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Examining Functional Spatial Perception in 10-Year-Olds and Adults

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Abstract

This study examined a specific type of spatial perception, functional spatial perception, in 10-year-old children and adults. Functional spatial perception involves anticipating actions made with objects to fulfill a function, or, in this case, fitting objects through openings. We examined accuracy, sensitivity, and consistency in participants' abilities to adjust a window to the smallest opening through which a small wooden cube would fit. Success at this task requires accounting for the dimensions of both the object and the opening. In life circumstances, poor decisions at similar tasks may result in injury, frustration, or property damage. As much previous work in this area included very young children and adults, we sought to determine whether older children (10-year-olds) would show adult-like skills. Ten-year-old participants were as equally accurate and sensitive as adults, and both groups left a safety margin in performing this task; but we found that adults made more consistent judgments than 10-year-olds. There are developmental implications for these findings, given daily real-life needs to accurately gauge functional spatial relations and navigate objects in real life.

Keywords

perceptual-motor control, visuospatial perception, object relations, fitting

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Introduction

On a daily basis, people use spatial perception to determine how best to use objects in relation to each other. Activities such as preparing a meal and navigating through the environment require relating the spatial characteristics of two or more objects to each other. For example, safely parking a car requires a consideration of space dimensions and the car's orientation in relation to surrounding cars and objects. Being able to extract and use object spatial information is an important aspect of learning, tool use, and personal survival. Prior research has linked spatial intelligence to science, technology, engineering, and mathematics achievements (for review, see Anderson, 2014). In this introduction, we delve into functional spatial perception, as it relates to human actions involving object use.

Functional spatial perception refers to prospectively planning actions with objects to serve some purpose (after Gelman & Ebeling, 1989). Functional spatial perception is used for a wide range of tasks such as locomotion and even eating. Frequently, we use objects to perform functions like pounding a hammer on a loose nail. To evaluate whether the objects afford the intended function, we must consider their spatial features. Pertinent information may include the objects' relative orientation, position in space, relative size, and shape. This is in contrast to spatial perception that is unrelated to actions, such as perceiving that an artist used oil instead of watercolor paint or perceiving object characteristics like absolute height without considering how the objects might be used. The range of possible functional actions associated with objects is constrained by the combined spatial features of the objects. Much as we might imagine how pieces of a jigsaw puzzle fit together to solve the puzzle, successful completion of functional tasks requires careful consideration of how objects may be used together to complete an action. In functional spatial perception, however, neglecting relevant object features can have serious consequences. For instance, from 2002–06, about 18,000 bodily injuries were attributed to automobile drivers backing into people; another 30,000 injuries were caused by drivers backing into other objects such as poles, trees, and fences (Austin, 2008). Erroneous decisions based on poor functional spatial perception may also lead to task failure and missed opportunities, such as being unable to change a tire because of purchasing the wrong-size spare.

In some traditional spatial perception research, participants were presented with line drawings of abstract figures and objects. One such widely used test is Vandenburg and Kuse's (1978) version of the Mental Rotations Test, originally created by Shepard and Metzler (1971). In this task, participants are presented with four line drawings of a figure and must decide which two drawings show the same figure from different orientations. Another frequently used method is the Water Level Test designed by Piaget and Inhelder (1956), in which participants view line drawings of bottles tilted at different angles and must draw in the water level line within the bottle. In the Cube Rotations Test, participants are given line drawings of seven cubes with distinctive symbols on each side and must decide which two show the same cube from different viewpoints (Ekstrom, French, Harman, & Dermen, 1976). Although these paradigms ensure high experimental control and deepen our understanding of mental rotation processes, methodological concerns make them inappropriate for studying functional spatial perception. Participants do not consider the stimuli functionally, because they are not asked to use them in an action even though a critical role of adaptive perception is to guide action (Gibson, 1979). Asking participants to use objects in a functional action requires three-dimensional rather than two-dimensional perception. Functional spatial perception has high ecological validity, because participants work with tangible, real objects, and the focus is on several objects simultaneously. Developing a newer research method for analyzing functional spatial perception might provide a means of calculating participants' responses through a free movement range rather than from within a limited choice set.

