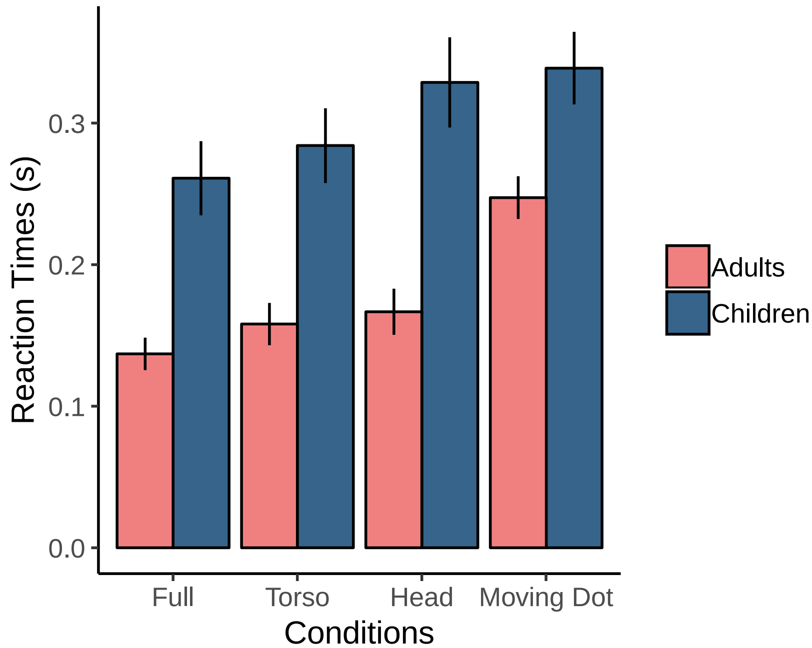

Figure 3: The reaction times of the adults and children in each of the four conditions. Children reached more slowly than adults. Error bars indicate the standard error of the mean.

We further investigated the pair-wise effects of condition with two-tailed *t*-tests. For adults, all conditions significantly differed from one another (all $t(12) > 2.69$, all corrected $p < 0.03$), except the torso condition did not differ significantly from the head condition ($t(12) = 1.01$, corrected $p = 0.33$). For children, all conditions differed from one another (all $t(12) > 3.8$, all corrected $p < 0.01$), except that the Torso condition was not significantly different from the Full condition ($t(12) = 2.08$, corrected $p = 0.07$) and the Moving Dot condition was not significantly different from the Head condition ($t(12) = 0.76$, corrected $p = 0.48$). Because both of these pairs of conditions differed only with respect to the visibility or invisibility of the head, these two negative effects combined with the previous ANOVA suggest that children did not use the information in the Head condition to improve their performance, in contrast to adults. Taken together, these results suggest that children may be using information in the head, neck, and shoulders less efficiently than adults.

Even though the confederates were instructed to act similarly across age groups, it is possible that they might have unintentionally moved slower when interacting with children. Unintentional changes in movement, depending on the behavior of opponents in competitive settings, have been demonstrated in previous studies (Naber, Pashkam, & Nakayama, 2013). To determine whether this possible speed variation was the source of the difference between children and adults, we re-ran the main analyses while controlling for the speed of movement. The difference in time between the Attacker's start and her contact with the target (i.e., the movement time) was added as a factor to the ANOVA comparing adults and children and condition. Because the distance between the start position of the finger and targets were the same in all trials, the movement time can be used as a proxy for velocity.

The confederate attacker reached more quickly when playing against adults (M=0.17s, SD = 0.008s) than against children (M = 0.22s, SD = 0.027s, $t(14) = 5.17$, $p < 0.001$). However, after including the movement time in the analysis, the main effect of age ($F(1,24) = 78.58$, $p < 0.001$), condition ($F(1,24) = 71.44$, $p < 0.001$), and the interaction between age and condition ($F(1,24) = 5.93$, $p = 0.001$) did not change qualitatively. This indicates that the Attacker's speed of movement is not the source of difference between age groups.

