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Development of Multiple Object Tracking via Multifocal Attention

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Multifocal attention is the ability to simultaneously attend to multiple objects, and is critical for typical functioning. Although adults are able to use multifocal attention, little is known about the development of this ability. In two experiments, we investigated multifocal attention in 6–8-year-old children and adults using a child-friendly, computerized multiple object tracking task designed to encourage the use of multifocal attention. We also investigated whether multifocal attention in children is deployed independently across left and right hemifields of vision, as in adults. Our results suggest that children's capacity for multifocal attention increases significantly across middle childhood. We also found evidence that at least one signature of hemifield-independent multifocal attention, the bilateral field advantage, can be observed in children.

Keywords: multifocal attention, multiple object tracking, attention, development, hemifield independence

Supplemental materials: http://dx.doi.org/10.1037/dev0001064.supp

In order to navigate a dynamic world, we must track objects as they move in our environment. For example, to cross a busy intersection safely and successfully you must keep track of the locations of multiple cars and pedestrians as you yourself navigate through space. Doing so requires you to allocate visual attention to the objects in your field of view, and to maintain your attentional focus on those objects as they move.

Although early models of attentional processing assumed a single focus of attention spread over continuous regions of space (Hoffman, 1979; Posner, Nissen, & Ogden, 1978; Posner, Snyder, & Davidson, 1980), more recently researchers have found evidence for multifocal attention: the ability to attend to distinct objects or locations simultaneously (Awh & Pashler, 2000; McMains & Somers, 2004). Strict tests of multifocal attention require presentation of stimuli in such a way that strategies such as shifting gaze or shifting a single focus of attention would make attending to the objects extremely difficult (e.g., Yantis, 1992). These studies show that adults can split their attention between noncontiguous locations simultaneously while ignoring or suppressing information presented at unattended locations (e.g., Awh & Pashler, 2000).

The ability to split attention is especially efficient when information is divided between left and right hemifields of vision, resulting in a bilateral field advantage for attentional processing (Awh & Pashler, 2000; Chakravarthi & Cavanagh, 2009; Delvenne & Holt, 2012; McMains & Somers, 2004; Reardon, Kelly, & Matthews, 2009; Walter, Quigley, & Mueller, 2014). The bilateral field advantage is evidenced in multiple object tracking (MOT) tasks (Alvarez & Cavanagh, 2005; Pylyshyn & Storm, 1988), which require participants to select relevant information (i.e., targets) and maintain that information as those targets move among distractors (Alvarez & Franconeri, 2007; Sears & Pylyshyn, 2000; Yantis & Johnson, 1990). For example, Alvarez and Cavanagh (2005) found that participants tracked objects more efficiently when the objects were divided evenly between left and right visual hemifields, compared to when they were presented all within the same visual hemifield, suggesting that multifocal attention may be deployed somewhat independently across left and right visual hemifields. While hemifield independence can improve MOT when objects remain within their original hemifields, it also can lead to decreased tracking performance when objects move from one hemifield to another. For example, adults have more difficulty tracking objects that move between hemifields

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Our study design, hypotheses, and analysis plan were preregistered and are available at: https://osf.io/8xtpn/.

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(e.g., traveling from the right to the left hemifield) compared to within their original hemifields (Minami, Shinkai, & Nakauchi, 2019; Strong & Alvarez, 2019).

While much work has investigated multifocal attention in adults, less is known about the development of multifocal attention. Some previous work has investigated children's ability to track multiple moving objects among distractors using tasks that did not control for single-focal or gaze-shifting strategies (Nava, Föcker, & Gori, 2020; Ryokai, Farzin, Kaltman, & Niemeyer, 2013; Trick, Jaspers-Fayer, & Sethi, 2005). For example, Trick and colleagues (2005) designed a task in which 6-, 8-, 10-, and 12-year-olds and adults were shown 10 items, some of which were happy faces (distractors) and others that were spies (targets). After the targets were shown, all items were masked and moved randomly around the screen. Once the items stopped moving, participants were instructed to indicate which items were the initially cued targets. They manipulated the number of targets (1–4) in order to investigate MOT capacity. Their results suggested that 6- and 8-year-olds were able to reliably track up to two moving targets among distractors, but 6-year-olds performed significantly worse than 8-year-olds. By age 10, children were able to track up to three targets, and 12-year-olds and adults were able to track up to four targets. These results suggest that children can track multiple objects, and that this ability develops significantly across middle childhood. However, it is unclear what attentional mechanisms children were engaging in these tasks, since children could have relied on strategies requiring a single focus of attention rather than multifocal attention to succeed (Yantis, 1992).

Furthermore, if children can engage in multifocal attention, it is unknown whether multifocal attention in children bears the same signatures as multifocal attention in adults—namely, hemifield independence. In adults, hemifield independence in multifocal attention is thought to arise from communication between brain hemispheres facilitated by the corpus collosum (CC; Chiarello, 1988; Myers & Sperry, 1958; Ramon & Rossion, 2012; Schüz & Preiβl, 1996). Individual differences in connectivity between hemispheres is associated with the strength of bilateral processing during visual attention tasks (Qin et al., 2016). For example, split brain patients with lesions to the CC are faster than controls at processing information presented in separate hemifields, exhibiting a stronger bilateral field advantage (Luck, Hillyard, Mangun, & Gazzaniga, 1989). However, these patients are also slower to process information that must be integrated across both hemifields (Mohr, Pulvermüller, Rayman, & Zaidel, 1994). The CC develops across childhood and into adolescence, with connectivity increasing dramatically throughout this period (Gbedd et al., 1999; Keshavan et al., 2002; Luders, Thompson, & Toga, 2010). As a result, the way multifocal attention is deployed across visual hemifields in children may be different than the way it is deployed in adults. Children may exhibit a bilateral field advantage similar to or greater than adults when tracking objects in separate hemifields. However, when the task requires integration of information across the hemifields, like when objects move between the hemifields (Minami et al., 2019; Strong & Alvarez, 2019), children may have more difficulty tracking that information.

Across two experiments, we investigated multifocal attention in 6–8-year-old children and adults using computerized MOT tasks. We tested 6–8-year-olds because children of this age have previously been shown to be able to complete MOT-style tasks (e.g., Trick et al., 2005) and because this is a developmental period associated with robust CC maturation (Gbedd et al., 1999; Luders et al., 2010; for a review see Knyazeva, 2013). Our tasks were designed based on previous adult research investigating multifocal attention (Alvarez & Cavanagh, 2005; Strong & Alvarez, 2019). Critically, we paired our targets with distractors so that they moved together, with each target/distractor pair engaging in a controlled orbital movement. The close pairing and controlled movement of the target/distractor pairs were chosen to make strategies that are reliant on a single focus of attention difficult (i.e., attentional switching or grouping; Yantis, 1992). For example, if participants attempted to shift their attention between targets they would likely lose one of the targets during the shift, as the target is perceptually grouped with, and subsequently difficult to distinguish from, an identical distractor object (Yantis, 1992). Additionally, participants are unlikely to be able to group multiple targets together and track the group (instead of the individual targets); since targets are closely paired with distractors, target-distractor pairs are the more likely unit of perceptual grouping, making grouping multiple targets across pairs much more challenging (Koffka, 1935; Yantis, 1992).