Fitting Objects Through Openings

One possible task for understanding functional spatial perception is fitting handheld objects through openings. This task mirrors many daily activities such as packing groceries into bags, shoving letters into envelopes, and navigating large boxes through doorways. A classic paradigm in robotics is a type of fitting problem, called the peg-in-hole insertion task, in which robots use sensory feedback and trial and error learning to solve the problem (Saadia, Amirat, Pontnau, & M'Sirdi, 2001). The *Bayley Scales of Infant Development* (Bayley, 1969) also include fitting tasks to help measure infants' intelligence. Fitting a three-dimensional object through a two-dimensional opening is not a trivial task. According to Shutts, Örnkloo, Von Hofsten, Keen, and Spelke (2009), it involves solving three representational problems. First, a three-dimensional object may look different from its two-dimensional profiles, depending on the viewing angle. For example, the profile of a square pyramid may look like a square or equilateral triangle, depending on how it is held. Second, one must compare the size and shape of the negative space created by the opening to that of a solid object. Finally, one must mentally rotate the object to determine the correct alignment that will allow it to pass through the opening.

Correctly fitting objects through an opening involves sensitivity, accuracy, and consistency (Ishak, Franchak, & Adolph, 2014). For a successful fit, sensitivity to the sizes of both objects is essential, relative size calculations must be accurate, and there must be consistency over time. The few prior studies requiring adults to fit objects through openings have found them to be highly sensitive to relative size information, but participants do not consistently make accurate decisions. For instance, participants showed a 50% frequency of trying to fit handheld objects through openings that were 7% too small

(Wagman & Taylor, 2005). Similarly, participants showed a 50% frequency of trying to fit objects through openings that were 10% too small when running and openings that were 18% too small when walking (Wagman & Malek, 2007). Some research with adults navigating wheelchairs through doorways found that adults had a 50% frequency of trying to fit the chair through openings that were 7% smaller than the wheelchair (Higuchi, Takada, Matsuura, & Imanaka, 2004), though, more recently, Yasuda, Wagman, and Higuchi (2014) found that adults' estimates of the needed opening closely matched the actual wheelchair width.

It is unclear whether children display adult levels of sensitivity, accuracy, and consistency at these tasks. Research using various methods has suggested that young children have a more rudimentary understanding of how to relate objects to openings. There seems to be a developmental timeline such that, by six months, infants have a basic understanding of functional spatial relations and tend to look longer at a display showing a too-large cube fitting inside a much smaller box (impossible condition) than at a display showing the cube fitting into the box (possible condition; Smitsman, DeJonckheere, & De Witt, 2009). Kinematic measures revealed that, by 10.5 months, infants planned their actions to account for the size of the opening, moving their hand slower when fitting a ball into a tube than when throwing it into a large tub (Claxton, Keen, & McCarty, 2003). Several studies have shown improvements between 14-26 months for fitting a variety of shapes into openings and advancements between 18-24 months for fitting disks into horizontal and vertical openings (Fragaszy, Kuroshima, & Stone, 2015; Jung, Kahrs, & Lockman, 2015; Örnkloo & Von Hofsten, 2007; Street, James, Jones, & Smith, 2011). Research with children between 15-30 months showed increasing efforts to account for dimensions and shapes of the objects and openings; if presented with a small, circular opening, 15-month-olds picked the large, nonmatching cube with 72% frequency, whereas 30-month-olds picked the cube with only 9% frequency (Shutts et al., 2009).

No studies have specifically tasked *older* children with fitting objects through openings, though several studies asked 10-12-year olds about navigating bicycles between different-sized virtual traffic openings. In these studies, participants pedaled a real bicycle through different-sized traffic gaps, projected onto large screens in a virtual environment. The most relevant dimensions were the width of the bicycle combined with the child's body extending beyond the bicycle's sides. Both these older children and their adult counterparts were sensitive to gap size, as all participants attempted to bike through large gaps in the traffic, avoided small ones, and adjusted their speed according to the gap size (Chihak, Grechkin, Kearney, Cremer, & Plumert, 2014; Chihak et al., 2010; Plumert, Kearney, Cremer, Recker, & Strutt, 2011). However, in these studies, the older children were less accurate than adults, as they produced 22 erroneous decisions (versus none for adults) that would have led to real-world collisions (Chihak et al., 2010). In another similar study, children made five times more erroneous decisions than adults (Chihak et al., 2014). In addition, 10-12-year-olds varied more than adults in the time they afforded themselves to cross the street before oncoming traffic, thus demonstrating less consistency than adults' for these decisions.