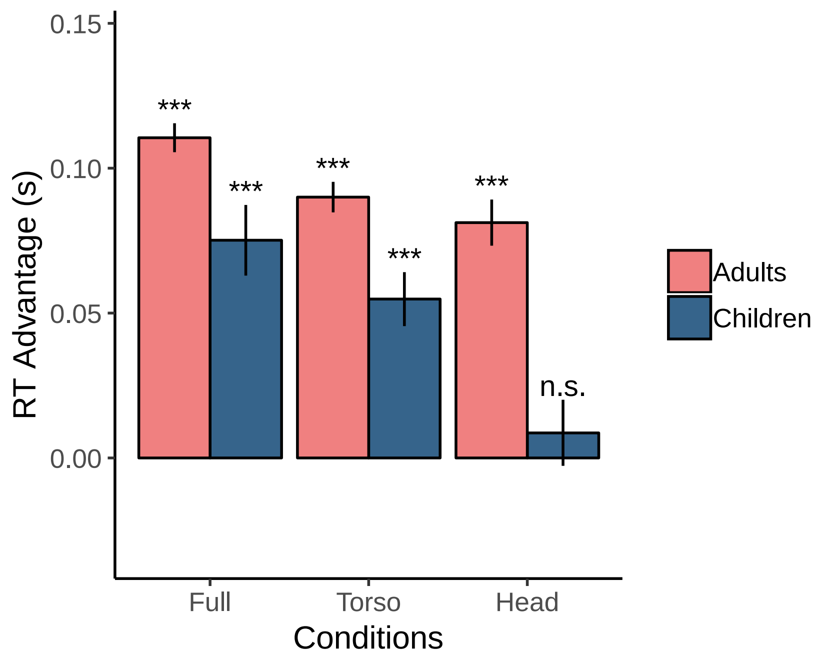

Figure 4: The reaction time advantage of the adults and children for the Full, Torso, and Head conditions relative to the Moving Dot condition (not shown). The tests shown immediately above the bars compare this advantage to zero. Error bars indicated standard error of the mean. (n.s. $p > 0.05$, *** $p < 0.001$)

Reaction Time Advantage

In the previous reaction time analysis, we found that adults were faster than children in all conditions. This finding is unsurprising and provides little insight into our main research question, which is whether adults and children differentially read information from the body of the Attacker. Thus, in our final series of analyses, we used the Moving Dot condition as a control condition to account for the baseline differences in the reaction times of children and adults. We computed an “RT advantage” measure by calculating the reaction time advantage that participants gain by having access to information from different body segments (Figure 4). The RT advantage was calculated by subtracting the reaction time of the Full, Torso, and Head conditions from that in the Moving Dot condition, separately for children and adults. In a two-way mixed-design ANOVA, we found a main effect of age group ($F(1,24) = 20.64$, $p < 0.001$)

and condition ($F(3,72) = 24.58$, $p < 0.001$) as well as an interaction between age group and condition ($F(3,72) = 4.93$, $p = 0.01$) on the RT advantage.

To further investigate the main effect of condition and age, we compared the reaction time advantage of the adults and children in each condition to zero. This test is the same as if each condition were compared directly to the Moving Dot condition. We found that the reaction time advantage in all conditions was greater than zero (all $t(12) > 5.66$, all corrected $p < 0.001$) except for the Head condition in children ($t(12) = 0.74$, corrected $p = 0.48$). Thus, after accounting for the finding that children are generally slower at the task than adults, children only seemed to be impaired in the Head condition but were able to read the information from body parts visible in the Torso condition.

Because our participants came from a large age range, the question might arise whether the oldest children were better at reading information in the head of the Attacker than the youngest children. To answer this question, we performed a regression analysis of the children's ages against their RT advantage in the Head condition. We did not find an effect of age on the RT advantage ($t(11) = 0.32$, $p = 0.78$). Interpretations of these findings is limited due to the small number of children, but these results suggest that the ability to read the information from the Head of the Attacker either develops later in childhood or on a slow time scale that we have not captured in the current group of children.

Learning

To test whether children and adults improved during the experiment, we investigated whether children and adults responded more quickly on the later trials of each experimental block (Figure 5). Each experimental condition was performed in one block and were analyzed separately. The first trial was excluded from the regression analysis due to a novelty effect in all conditions and groups. Using a linear mixed effects model of reaction time against trial with subject as a random effect, neither adults nor children were found to improve within an experimental block (all $F < 4.78$, all corrected $p > 0.12$). Extending what had previously been found in adults (Vaziri-Pashkam et al, 2017), these findings suggest that children show no short-term improvements in their ability to predict the actions of others during the experiment.