The present study had two aims. The first aim was to investigate whether children can engage in multifocal attention (Experiment 1), and to investigate how the capacity for multifocal attention changes over development (Experiment 2). In Experiment 1, we asked children and adults to track two targets among distractors. If children can engage in multifocal attention, we expected children (and adults) to be able to track two targets at above-chance levels. In Experiment 2, we varied the number of targets children and adults were asked to track (from 1–4), to investigate the development of the capacity of multifocal attention.

Our second aim was to investigate whether children also would show signatures of hemifield-specific processing in multifocal attention. We leveraged two previously used methods for investigating hemifield-specific processing in adults. In Experiment 1, we asked whether children and adults would show a "crossover cost" for tracking objects that move between compared to within hemifields, after Minami et al. (2019) and Strong and Alvarez (2019). In Experiment 2, we asked whether children and adults would show a bilateral field advantage in tracking objects presented in separate hemifields compared to within the same hemifield, after Alvarez and Cavanagh (2005).

Experiment 1

Method

Participants. This study was conducted as a preregistered confirmatory study following an initial exploratory study. In the initial exploratory study, we tested a small number of 6- and 7-year-olds and adults (n = 12 per age group) in order to get a sense of the kinds of effect sizes we might expect (allowing us to determine a sample size for the confirmatory experiment). The preregistration for the current confirmatory experiment can be found at https://osf.io/8xtpn/.

Our target sample was 80 participants (60 children and 20 adults) determined through a power analysis (G*Power) with a moderate effect size (f = .25; power = .95) to detect a potential Movement (2 levels) × Age (4 levels) interaction effect using a mixed factors analysis of variance (ANOVA; suggested $n = 76$). Data were collected at four different locations (Boston University, Harvard University, Children's Museum and Theater of Maine, and Connecticut Science Center). Due to the nature of museum testing, we exceeded our target sample, with 71 children (twenty-five 6-year-olds, $M = 6.42$, $SD = .34$, 8 girls; twenty-three 7-year-olds, $M = 7.45$, $SD = .32$, 12 girls; and twenty-two 8-year-olds, $M = 8.43$, $SD = .23$, 11 girls) and 21 adults ($M = 20.29$, $SD = 3.13$, 16 women) participating. Of the 71 children, 42 participated at Boston University, eight at the Children's Museum and Theater of Maine, and 21 at the Connecticut Science Center. Of the 21 adults who participated, 12 participated at Boston University, nine at Harvard University, and two at the Children's Museum and Theater of Maine. Overall performance did not differ between participants run in the lab compared to museums, $t(89) = -1.01$, $p = .316$. One additional 6-year-old started the task, but was excluded because of a computer malfunction.

Stimuli. Stimuli were presented on a laptop computer with a 13-in. display. Participants were seated approximately 20 in. away from the screen. All targets and distractors were moving dots (yellow, white, or orange) with a diameter of 1 degree visual angle (dva). Target and distractor dots were presented in pairs with a distance of 5 dva between their midpoints. The midpoints of each of the two dot pairs were located 180° apart along an imaginary circle of radius 7.8 dva with an origin at the center of the screen; in each quadrant, the midpoint of the dot pair was an equal distance from the horizontal and vertical midlines. Three animal cartoon images (monkey, dog, and bunny) were also used.

Procedure. The procedure used in this study was approved by Boston University's Institutional Review Board (IRB) under the protocol number 3594E and title, "Development of Working Memory for Objects in Social and Nonsocial Contexts." We created a new child-friendly MOT task based on adult MOT tasks designed to specifically assess multifocal attention (Minami et al., 2019; Strong & Alvarez, 2019). Participants were told that they were going to play a game where the goal was to feed an animal (monkey, dog, or bunny; presented at fixation) its favorite food. The "foods" were represented by moving dots (bananas/yellow, bones/white, and carrots/orange, respectively). On each trial, participants saw four identical dots presented in two pairs. Each pair occupied one of four quadrants around a cartoon animal image presented at fixation and were always presented in diagonal quadrants (Figure 1). Participants were told that, at the beginning of each trial, some of the foods (i.e., dots) would flash, and that those were the animal's favorite foods. They were then told that the dots would move around, and their job was to keep track of the animal's favorite foods while keeping their eyes on the animal in the center of the screen.

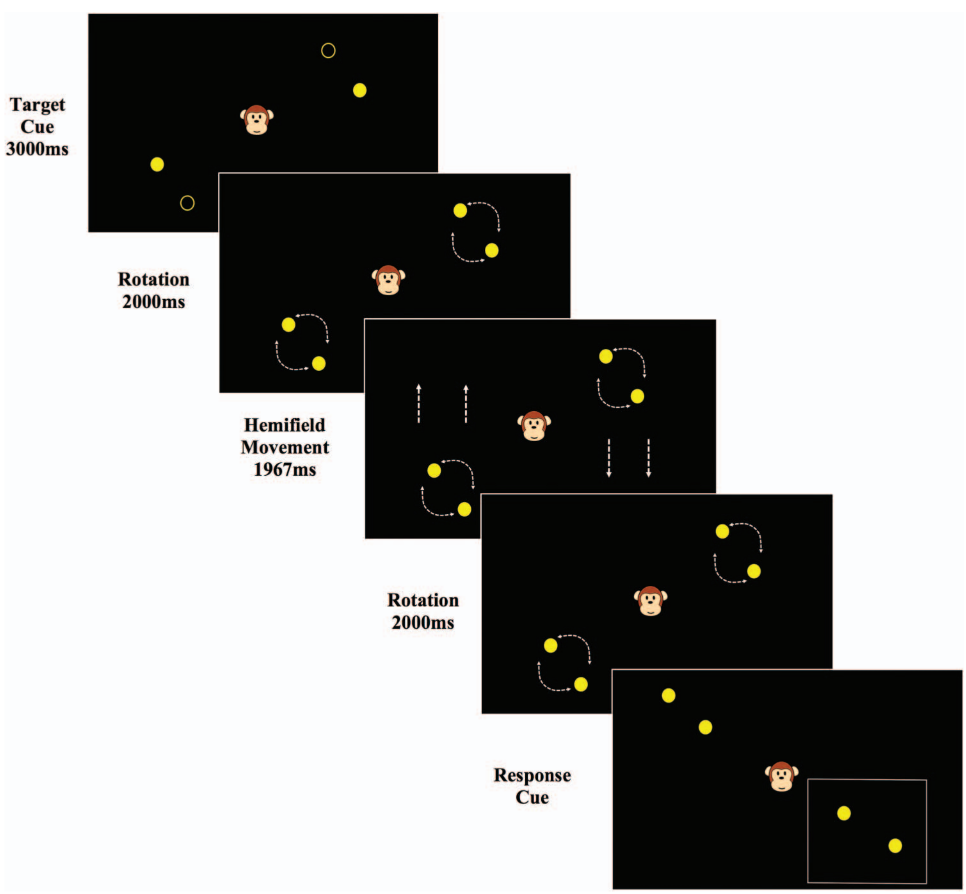

Figure 1. Example of a within hemifield trial for Experiment 1. See the online article for the color version of this figure.