Current Study

In light of this prior literature, we compared the accuracy, consistency, and sensitivity of older children (10-11-year-olds) and adults' decisions on a functional spatial perception task. Participants adjusted a window to the smallest opening that they thought would accommodate a handheld cube. Thus, our design veered from traditional presentations of two-dimensional stimuli, such as computer-based line drawings. Our participants dealt with real three-dimensional objects in relation to one another within a functional task, and, instead of selecting from among a few fixed response choices, participants could make continuous 0.10-cm incremental adjustments to the window opening. We assessed sensitivity within probe trials that allowed participants to indicate whether they thought the cube would fit. Scaling their responses to opening size gave evidence of sensitivity to opening size. A finely adjustable apparatus permitted us to precisely determine participants' estimates, and we indexed accuracy by calculating the discrepancy between participants' responses and the actual smallest viable opening. We examined the consistency of participants' estimates by calculating the coefficient of variation over repeated trials. Our participants included both adults and 10-year-olds to address the gap in the literature with regard to whether older children would perform as well as adults. From past research, we expected that 10-year-olds would be as sensitive to opening size as adults, but that they would provide less accurate predictions and would be less consistent in their responses.

Method

Participants

Our study involved 17 children (8 girls, 9 boys; mean $(M)_{\text{age}} = 10.34$ years, standard deviation $[SD] = 0.64$) and 15 college-aged adults (7 women, 8 men; $M_{\text{age}} = 21.48$ years, $SD = 1.15$) who participated for course credit. Participants were primarily from middle-class Caucasian families, and all had normal or corrected-to-normal vision. Parents of all child participants and all college-aged adults signed an informed consent form, and both the protocol and consent form were approved by the university's institutional review board. Child participants verbally assented to participating before the start of the study.

Materials

Participants faced an adjustable apparatus and a wooden cube ($3.80\,\text{cm}^3$) positioned 8.0 and 3.0 centimeters (cm) away from the edge of a table, respectively.

The apparatus comprised a wooden frame (33.8 cm × 38.8 cm) that contained two 0.40-cm-thick fiberboards. Right triangles were cut from fiberboards to create diamond-shaped openings. The fiberboards overlapped like a camera shutter so that the total depth of the opening was 1.40 cm. Turning a knob on the back of the apparatus adjusted the fiberboards in 0.10-cm increments. A ruler (hidden from participants' view) affixed to the back edge of the fiberboard indicated the length of one side of the opening. When the panels were closed, the opening was 0 cm long; when the panels were completely open, each side of the opening was 15 cm long. The center of the opening remained fixed at 16.90 cm from the top and bottom edge of the frame. The cube remained centered in front of the apparatus on the table, and participants were never permitted to handle the cube. A video camera recorded the experimental session.

Procedure

Once participants were seated in front of the apparatus, an experimenter explained that it could make large and small windows. She informed participants that an assistant would be adjusting the window. Then, she pointed to the cube and told them to say "Stop" when the opening reached the smallest window through which they thought the cube could fit. After they said to stop, they could request that the assistant adjust the window size until they felt comfortable with their estimate. (Every participant made this request.) To examine participants' use of their visual-spatial ability, they were instructed not to touch the cube. To prevent influencing participants' decisions, experimenters never looked at the apparatus during the trials. At the end of each trial, the experimenter recorded the size of the estimate. The starting position of the apparatus alternated between 0-15 cm for each trial. Roughly half (16) of the participants started at 0 cm. Participants gave four estimates: two trials starting 0 cm and two trials starting at 15 cm.