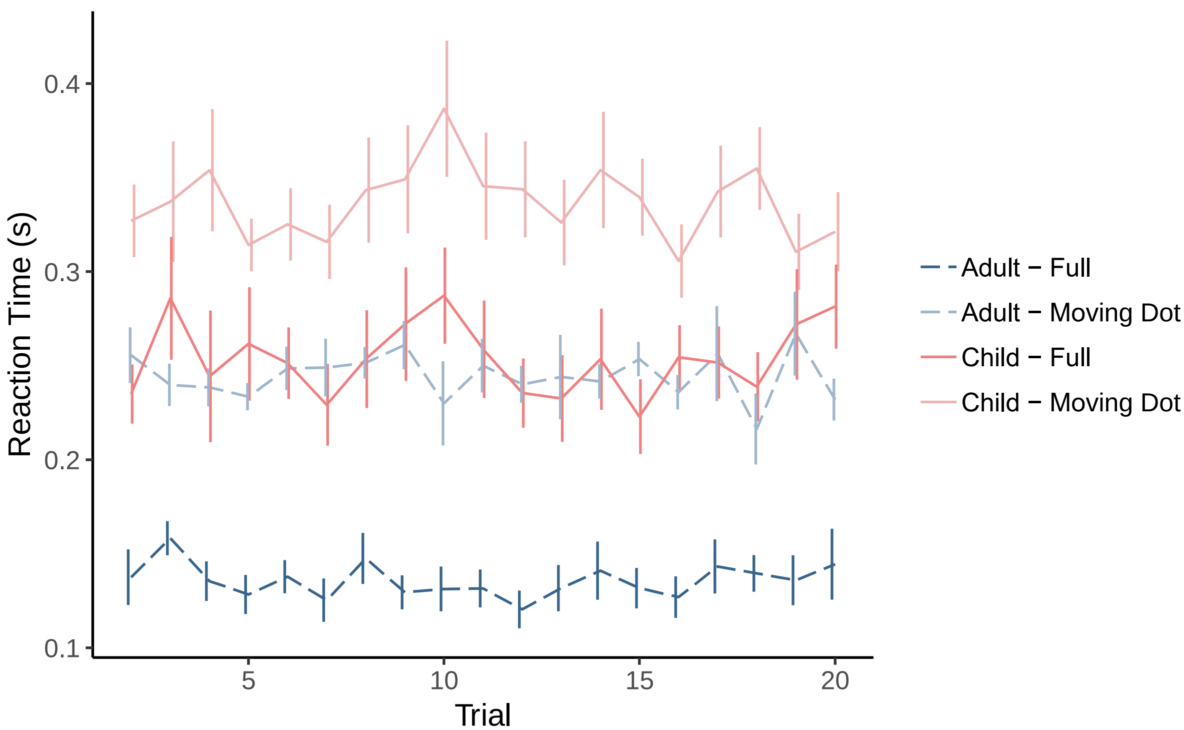

Figure 5: The reaction time for adults and children in the Moving Dot and Full body conditions after the first trial. The reaction times of children and adults do not decrease during a block suggesting that neither group is learning during the experiment. The Torso and Head conditions are not shown to avoid clutter but have the same pattern (see Results).

DISCUSSION

We asked whether 6- to 8-year-old children are able to use kinematic information available in the body of others to predict their goals, and compared children's performance to that of adults. Our results suggest that children, like adults, can use subtle, preparatory movements in the body for action prediction. In contrast to adults, however, children do not use information in the head, neck, and shoulders to improve their predictions. Children perform no better when the head and shoulders are visible than they do when presented with a solitary dot, and no better when both the head, shoulders, and torso are visible than when the torso is visible alone.

In comparing the reaction time of children and adults directly, unsurprisingly, we found that children react more slowly than adults in all conditions. Our primary question of interest was whether children are able to read preparatory information from the body of the Attacker similarly to adults. Thus, the finding that children predict the actions of others more slowly in a competitive context regardless of the amount of information available is not informative to our central aim.