At the start of each trial, one dot within each pair flashed briefly (3,000 ms) to indicate that these were the targets. The target/distractor pairs then orbited in place at a local rotation speed of 225°/s (speed was determined based on pilot testing with 6–8 year-old children). The initial spin direction (clockwise or counterclockwise) was randomly determined separately for each dot pair. While remaining in their original quadrants, dot pairs moved in their original spin direction for at least 50 frames (833 ms), after which there was a 1/75 chance they would change spin direction on each frame. Following each change of spin direction, dot pairs again rotated in the same direction for at least 50 frames before again having a 1/75 chance of changing direction on each frame. After 2,000 ms, the target/distractor pairs moved to an adjacent and previously unoccupied quadrant (shifting 90 degrees along an imaginary circle of radius 7.8 dva) at a speed of 45°/s (1,967 ms) while continuing to orbit each other. During half of the trials the pairs shifted vertically (within hemifield movement), while on the other half the pairs shifted horizontally (between hemifield movement). Once reaching their final locations, the dot pairs orbited for another 2,000 ms, spinning in the same direction as they did during the shift between quadrants for at least 833 ms before again having a 1/75 chance of changing direction on each frame (following the same parameters as the first 2,000 ms of motion). Total movement lasted for 6.0 s. These parameters were selected based on a previous study using a similar design with adult participants (Strong & Alvarez, 2019). Critically, display parameters encouraged the use of multifocal attention over other potential strategies. Because each target was always closely grouped with a distractor, our task discouraged tracking strategies such as grouping targets into a single shape, shifting gaze between targets, or shifting focal attention between targets (Yantis, 1992); instead our task encouraged maintaining fixation and tracking the objects using multifocal attention (see Figure 1).

After the objects stopped moving, we probed participants on one of the pairs by surrounding the pair with a square and asking participants to select which of the two objects in the pair was the animal's favorite food (chance = 50%). Child participants selected a target by pointing, and the experimenter then clicked on the indicated target with a mouse. Adult participants clicked the target themselves. Note that participants did not know which pair would be probed; the probed pair was randomly selected on each trial (Strong & Alvarez, 2019). Participants received feedback on each trial. If they selected the target, the animal in the center smiled; if they selected a distractor, the animal in the center looked surprised.

Participants completed a total of 24 test trials (3 blocks of 8 trials, 1 block for each animal/color). Each block consisted of four within-hemifield trials and four between-hemifield trials, with trial order randomized in each block.

Before completing test trials, participants completed eight practice trials (cat, red; 4 trials with only 1 pair of dots, and 4 trials with 2 pairs of dots). During practice, participants were given feedback on their performance from the experimenter. Specifically, children were told to maintain fixation throughout the trials and were instructed on how to determine if their responses were accurate (i.e., animals smile = correct or looked surprised = incorrect). There was no criterion for success during practice trials; however, performance (percent correct) during practice trials was high across age groups (6-year-olds, M = 76.0%; 7-year-olds, M = 82.6%; 8-year-olds, M = 92.6%; adults M = 89.9%).

A video of an example trial can be found at https://osf.io/8xtpn/.

Results

Comparisons against chance. To examine whether participants could successfully track two targets using multifocal attention, we computed the percentage of trials in which participants correctly selected the target. We then compared each age group's (6-year-olds, 7-year-olds, 8-year-olds, and adults) performance to chance level (50%) using two-tailed one-sample t tests (to correct for multiple comparisons, α = .013). We also used Bayes factor analysis (Rouder, Speckman, Sun, Morey, & Iverson, 2009), which allowed us to obtain the odds in favor of the alternative over the null hypothesis. Bayes factors between 1 and 3 are considered "anecdotal" evidence, 3 and 10 are considered "moderate" evidence, between 10 and 100 are considered "strong" evidence, and greater than 100 are considered "decisive" evidence for the alternative over the null hypothesis (Jeffreys, 1961; Lee & Wagenmakers, 2013; Ly, Verhagen, & Wagenmakers, 2016). These analyses were conducted using the Jeffreys-Zellner-Siow prior as suggested by Rouder et al., 2009. Results are summarized in Table 1. All participants, regardless of age, performed at above-chance levels.

Examining subset tracking strategies. Chance performance of 50% is expected only if participants fail to track each of the two targets. Participants can achieve performance above 50% by strategically tracking only one of the objects. In Experiment 1, if participants reliably tracked only one of the objects (which would not require multifocal attention), they would be expected to select the target object correctly on the trials in which that object was part of the cued pair, and to choose randomly when the other pair was cued. If participants used this strategy and identified the target they strategically tracked 100% of the time (an unlikely but conservative assumption for assessing the ability to track multiple targets; see Trick et al., 2005, for similar logic), chance would be given by (100% × .5) + (50% × .5) = 75%. To investigate the possibility that participants were using this focal attention strategy, we conducted an exploratory analysis comparing participants' percent correct to 75% using one-sampled t tests for each age group. The results are summarized in Table 2. We found that 6-year-olds' performance was not reliably different from the 75% chance level, with Bayes factor analysis offering moderate support for the null

Table 1

Results of Two-Tailed One-Sample t-Tests Comparing 6- (n = 25), 7- (n = 23), and 8-Year-Old (n = 22) Children's and Adults' (n = 21) Mean Proportion Correct Responses to Chance (50%)

Age group	M % correct	t	Cohen's d	JZS BF_{10}
6-year-olds	71.67	6.93	1.39	52,631
7-year-olds	83.70	9.89	2.06	9,748,488
8-year-olds	88.83	17.51	3.73	159,803,122,553
Adults	91.07	17.04	3.72	39,317,449,083

Note. Jeffreys-Zellner-Siow (JZS) Bayes factors (BF) show the odds of the alternative hypothesis (that participants' mean proportion correct responses are different than would be expected by chance) over the null hypothesis. All $ps < .001$.

Table 2
Results of Two-Tailed One-Sample t-Tests Comparing 6-, 7-, and 8-Year-Old Children's and Adults' Mean Proportion Correct Responses to What Would Be Expected by Chance if Participants Were Only Reliably Tracking One of the Two Objects (75%)

Age group	t	p	Cohen's d	JZS BF_{10}
6-year-olds	−1.06	.297	.21	0.26
7-year-olds	2.55	.018	.53	2.54
8-year-olds	6.24	<.001	1.33	6,452
Adults	6.67	<.001	1.45	12,500

Note. Jeffreys-Zellner-Siow (JZS) Bayes factors (BF) show the odds of the alternative hypothesis (that participants' mean proportion correct responses are different than would be expected by chance) over the null hypothesis. to correct for multiple comparisons, alpha = .013.

hypothesis. Seven-year-olds' performance fell just short of our strict criterion for statistical significance, with Bayes factor analysis offering anecdotal support for the alternative hypothesis. Both 8-year-olds' and adults' performance was significantly above 75%, with Bayes factor analysis indicating decisive odds in favor of the alternative hypothesis. Note that this exploratory analysis does not necessarily show that 6-year-olds were strategically tracking only a single object. It is also possible that 6-year-olds always used multifocal attention to track both targets, but did so inefficiently, resulting in performance that is indistinguishable from strategically tracking only one target. For example, 6-year-olds may have reliably tracked two objects on some trials, but strayed their attention and thus lost track of targets on others. Thus, 6-year-olds' performance may be consistent with both multifocal and single-focal attention strategies.