To determine whether participants were sensitive to opening size, they were presented with five probe trials that were based on the average of the four estimates they provided. The probe trials were $\pm 1.00, \pm 0.50$, and 0 cm away from their average estimate. Trials were presented in one of two quasirandom orders. Participants said "Yes" or "No" depending on whether they thought that the cube would fit through the current window. Sessions took approximately 10 minutes for each participant to complete.

Data Analysis

We first examined participants' predictions of the smallest opening through which they thought the cube would fit by averaging their four estimates together. We calculated accuracy subtracting each participant's averaged estimate from 3.90 cm, the smallest actual viable opening. Positive numbers indicated that participants had overestimated the opening size and negative numbers indicated that they underestimated its size. To examine the consistency of responses across the four trials, we calculated the coefficient of variation for each age group as a ratio of the *SD* to the *M* for each age group. Typically, coefficient of variation values less than .10 indicate consistent responses. Finally, we determined whether participants were sensitive to opening size by examining the proportion of participants in each age group who stated the cube could fit through each of the five probe trials and absolute opening size. Across data, we used analyses of variance (ANOVAs) and independent samples *t* tests to compare children's and adults' responses. Statistical significance was set at $p < .05$ level.

Results

As shown in Figure 1, the average estimate for the children was 4.44 cm ($SD = 0.66$) and for the adults, it was 4.34 cm ($SD = .42$). Individual averages ranged from 3.40-7.00 cm. We analyzed the data for gender differences for children and adults with separate *t* tests and found none; therefore, data were combined across gender for further analyses. There was no statistically significant difference between children and adults' responses for the smallest viable opening estimates, $t(32) = .54$, $p > .05$.

Overall, both age groups made highly accurate predictions, with overestimates hovering around 0.50 cm ($M = 0.54$ cm, $SD = 0.66$ for children; $M = 0.44$ cm,

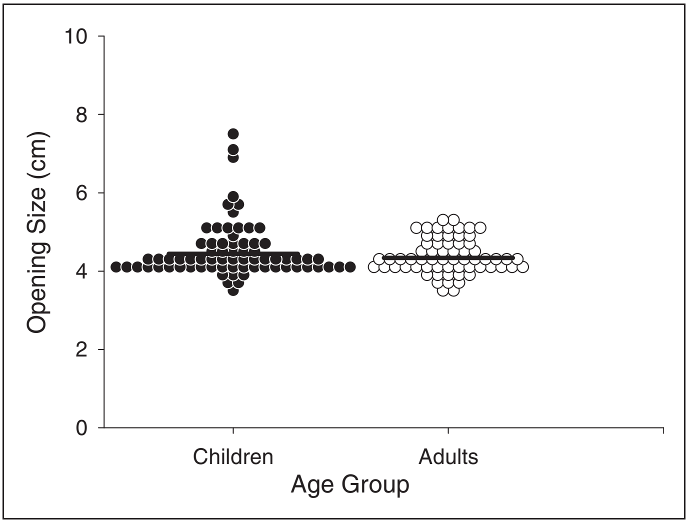

Figure 1. Individual estimates provided by children (black circles) and adults (white circles). Horizontal black bars indicate mean estimates for each group.

$SD = 0.42$ for adults). These values indicate that children and adults picked openings that were approximately 14% and 11% larger, respectively, than the cube itself. A *t* test confirmed that there was no significant accuracy difference between child and adult groups, $t(32) = .59$, $p > .05$.

A *t* test on the coefficients of variation revealed that adults were more consistent across their four predictions than were children—.15 for children versus .10 for adults, $t(32) = 11.09$, $p < .001$. Of note, a paired samples *t* test revealed that children's estimates were significantly smaller when the starting position of the apparatus was 0 cm versus 15 cm—4.32 cm versus 4.57 cm, respectively, $t(16) = 2.68$, $p = .02$. Adults gave similar estimates, regardless of the starting position.