By occluding large, non-overlapping sections of the Attacker's body, we replicated the previous finding that adults can use distributed information in the body for action prediction (Pesquita et al., 2016; Vaziri-Pashkam et al., 2017). Children were not able to use the distributed information in the body as efficiently as adults. When only the head, neck, and shoulders were visible, children's reaction times did not differ from the control condition in which only a dot moved on the screen. This result suggests that children are not using additional information in the upper part of the body to inform decisions beyond what is available in the Moving Dot condition. Further, children perform no better when the head and shoulders are visible than they do when presented with a solitary dot, and no better when both the head, shoulders, and torso are visible than when the torso is visible alone. However, like adults, children were able to use subtle additional information in the lower portion of the body to speed reaction times beyond those in the dot condition. These results show that while children use preparatory movements in the body for action prediction, they do not use information available in the upper portion of the body unlike adults to predict the direction of a reaching action.

Both adults and children have experience viewing and performing reaches, but the experimental game was a novel context for all participants. For this reason, we investigated whether children and adults are able to predict the target of the Attacker's reach more quickly at the end of participation than the beginning. Replicating prior work in adults (Vaziri-Pashkam et al, 2017), we did not find that to be the case for either children or adults. For these simple actions, adults seem to be experts at predicting common actions without training, and while children improve throughout development, there is no improvement during a single experimental session. Thus, while even in infancy children are able to predict actions of adults (Woodward, 1998; Cannon & Woodward, 2012), our current study of action prediction in a realistic context suggests that action prediction may have a prolonged developmental timescale.

Why are children unable to read information in the head, neck, and shoulders of an actor, when they are relatively good at reading information from the actor's torso, arm, and hand? Note that the current study focused on the prediction of a large reaching action. During a reaching action, there are larger movements in the lower portion of the body visible in the Torso condition than in the upper portion of the body visible in the Head condition. One possibility is that the visual system of Adults may be more sensitive to the smaller movements of the Attacker's eyes, head, neck, and shoulders than are children.

A second possibility is that adults have a more developed cognitive model of human movements that specifies how a distant head movement relates to a concurrent arm movement. Because adults have more motor experience reaching, they also may be better at simulating the future reaching action of a conspecific. This possibility aligns with the direct-matching hypothesis that motor experience for an action is necessary for predicting that action (Cannon et al., 2012; Falck-Ytter et al, 2006; Kanakogi & Itakura, 2011; Kochukhova & Gredebäck, 2010). Note, however, that much of the direct-matching research has focused on whether infants have experience with the motor action at all. In the present study, although adults have more experience reaching, children do also have experience reaching. Ultimately, the current study does not reveal the causes of the developmental change that it documents.

Another possible source of the difference between children and adults is the behavior of the confederate Attackers. Although the confederate Attackers in our study were instructed to reach at the same speed when playing with both adults and children, prior work has shown that, in a competitive context, a competitor may unintentionally reach more slowly if their opponent is slower (Naber et al, 2013). To ensure that the behavior of the Attacker was not the main source of our findings, we controlled for the velocity of the Attacker's reach by adding the velocity of each Attacker to the ANOVA of RT by age group and condition. After considering the effects of velocity in this way, all previous findings of differences between age groups and conditions remained. Thus, this analysis alleviates the concern that the Attacker behaving differently toward the two age groups explains our findings.

In conclusion, the current study suggests that while the adults' and childrens' action prediction performance does not improve within an experimental session, prediction shows an improvement from 6- to 8-years of age to adulthood. In order to better understand how the adult visual system has been optimized for prediction, future research should investigate the contributions of visual and motor experience in prediction throughout development.

REFERENCES

Ambrosini, E., Reddy, V., de Looper, A., Costantini, M., Lopez, B., & Sinigaglia, C. (2013). Looking ahead: anticipatory gaze and motor ability in infancy. *PLoS One, 8*(7), e67916.

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using “lme4.” Journal of Statistical Software, 67(1), 1-48.

Benjamini, Y. & Hochberg, Y. (1995). Controlling the false discovery rate: a practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society Series B*, *57*, 289–300.

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision*, *10*, 433-6.

Brandone, A. C., Harwitx, S. R., Aslin, R. N., & Wellman, H. M. (2014). Infants' goal anticipation during failed and successful reaching actions. *Developmental Science, 17*(1), 23-24.