Comparisons across age. We next examined whether participants' tracking performance varied as a function of age. In order to fairly compare performance across age groups, we first removed participants who did not perform above 60%. We reasoned that these participants may not have been engaged in the task, since their performance was close to the 50% chance level, and therefore were not likely to have been engaging in MOT. Since we were interested in how multifocal attention changes with development, we opted to include only those participants who showed evidence of engaging in the task. This resulted in the removal of five 6-year-olds, three 7-year-olds, and one adult. Using our final sample of 82 participants, we ran a one-way ANOVA with age group as a factor, and found a significant effect of age group, $F(3, 78) = 8.595$, $p < .001$; $\eta_p^2 = .248$. Bonferroni comparisons revealed that 7-year-olds ($p = .005$), 8-year-olds ($p = .003$), and adults ($p < .001$) performed significantly better than 6-year-olds; no other comparisons were significant (Figure 2). These analyses did not change if participants who performed close to chance were included (we observed a significant main effect of age group $F(3, 87) = 9.394$, $p < .001$; $\eta_p^2 = .245$; Bonferroni comparisons revealed that 7-year-olds ($p = .019$), 8-year-olds ($p < .001$), and adults ($p < .001$) performed better than 6-year-olds).

Hemifield independence: Crossover costs. To examine whether the movement of the dot pairs within or between hemifields impacted performance, we again looked at only those participants who showed evidence of engaging in the task, and ran a 2 × 4 mixed factors ANOVA with movement type (between hemifield or within hemifield) as a within-subjects factor and age group (6-year-olds, 7-year-olds, 8-year-olds, and adults) as a between-subjects factor. We did not observe a main effect of movement type, $F(1, 78) = .873$, $p = .353$; $\eta_p^2 = .011$ nor a Movement Type × Age Group interaction, $F(3, 78) = .268$, $p = .848$; $\eta_p^2 = .010$. There was a main effect of age, $F(3, 78) = 8.595$, $p < .001$; $\eta_p^2 = .248$, again with 7-year-olds, 8-year-olds, and adults outperforming 6-year-olds overall. Figure 2 shows mean percent correct across ages for within and between hemifield trials. These analyses did not change if participants who performed close to chance were included (we observed a main effect of age, $F(3, 78) = 9.395$, $p < .001$; $\eta_p^2 = .245$, no main effect of movement type, $F(1, 87) = .743$, $p = .391$; $\eta_p^2 = .008$, and no Movement Type × Age Group interaction, $F(3, 87) = .555$, $p = .646$; $\eta_p^2 = .019$).

Performance across trials. To examine whether participants' performance was impacted by repeated exposure to the test trials, we conducted a series of exploratory logistic regressions on participants' responses on each trial (one for each age group), with participant ID (covariate) and Trial (1–24) as predictors. We found a significant effect of trial for 6-year-olds ($p = .005$; odds ratio [OR] = .95; 95% CI [.92, .99]): participants' performance decreased as they completed more trials. No other age groups had significant trial-related effects (7-year-olds: $p = .08$; $OR = 1.04$; 95% CI [1.00, 1.09]; 8-year-olds: $p = .16$; $OR = 1.03$; 95% CI [.99, 1.07]; adults: $p = .40$; $OR = 1.02$; 95% CI [.97, 1.08]).

Discussion

In Experiment 1, we examined whether children could track multiple objects using multifocal attention. We designed a new child-friendly MOT task in which target and distractor pairs were yoked, with the goal of making tracking both targets using single-focal strategies difficult (e.g., Yantis, 1992). Our results partially suggest that by age 7 children are able to successfully track two objects during a task meant to elicit multifocal attention, suggesting that by 7 years children are able to engage in multifocal

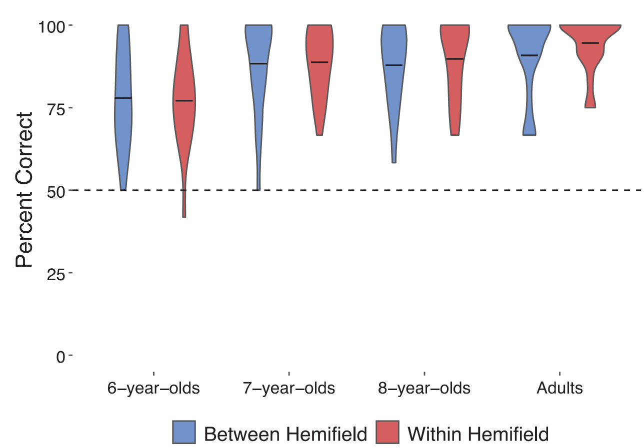

Figure 2. Violin plots of the mean proportion correct across all trials for 6- ($n = 20$), 7- ($n = 20$), and 8-year-olds ($n = 22$) and adults ($n = 20$). Dashed line represents chance level. See the online article for the color version of this figure.

attention to track objects. Further, our results suggest that the ability to engage in multifocal attention may undergo development between 6 and 8 years of age. Results from 6-year-olds were somewhat more equivocal; 6-year-olds' tracking performance was reliably greater than 50%, suggesting that they were not simply guessing. However, their performance was consistent with both multifocal and focal attentional strategies, making it difficult to determine whether these children were in fact engaging in multifocal attention.

We did not observe any hemifield-specific tracking deficits at any of the age groups investigated, including adults, contrary to previous research (Minami et al., 2019; Strong & Alvarez, 2019). However, our task was designed for children, so both the rotational (225°/s) and crossover (45°/s) speeds were slower than in previous adult studies, which averaged 371°/s rotational speed and 208°/s degrees/second crossover speed (Strong & Alvarez, 2019). It is possible that hemifield crossover effects are modulated by the difficulty of the tracking task, and that the differences in speed may have contributed to the lack of difference observed for within versus between hemifield movement in our study. However, we are not aware of any previous work that has looked at the impact of object speed on hemifield crossover effects. Additionally, our experiment included fewer trials than previous assessments of between-hemifield crossover costs (a necessity due to having children as participants), resulting in lower statistical power than is typical to detect a cost for tracking targets that move between the hemifields. Further work is needed to examine these possibilities.

In Experiment 1, children were tasked with tracking two targets among two distractors. In Experiment 2, we sought to examine the capacity of multifocal attention and how capacity estimates may change across development. We had children and adults complete a MOT task that was similar to the task used in Experiment 1, except we manipulated the number of targets (1–4) children were required to track, allowing us to examine how tracking performance varies as a function of the number of targets. We predicted that tracking performance should approach chance as the number of targets approaches children's tracking capacities.