As shown in Figure 2(a), participants in both age groups adjusted their decisions according to the probe size. For openings larger than their estimate (+0.50 and +1.00 cm) almost all of the participants correctly indicated that the cube would fit through successfully. For openings 1.00 cm smaller than their averaged estimate, only three participants incorrectly indicated that the cube would fit. However, for openings 0.50 cm smaller than their averaged estimate, 14 (44%) participants incorrectly indicated that the cube would fit. A 2 (Age Group) × 5 (Probe Trials) ANOVA on proportion of "Yes" responses confirmed a main effect for probe trials, $F(4, 108) = 69.76$, $p < .001$, partial $\eta^2 = .72$. There was no main effect for age and no interaction between age and probe trials (both *p*s > .05). A significant linear trend, $F(1, 27) = 180.02$, $p < .001$, partial $\eta^2 = .87$, for probe trials confirmed that the proportion of "Yes" responses decreased for openings smaller than the averaged estimate.

As shown in Figure 2(b), examination of participants' responses based on absolute opening size yielded similar findings. Both children's and adults' responses were close to 100% for openings larger than 4.00 cm. Recalling that 3.90 cm was the smallest viable opening, although the cube could have fit through 4.00-cm openings, only 63% of adults and 69% of children responded as such. It should be noted that the percentage of "Yes" responses decreased gradually rather than abruptly for openings smaller than 4.00 cm, despite the fact that the cube was unable to fit through those openings. Furthermore, 50% of adults and children said the object would fit through openings near 4.00 cm 50% of the time. A 2 (Age Group) × 4 (Absolute Opening Size Increment) ANOVA on proportion of "Yes" responses revealed only a main effect for risk, $F(3, 57) = 31.36$, $p < .001$, partial $\eta^2 = .62$. There was no main effect for age and no interaction between age and probe trials (both *p*s > .05).

Discussion

We examined the sensitivity, accuracy, and consistency of older children's and adults' functional spatial perception in one of the first studies to ask older children about their perception of three-dimensional objects' relations. Our findings

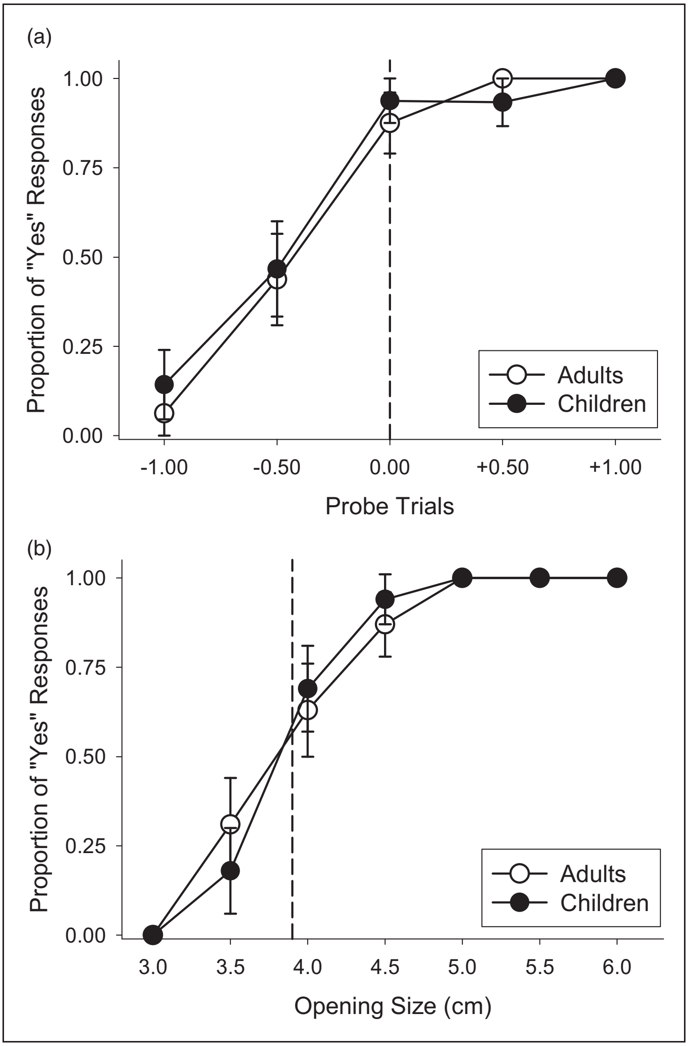

Figure 2. (a) Proportion of "Yes" responses for each of the five probe trials. Dashed vertical line indicates the averaged estimate for each participant. (b) Proportion of "Yes" responses based on opening size. Dashed vertical line indicates 3.90 cm. Note: Each increment on the *x*-axis consists of responses for a 0.50-cm span of openings; the label on the *x*-axis corresponds to the midpoint of the span. Error bars indicate standard errors.