Cannon, E. N., Woodward, A. L., Gredebäck, G., von Hofsten, C., & Turek, C. (2012). Action production influences 12-month-old infants' attention to others' actions. Developmental science, 15(1), 35–42.

Cannon, E. N., & Woodward, A. L. (2012). Infants generate goal-based action predictions. *Developmental Science, 15*(2), 292–298.

Cavallo, A., Koul, A., Ansuini, C., Capozzi, F., & Becchio, C. (2016). Decoding intentions from movement kinematics. *Scientific Reports, 6*, 37036.

Diaz, G. J., Fajen, B. R., & Phillips, F. (2012). Anticipation from biological motion: The goalkeeper problem. *Journal of Experimental Psychology: Human Perception & Performance, 38*(4), 848-864.

Falck-Ytter, T., Gredebäck, G., & von Hofsten, C. (2006). Infants predict other people's action goals. *Nature neuroscience, 9*(7), 878.

Flanagan J. R., Johansson R. S. (2003). Action plans used in action observation. *Nature, 14*, 769–771.

Gredebäck, G. & Kochukhova, O. (2010). Goal anticipation during action observation is influenced by synonymous action capabilities, a puzzling developmental study. *Experimental Brain Research, 202*, 493–497.

Gredebäck, G. & Falck-Ytter, T. (2015). Eye movements during action observation. *Perspectives on Psychological Science, 10*(5), 591-598.

Geangu, E., Senna, I., Croci, E., & Turati, C. (2015). The effect of biomechanical properties of motion on infants' perception of goal-directed grasping actions. *Journal of Experimental Child Psychology, 129*, 55–67.

Hodges, P. W., Cresswell, A. G., Daggfeldt, K., & Thorstensson, A. (2000). Three-dimensional preparatory trunk motion precedes asymmetrical upper limb movement. *Gait & Posture, 11*(2), 92-101.

Hodges, P. W., Cresswell, A. G., & Thorstensson, A. (1999). Preparatory trunk motion accompanies rapid upper limb movement. *Experimental Brain Research, 124*(1), 69–79.

Kanakogi, Y. & Itakura, S. (2011). Developmental correspondence between action prediction and motor ability in early infancy. *Nature Communications,* 2, 341.

Kochukhova, O., & Gredebäck, G. (2010). Preverbal Infants Anticipate That Food Will Be Brought to the Mouth: An Eye Tracking Study of Manual Feeding and Flying Spoons. *Child Development*, *81*(6), 1729-1738.

McMahon, E. G., Zheng, C. Y., Pereira, F., Gonzalez, R., Ungerleider, L. G., & Vaziri-Pashkam M. (2019). Subtle Predictive Movements Reveal Actions Regardless of Social Context. *Journal of Vision*, *19*(7), 16.

Naber, M., Vaziri-Pashkam, M., & Nakayama, K. (2013). Unintended imitation affects success in a competitive game. *Proceedings of the National Academy of Sciences*, *110*(50), 20046-20050.

Pesquita, A., Chapman, C. S., & Enns, J. T. (2016). Humans are sensitive to attention control when predicting others' actions. *Proceedings of the National Academy of Sciences*, *113*(31), 8669–8674.

Pinheiro J, Bates D, DebRoy S, Sarkar D, R Core Team (2019). nlme: Linear and Nonlinear Mixed Effects Models. R package version 3.1-139, https://CRAN.Rproject.org/package=nlme

R Core Team (2019). R: A language and environment for statistical computing. *R Foundation for Statistical Computing*, Vienna, Austria. https://www.R-project.org/.

Rosander, K. & von Hofsten, C. (2011). Predictive gaze shifts elicited during observed and performed actions in 10-month-old infants and adults. *Neuropsychologia, 49*(10), 2911-2917.

Vaziri-Pashkam, M., Cormiea, S., & Nakayama, K. (2017). Predicting actions from subtle preparatory movements. Cognition, 168, 65-75.

Wickham, H. (2016). ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag, New York.

Wickham, H. (2011). The Split-Apply-Combine Strategy for Data Analysis. *Journal of Statistical Software*, *40*(1), 1-29.

Woodward, A. L. (1998) Infants selectively encode the goal object of an actor's reach. *Cognition, 69*(1), 1-34.