Unlike in Experiment 1, in Experiment 2 target/distractor pairs only rotated in their original locations, and did not move between or within hemifields. Instead, we explored another signature of hemifield independence in multifocal attention: the bilateral field advantage. The bilateral field advantage differs from crossover effects in that information is not exchanged between the visual hemifields (Alvarez & Cavanagh, 2005; Strong & Alvarez, 2019). Instead, previous work with adults found that adults' tracking capacities increased when objects were presented in separate visual hemifields, suggesting that each hemifield may have its own capacity limits (e.g., Alvarez & Cavanagh, 2005). We asked whether children also show a bilateral field advantage when tracking multiple objects during a task designed to elicit multifocal attention, and whether this changes with development, by including two 2-target blocks, one in which the targets were presented in separate hemifields (bilateral trials) and one in which the targets were presented in the same hemifield (unilateral trials).

Experiment 2

Method

Participants. Our target sample was 80 participants (60 children and 20 adults), sufficient to detect an interaction between age group (4 levels) and hemifield presentation type (2 levels; see Experiment 1). A separate power analysis with a moderate effect size ($f = .25$; power $= .95$) to detect a potential set size (4 levels) by age (4 levels) interaction effect using a mixed factors ANOVA suggested a sample of $n = 52$, suggesting sufficient power to potentially detect developmental change in capacity (Faul, Erdfelder, Buchner, & Lang, 2009). Data were collected at four different locations (Boston University, Harvard University, Children's Museum and Theater of Maine, and Connecticut Science Center). Due to the nature of testing in museums, we exceeded our target sample, with 69 children (twenty-seven 6-year-olds, $M = 6.37$, $SD = .27$, 9 girls; twenty-two 7-year-olds, $M = 7.31$, $SD = .28$, 6 girls; and twenty 8-year-olds, $M = 8.52$, $SD = .31$, 9 girls) and 20 adults ($M = 22.35$, $SD = 6.90$, 18 women) participating. Of the 69 children who participated, 23 were tested at Boston University, nine at the Children's Museum and Theater of Maine, and 37 at the Connecticut Science Center. Of the 20 adults who participated, 18 were tested at Boston University and two at Harvard University. Overall performance did not differ between participants run in the lab compared to in the museums, $t(67) = .565$, $p = .574$; adults were excluded from location comparison since all completed the task within a lab setting. Since Experiment 1 suggested that even children in our youngest age group could do the task at rates above guessing level, we excluded any participants whose performance fell below 60% on one or two target trials to ensure that participants were attending to the task and likely engaging in multifocal attention. Three additional children were excluded based on this criterion (two 6-year-olds, and one 7-year-old). One additional child participated but was excluded because of a computer malfunction. This study was preregistered (https://osf.io/8xtpn/).

Stimuli. Stimuli were similar to Experiment 1, with several important differences. First, dot pairs were always presented within all four quadrants of the screen. Second, these dot pairs always remained within their original quadrants for the entire trial (rather than shifting between quadrants as in Experiment 1), where they rotated for 4,000 ms. Finally, five animal cartoon images (monkey, dog, bunny, hippo, and bear) and five different colors of dots (yellow, white, orange, purple, and gold) were used.

Procedure. The procedure used in this study was approved by Boston University's IRB under the protocol number 3594E and title, "Development of Working Memory for Objects in Social and Nonsocial Contexts." As in Experiment 1, participants were told that they were going to play a game in which the goal was to feed an animal (monkey, dog, bunny, hippo, bear; presented at fixation) its favorite food (targets; bananas/yellow, bones/white, carrots/orange, grapes/purple, and honey/gold, respectively). Also as in Experiment 1, targets briefly flashed at the start of each trial, and participants were tasked with tracking the targets among distractors while fixating the animal at the center of the screen. However, unlike in Experiment 1, on each trial participants were presented with four orbiting pairs of dots (one in each quadrant) which remained in each quadrant for the duration of the trial. The original spin direction (clockwise or counterclockwise) was randomly selected separately for each dot pair. On each frame, each dot pair had a 1/75 chance of changing spin direction, with the restriction that the dots must rotate in the same direction for at least 50 frames (833 ms) before changing direction. Additionally, rather than requiring participants to always track two targets, we manipulated the number of targets present on each trial (see Figure 3).

Participants were presented with five blocks of eight trials each, for a total of 40 test trials. The number of targets (1–4) and distractors (4–7) varied between blocks (1 Set Size 1 block with 1 target/7 distractors, 2 Set Size 2 blocks with 2 targets/6 distractors, 1 Set Size 3 block with 3 targets/5 distractors, and 1 Set Size 4 block with 4 targets/4 distractors). One of the Set Size 2 blocks consisted of unilateral trials, in which the pairs containing targets occupied quadrants within the same hemifield. The other Set Size 2 block consisted of bilateral trials, in which the pairs containing targets occupied quadrants in opposite hemifields (Figure 3). We opted to manipulate whether targets were tracked unilaterally or bilaterally only for Set Size 2, since this allowed us to keep the number of target-distractor pairs consistent across set sizes without making the display more complex (by, e.g., increasing the number of target-distractor pairs in each visual hemifield). All blocks were presented in Williams design order (size = 5; Williams, 1949). This design uses Latin squares (i.e., condition orders do not appear twice in a matrix row or column) and is balanced for carryover effects.

Before completing the test trials, participants first completed eight practice trials (2 for each block type; Set Size 2 trials were combined). During practice, block presentation was fixed in ascending order (1–4 targets). As in Experiment 1, participants were told to maintain fixation throughout the trials and were instructed on how to determine if their responses were accurate (if the animal character smiled or looked surprised). There was no criterion for success during practice trials, but practice performance (percent correct) was relatively high across age groups (6-year-olds, M = 74.1; 7-year-olds, M = 84.7; 8-year-olds, M = 90.1; adults M = 95.0).

Results

Comparisons against chance. For these analyses, we collapsed across Set Size 2 trials and compared each age group's