support several of our hypotheses. We hypothesized that 10-year-olds' estimates would be less accurate than those of adults, but this was not the case. However, coefficient of variation analyses supported our hypothesis that adults' estimates would be more consistent than older children's estimates. Regarding our third variable, overall, both older children's and adults' responses to the probe trials showed that they were similarly sensitive to opening size, and their probe trial responses showed that both groups would sometimes err by choosing openings that were slightly too small.

Functional Spatial Perception

Asking participants to use an object in an action tapped into their functional spatial perception skills. Because of the method we used, participants most likely based their decisions on the dimensions of the cube, but neither the children nor the adults seemed to interpret the task as to simply match the window to the cube. Their estimates suggested that they sought to avoid touching the sides of the apparatus, because they overestimated the openings by 13% (overall). Participants' estimates reflect a liberal response criterion, as they incorrectly indicated that the cube would not fit through openings that it could have. On the probe trials, participants did not unanimously respond that the cube would fit until openings were five cm in size. Yet, they did not unanimously respond that the cube would not fit until openings were three cm, perhaps because there was no penalty for incorrect decisions. Although we did not collect confidence ratings, participants did not seem to feel confident about their estimates. Many commented that they would have been more accurate if they had been allowed to hold the cube just once.

It is possible that participants' overarching caution about making errors prevents mishaps in real life where mistakes may be costly. In our study, at least for navigating a cube, participants left approximately a 13% margin of safety. Is this amount too small or too large? On the one hand, 13% would allow the cube to fit if it was not exactly aligned with the sides of the opening, but, on the other, there may be opening-object combinations for which that safety margin would be insufficient for a safe, successful passage. For example, a rectangular prism could not fit sideways with this safety margin. There are no clear guidelines for how much space one should leave for fitting real objects into openings. Even for a task as commonplace as parallel parking, the Department of Motor Vehicles simply advises that the parking space should be several feet longer than the car ("How to Parallel Park," n.d.). Presumably variations in vehicle length, parking conditions, and driver skill prevent more specific recommendations. In naturalistic observations, drivers typically choose spaces that are 1.5 times the length of their vehicles (Cullinane, Smith, & Green, 2005). Artificial intelligence programs designed for autonomous vehicles have used anywhere from 1.4 times to twice the car's length (e.g., Zhao & Collins, 2004). It could be that safety margins are dependent on the action, penalty for error, a ratio of dimensions, and the decider's risk-taking proclivities.

Previous research with other objects suggested that participants would occasionally underestimate opening sizes, though in the current study it was rare

(12% of all estimates) for adults and older children to underestimate the smallest viable opening. The percentage of underestimates in this study was far less than Wagman and Taylor (2005) who found that adults underestimated which openings a handheld object would fit through on almost 20% of trials. This pattern was not just for a few trials, as Yasuda et al. (2014) and Wagman and Malek (2007) found that adults consistently underestimated the smallest doorway they could walk through while holding a bar horizontally. Higuchi et al. (2004) found that adults consistently underestimated openings safe for a wheelchair by 4% to 7%, perhaps suggesting greater caution when risk of injury is at stake.

Several methodological differences in this study and those before it might account for our finding of relatively fewer participant underestimates. Our target object was much smaller than the one used in other research (e.g., 3.8 cm vs. 68 cm in Higuchi et al., 2004). In addition, our apparatus and target object were not only closer to the participants but also closer to each other. Both factors may have enabled our participants to better incorporate visual information in their estimates than participants in other studies. Also, we asked participants to give point estimates to a gradually changing adjustment while other researchers' participants evaluated fixed or constant stimuli. Research in other fields has found the method of adjustment to be a preferable response format to the fixed or constant stimuli method (Rolland, Meyer, Arthur, & Rinalducci, 2002).