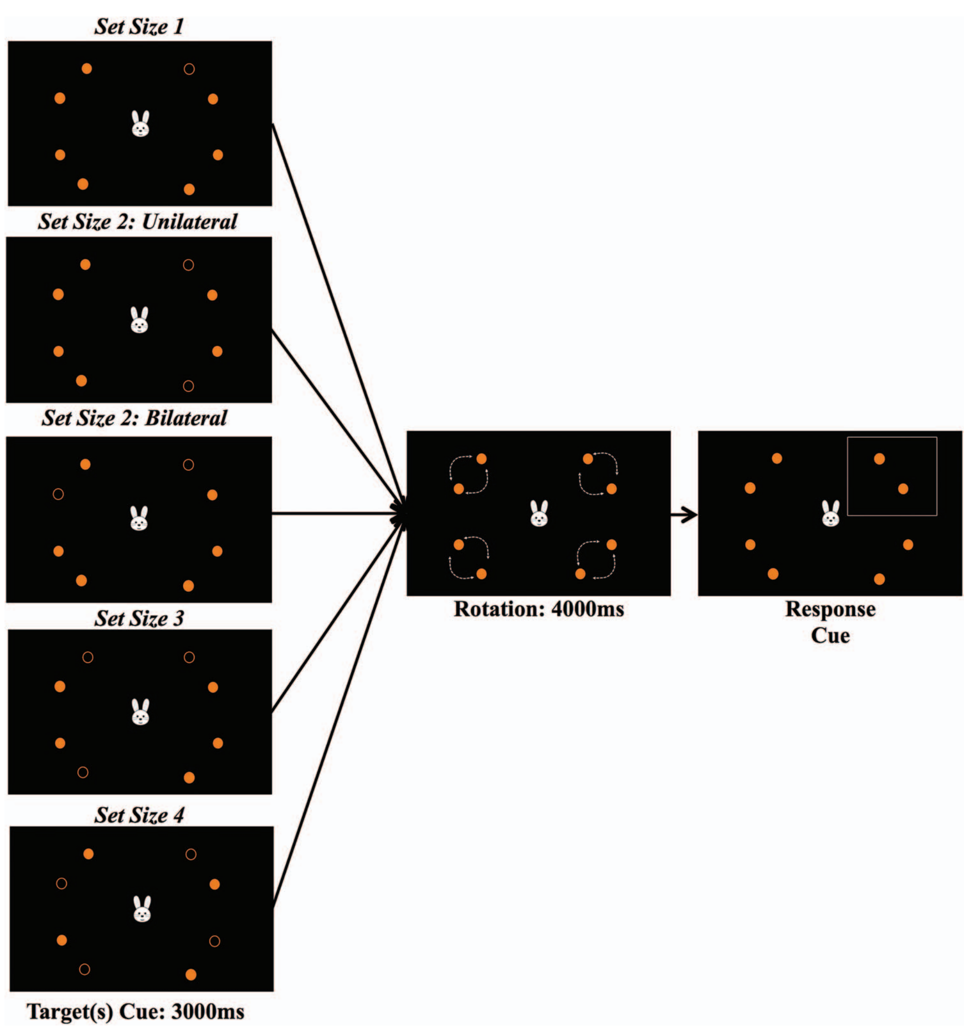

Figure 3. Time course of trials for Experiment 2. See the online article for the color version of this figure.

(6-year-olds, 7-year-olds, 8-year-olds, and adults) overall performance at each set size (1–4) to chance level (50%) with alpha set to .003 to correct for multiple comparisons. The results, summarized in Table 3, suggested that all participants could track up to four targets at rates significantly above chance (ps $<$.001). These analyses did not change if participants who performed poorly on one and two target trials were included (Table S2 in the online supplemental materials).

Examining subset tracking strategies. Chance performance was 50% for all set sizes (a single target-distractor pair was cued at the end of each trial), and performance close to 50% suggests that participants were guessing. However, performance above 50% at Set Size 2 or greater does not necessarily indicate that participants were tracking all target objects, but also could be consistent with participants strategically tracking only a subset of the targets. Therefore, as in Experiment 1, we conducted an exploratory analysis to investigate whether participants may have been using a subset-tracking strategy in Experiment 2.

However, unlike in Experiment 1, in which the chance computation assumed perfect tracking of the subset (100% correct), the design of Experiment 2 allowed us to instead use participants' own performance to compute what would be expected by chance under different subset-tracking strategies. For example, if a participant's performance was 90% correct for Set Size 1 trials, and they tracked only a single object on Set Size 2 trials, that participant could be expected to achieve 90% correct on the trials in which the tracked object was part of the cued pair, and 50% correct on trials in which the other pair was cued. For this participant, chance at Set Size 2 if the participant only tracked one target is given by (90% × .5) + (50% × .5) = 70%. For a participant who achieved only 80% correct on Set Size 1 trials, chance at Set Size 2 if the participant only tracked one object is given by (80% × .5) + (50% × .5) = 65%. Thus, for each participant, we calculated chance using their own performance at each set size as an estimate for how they would perform if they were tracking that number as a subset of a larger set. For Set Size 2 we calculated the expected performance if the participant were to track only a single object; for Set Size 3 we separately calculated the expected performance if the participant were to track either one target or two targets (using their performance at Set Sizes 1 and 2, respectively); and for Set Size 4 we separately calculated expected performance if the participant were to track one, two, or three targets (using their performance at Set Sizes 1, 2, and 3, respectively). This allowed us to compute a more realistic estimate of chance titrated to participants' actual tracking performance, rather than assuming perfect tracking of the subset. Table S1 in the online supplemental materials shows the formulas used to compute chance at each set size.

We used paired samples t tests to compare participants' actual performance to their titrated chance value for each subset strategy at each set size in each age group. To correct for multiple comparisons, alpha was set to .002. The results are summarized in Table 4. For Set Size 2, all participants performed better than would be expected if they were relying on focal attention (i.e., tracking only a single object), confirming that children as young as 6 can track two objects during a task designed to elicit multifocal attention, at least within the context of the parameters used in Experiment 2. For Set Size 3, 6- and 7-year-olds' performance was not different than what would be expected if they were tracking only a single object; that is, 6- and 7-year-olds' performance was consistent with both a multifocal and a focal attention strategy when they were tasked with tracking three objects. Eight-year-olds reliably tracked up to four objects at rates greater than chance for all subset strategies. However, adults' performance at Set Size 4 was consistent with a strategy of tracking only three of the objects (which should require multifocal attention). Note that this exploratory analysis cannot distinguish between strategies in which all objects were tracked and strategies in which only a subset of objects are tracked; rather, the analysis can provide insights into whether other tracking strategies could potentially yield the same performance. These analyses did not change if participants who performed poorly on one and two target trials were included (Table S3 in the online supplemental materials).

Comparisons across age. In order to examine age-related differences in tracking capacity, we ran a 4 (age: 6-year-olds, 7-year-olds, 8-year-olds, and adults) × 4 (set size: 1–4) mixed factors ANOVA on participants' percent correct responses. The assumption of sphericity was not met so a Greenhouse-Geisser correction was applied. We observed a main effect of set size ($F(2.49, 211.71) = 38.245$, $p < .001$; $\eta_p^2 = .310$) and a main effect of age ($F(3, 85) = 6.66$, $p < .001$; $\eta_p^2 = .190$), qualified by a significant Age × Set Size interaction ($F(7.47, 211.71) = 2.89$, $p = .005$; $\eta_p^2 = .09$; Figure 4). We followed up this interaction with one-way ANOVAs at each set size with age as a between-subjects factor. We observed no significant differences across age groups for Set Size 1, $F(3, 85) = 1.377$, $p = .255$, $\eta_p^2 = .05$, a small effect of age at Set Size 2, $F(3, 85) = 2.774$, $p = .046$, $\eta_p^2 = .09$, and significant effects of age at Set Size 3, $F(3, 85) = 7.103$, $p < .001$, $\eta_p^2 = .20$ and Set Size 4: ($F(3, 86) = 3.733$, $p = .014$, $\eta_p^2 = .12$), suggesting that improvement in tracking capacity with age was observed primarily at the larger set sizes (see Figure 4). These

Table 3
Mean Percent Correct and Results of Two-Tailed One-Sample t-Tests Comparing 6- (n = 27), 7- (n = 22), and 8-Year-Old (n = 20) Children's and Adults' (n = 20) Mean Percent Correct Responses for Set Sizes 1–4 Compared to a Chance Level of 50%

	6-year-olds			7-year-olds			8-year-olds			Adults		
Set size	M (%)	t	JZS BF_{10}	M (%)	t	JZS BF_{10}	M (%)	t	JZS BF_{10}	M (%)	t	JZS BF_{10}
1	93.5	30.87	$8.27 \times 10^{+18}$	96.5	27.70	$1.04 \times 10^{+15}$	94.3	22.99	$2.71 \times 10^{+12}$	97.5	32.05	$9.21 \times 10^{+14}$
2	86.6	17.58	$1.24 \times 10^{+13}$	89.1	14.73	6,516,356,054	93.4	25.84	$2.08 \times 10^{+13}$	94.3	23.69	$4.57 \times 10^{+12}$
3	70.8	6.24	14,925	80.0	6.72	17,241	86.2	10.64	7,515,406	92.3	18.14	45,892,611,289
4	72.6	5.65	3,521	70.4	4.47	143	85.5	9.95	2,675,728	84.2	10.15	3,629,764

Note. Jeffreys-Zellner-Siow (JZS) Bayes factors (BF) show the odds of the alternative hypothesis (that participants' mean percent correct responses are different than would be expected by chance) over the null hypothesis. All ps $< .001$.

Table 4
Results of Paired-Samples t-Test Comparisons Against Titrated Chance Values for Each Subset Strategy (Tracked 1 Object Only, Tracked 2 Objects Only, Tracked 3 Objects Only) in Experiment 2

	Tracked 1			Tracked 2			Tracked 3		
Set size	t	p	JZS BF_{10}	t	p	JZS BF_{10}	t	p	JZS BF_{10}
6-year-olds									
2	7.61	<.001	333,333						
3	1.92	.066	.79	−1.17	.252	.28			
4	3.05	.005	7.02	1.22	.235	.30	1.93	.064	.81
7-year-olds									
2	6.01	<.001	4,016						
3	3.26	.004	10.42	.76	.455	.22			
4	1.87	.075	.78	.098	.923	.16	−.393	.698	.18
8-year-olds									
2	15.21	<.001	2,381,292,565						
3	6.33	<.001	5,208	4.34	<.001	92.28			
4	16.54	<.001	9,640,412,609	24.22	<.001	$6.72 \times 10^{+12}$	10.26	<.001	4,265,301
Adults									
2	12.44	<.001	87,473,757						
3	10.75	<.001	8,734,387	5.07	<.001	420			
4	6.77	<.001	12,195	3.59	.002	19	.83	.41	.24

Note. JZS BF = Jeffreys-Zellner-Siow Bayes factors.

analyses did not change when participants who performed close to chance were included (we observed a main effect of *Set Size* ($F(2.56, 225.36) = 30.985$, $p < .001$; $\eta_p^2 = .260$), a main effect of age ($F(3, 88) = 8.79$, $p < .001$; $\eta_p^2 = .231$), and a significant Age × Set Size interaction ($F(7.68, 225.36) = 3.24$, $p = .002$; $\eta_p^2 = .10$), with follow-up one-way ANOVAs showing the same pattern of age-related differences for Set Sizes 2 ($p = .015$), 3 ($p < .001$), and 4 ($p < .001$).

Hemifield-independence: Bilateral field advantage. We asked whether we observed a bilateral field advantage in participants' performance on Set Size 2 trials. We ran a 2 (trial type: unilateral vs. bilateral) × 4 (age: 6-year-olds, 7-year-olds, 8-year-olds, and adults) mixed factors ANOVA on proportion correct for Set Size 2 trials. We observed a small but significant main effect of trial type, $F(1, 85) = 4.02$, $p = .048$; $\eta_p^2 = .045$, and no Trial Type × Age interaction, $F(3, 85) = .38$, $p = .769$; $\eta_p^2 = .013$; overall, participants performed better on bilateral than unilateral trials. There was also a small main effect of age, $F(3, 85) = 2.77$, $p = .046$; $\eta_p^2 = .089$; tracking two targets improved with age, regardless of trial type. When we included participants who performed poorly on one- and two-target trials, we did not observe a significant bilateral field advantage, $F(1, 88) = .75$, $p = .389$;

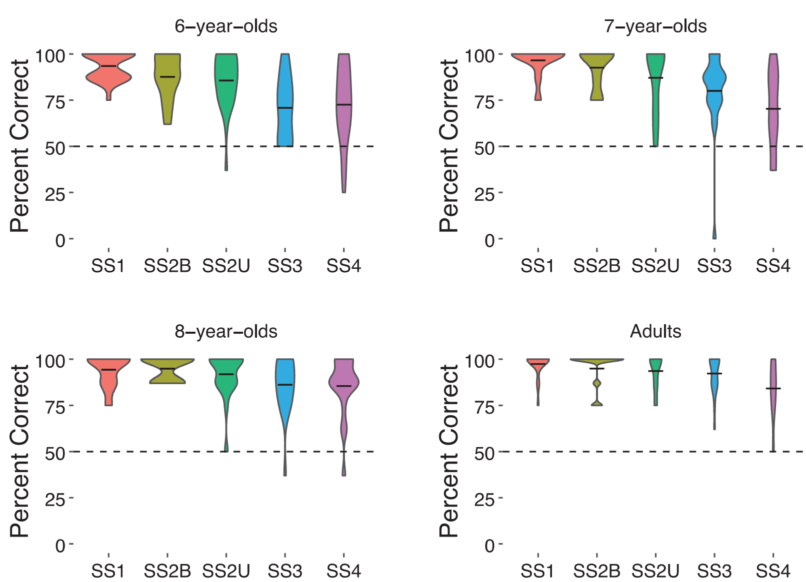

Figure 4. Violin plots of the mean proportion correct scores for set sizes 1–4 for 6-, 7-, and 8-year-olds and adults. SS = set size; SS2B = Set Size 2 bilateral; SS2U = Set Size 2 unilateral. See the online article for the color version of this figure.

η_p^2 = .008. Since these participants were unlikely to have been engaging multifocal attention during the task (and were completing the task near chance level), they would be unlikely to show this signature effect of multifocal attention. All other effects remained consistent; we did not find a Trial Type × Age interaction, $F(3, 88) = .77$, $p = .516$; $\eta_p^2 = .025$, but we did find a main effect of age, $F(3, 88) = 3.70$, $p = .015$; $\eta_p^2 = .112$; tracking two targets improved with age, regardless of trial type.

Performance across trials. We conducted a series of exploratory logistic regressions on participants' responses on each trial, one for each age group, with participant ID (covariate) and Trial (1–24) as predictors. We found a significant effect of trial for 6-year-olds on Set Size 1 ($p = .003$; $OR = .58$; 95% CI [.40, .83]); children's tracking performance decreased across the duration of the task. We also found a significant effect of trial for adults on Set Size 4 ($p = .02$; $OR = 1.29$; 95% CI [1.04, 1.61]); adults' performance improved across trials, but only for the largest set size. No other effects were significant. Results of all analyses can be found in the supplemental material (Table S4 in the online supplemental materials).