Functional Spatial Perception in Older Children

Unlike prior research involving 10-year-olds' estimates of virtual traffic gaps while riding bicycles, our data did not reveal a statistically significant difference between children's and adults' estimates and probe trial responses. Children may still be learning how to handle a bicycle and divide their attention between that and traffic judgments (Chihak et al. 2010). Also, as our 10-year-old participants did not have to respond by maneuvering a heavy object (bicycle), they could better attend to perceptual judgments. Other researchers have also found 10-year-olds capable of perceiving object relationships. When Forrester and Shire (1994) asked 8-9-year-olds and 10-11-year-olds to estimate the number of handheld cubes that would fit into various sized boxes, the slightly older children proved more accurate than their younger counterparts. Thus, there is a likely developmental progression with respect to varied functional spatial perception tasks. By the age of 10 years, these skills appear to be sufficiently developed for accurate decision making, at least with regard to small objects. This age has been associated with other measures of brain maturity, including the onset of many frontal lobe–mediated executive functioning skills (for review, see Best & Miller, 2010) and the fact that, by this age, children's brains have 95% of the volume of an adult brain (Caviness, Kennedy, Richelme, Rademacher, & Filipek, 1996), specifically in the cerebrum, cerebellum, and some subcortical structures (e.g., hippocampus).

Consistent decision making for manipulating objects is as important as accuracy and sensitivity, as inconsistency errors can also lead to serious accidents. Similar to Chihak et al.'s (2014) bicycle studies, our child participants were less consistent across their four estimates than were adults. Interestingly, children's estimates were larger when the starting position of the apparatus was 15 versus 0 cm, exemplifying the hysteresis effect (a different critical boundary for ascending vs. descending stimuli) found in much, but not all, psychophysical research. This finding is possibly caused by an overload in short-term memory capacity (Goldberg & Stewart, 1980) when people are given a high demand task. Although our task was simple, it may have been relatively more demanding for children than adults in relation to children's weaker short-term memory (Cowan, AuBuchon, Gilchrist, Ricker, & Saults, 2011), perhaps affecting their skills for ignoring irrelevant information (Hale, 1990). The combination of children's adult-like accuracy but poorer consistency, relative to adults, further describes the ongoing development of functional spatial perception. Sensitivity and accuracy appear to develop earlier than consistency, although a wider age range would further clarify the nature and timing of this developmental process. Further cognitive development and experience with objects may lead to more consistency, as other research has shown that between 10-13 years of age, children's ability to ignore irrelevant information improves (for review, see Hagen & Hale, 1973).

Limitations and Future Studies

While our research highlights key aspects of functional spatial perception, and we are the first to use this type of functional spatial perception task with older children, there are several limitations to our study that should be addressed by future research. Our participants were only asked to fit one object through one shape of opening (consistent with other studies in this field), leaving unclear whether our observed response pattern would be similar for objects and openings of other shapes and sizes. Furthermore, most participants reported that they found this task to be easy, perhaps because they did not have to contend with whether a three-dimensional shape matched its two-dimensional profile (Shutts et al., 2009). Separate areas of the human brain respond when reaching toward small versus large objects (Tarantino, De Sanctis, Straulino, Begliomini, & Castiello, 2014), and cells in the medial posterior-parietal area (V6A) of the macaque brain respond selectively when reaching toward differently shaped objects (Fattori, Breveglieri, Raos, Bosco, & Galletti, 2012). It is possible, therefore, that participants might not display the same caution with regard to making errors when working with other objects; future studies should test participants with a variety of items and openings. Another limitation is that our participants were asked only about one task action, while past research has shown that participants account for the perception–action system to be used when deciding which openings will accept a given object. For instance, Wagman and Malek

(2007) found that participants gave more conservative perceptual judgments when they anticipated running versus walking. Finally, we tested only two age groups; future researchers should better delineate the developmental progression in functional spatial perception skills.

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