Discussion

In Experiment 2, we examined limitations in children's and adults' ability to track multiple moving objects via a task designed to elicit multifocal attention. For all age groups, as set size increased performance decreased. However, tracking performance also improved with age, with the largest gains in performance observed at the larger set sizes.

The majority of participants' tracking performance was reliably above 50% at all set sizes, suggesting that participants were not simply guessing but were engaged in the task. We conducted additional exploratory analyses to examine whether participants' tracking performance at each set size was consistent with tracking only a subset of the objects. These analyses suggested that all age groups could reliably track both objects at Set Size 2, suggesting that participants' likely deployed multifocal attention. This contrasts with 6-year-olds' performance in Experiment 1, in which their performance at Set Size 2 was consistent with both focal and multifocal attentional strategies. The primary difference between Experiments 1 and 2 was that, in Experiment 1, the objects moved to different quadrants, which may have made tracking more difficult for 6-year-olds. If children lost track of one of the objects, they may nevertheless have retained focal attention on one of the objects, consistent with adult MOT studies (e.g., Scholl & Pylyshyn, 1999). Additionally, we used a more conservative analysis approach to examine participants' strategies for tracking two objects in Experiment 1 (with chance set to 75%) compared to Experiment 2, which used each participant's Set Size 1 tracking to estimate tracking strategy. Thus, children in Experiment 1 may not have met our more conservative criteria for successful tracking of two objects. Only 8-year-olds' performance at all set sizes and adults' performance up to Set Size 3 ruled out a subset-tracking strategy; younger children's performance was consistent with a strategy of tracking one or two objects only.

It is important to note that the number of targets an observer can track depends on many parameters, including the speed at which targets move (Alvarez & Franconeri, 2007), the spacing between items (Franconeri, Jonathan, & Scimeca, 2010), how often targets change motion direction (Ericson & Beck, 2013), and the allocation of targets between the left and right hemifields (Alvarez & Cavanagh, 2005). Therefore, estimates of tracking capacity are specific to the design in which they are measured. In the present design, we attempted to select design parameters that both made tracking using multifocal attention the most effective strategy and made the task moderately challenging. It is possible that capacity estimates could change if the parameters of the task were varied. Nevertheless, our results provide potential evidence for developmental change in multifocal attention across our age range.

In an exploratory analysis, we found that 6-year-olds' performance decreased across Set Size 1 trials, suggesting that children may have lost interest in these easier trials as the task progressed. Adults appeared to display learning effects during Set Size 4 trials, such that their performance increased across trials. This effect suggests that adults may be able to improve their tracking performance, when taxed, with repeated exposure. Indeed, training effects have been found during MOT tasks in adults, but they appear to be task dependent (Strong & Alvarez, 2017).

We also investigated the potential of a bilateral field advantage in children. Across participants, performance was better for bilateral than unilateral trails, suggesting that children, like adults (Alvarez & Cavanagh, 2005), show evidence for a bilateral field advantage, a signature of hemifield independence. Implications for our understanding of the development of multifocal attention are discussed in the next section.

General Discussion

Across two experiments, we examined MOT via multifocal attention in 6–8-year-old children and adults. Our task required participants to simultaneously track moving targets that were presented among moving distractors. Critically, targets and distractors were presented in yoked pairs, with the goal of making strategies such as shifting gaze or shifting focal attention less effective, thus providing a more stringent test for multifocal attention (e.g., Minami et al., 2019; Strong & Alvarez, 2019; Yantis, 1992). Our results suggest that by 6 years of age children are able to engage in multifocal attention to track multiple moving objects (at least 2 objects in our task) when targets move within a limited range (as in Experiment 2). However, this ability develops significantly between 6 and 8 years, with the largest developmental gains observed as the number of targets increased. By 8 years of age, children could reliably track 4 objects in our task that was designed to elicit multifocal attention.

Furthermore, our results suggest that children are able to track a subset of objects when their tracking limits are exceeded. That is, when children are tasked with tracking more objects than they are able to track, children are not reduced to simply guessing. Instead, the results of our exploratory analyses suggest that children who lose targets may nevertheless be left with focal attention, which they can use to track a single object, consistent with previous work with adults (e.g., Scholl & Pylyshyn, 1999). Future work should investigate the conditions under which children are able to engage in multifocal attention by asking children to report all targets (Sperling & Melchner, 1978) and enforcing fixation via eye tracking.

Overall, our results are consistent with previous developmental research suggesting 8-year-olds outperform 6-year-olds on tracking tasks (Trick et al., 2005). However, unlike previous research, we found that older children could track more than two objects during a task designed to elicit multifocal attention. This finding is contradictory to Trick and colleagues (2005), who found that 8-year-olds could reliably track up to two moving targets. The different findings may be a result of the stimuli used in our task. Our targets were always paired with distractors to promote multifocal tracking, which may have benefitted performance in comparison to the random movement used in Trick and colleagues' (2005) experiment. Trick and colleagues also assumed perfect tracking for subset strategies, which resulted in a more conservative, but potentially less realistic tracking estimate. Our approach used participants' individual tracking abilities, allowing our subset estimates to be calibrated to each participants' tracking performance. Future research should attempt to examine the role of task demands on multifocal MOT capacity.

What could potentially drive the developmental change we observed? One possibility is that multifocal attention itself is developing. Younger children may exhibit greater variability in their ability to deploy multifocal attention effectively, potentially deploying attention over fewer targets or shifting between focal and multifocal strategies. Another possibility is that processes that support effective multifocal attention, rather than multifocal attention itself, may be developing during this time. For example, younger children may have had more difficulty maintaining fixation across repeated trials, which could have resulted in poorer performance overall. Future work would directly measure children's gaze during the task to investigate this possibility.

In addition to examining tracking capacity, we were also interested in another signature of multifocal attention in adults: hemifield independence. Previous adult studies suggest that the hemifields of vision may control separate sources of attention, evident through both crossover costs (Minami et al., 2019; Strong & Alvarez, 2019) and bilateral field advantage (Alvarez & Cavanagh, 2005). We did not find evidence for a crossover cost in Experiment 1, but we did observe a small bilateral field advantage in Experiment 2 across all ages. Our inconsistent findings may be a result of task differences within our experiments (e.g., movement beyond quadrant for crossover, which likely requires coordination between hemifields), or differences between our task and previously used adult tasks (e.g., movement speed, number of test trials, animals instead of fixation cross, etc.). Future studies should examine crossover costs altering task designs. Further, in our task the bilateral field advantage was evident only at the group level; additional studies are needed to verify hemifield independence in children.

Summary

We examined multifocal attention in children and adults. Our results suggest that children as young as 6 years show some evidence of the ability to engage in multifocal attention. By age 7, children reliably engage in multifocal attention during our task, and this ability continues to develop across middle childhood. Hemifield independence may be present by age 6, with 6–8 year-olds and adults demonstrating a bilateral field advantage for MOT via multifocal attention.

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