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Development of spatial biases in school-aged children

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Highlights

- Children in early elementary school grades have a significantly greater leftward spatial attention bias relative to children in upper grade levels and adults.
- Children's leftward spatial attention bias diminishes gradually with advancing grade level.
- The developmental trajectory of spatial bias is independent of gender and handedness.
- Among children in early elementary school grades, the degree of leftward spatial bias predicts performance on a rapid automatized naming (RAN) test, a predictor of reading ability.

Abstract

In the adult brain, biases in the allocation of spatial attention can be measured using a line bisection task and are directly relatable to neural attention signals in the fronto-parietal attention network. Behavioral studies on the development of spatial biases have yielded a host of inconsistent results, likely due to variance in sample size, definition of experimental groups, and motor confounds introduced by using a paper-and-pencil version of a line bisection task. Here, we used a perceptual, computerized version of this task and examined the development of spatial biases in 459 children from grades 1-8 and 61 college freshmen. We found that children in early elementary grades exerted a significant leftward bias that gradually diminished with advancing grade level. We further show that among children in early elementary school grades, the degree of leftward spatial bias predicted better performance on a rapid automatized naming (RAN) test, a predictor of reading ability. Significant leftward biases in early elementary school grades may be due to reading experience, thereby reflecting an interaction of the attention network with the evolving reading network.

Key words: line bisection task; cognitive development; visuo-spatial attention

Introduction

The selection of information from cluttered visual environments is one of the most fundamental cognitive operations and the foundation for functional higher cognition. Visuo-spatial attention refers to the ability to selectively process information from a specific location in visual space and to filter out unwanted distracter information from other nearby locations. Early research on visuo-spatial attention was largely shaped by findings from a clinical syndrome known as visuo-spatial hemineglect (Bisiach & Vallar, 1988; Heilman et al., 1987; Rafal, 1994). In the most extreme case of visuo-spatial hemineglect following lesions of right parietal cortex (or other network parts in the right hemisphere), patients display a spatial bias towards the ipsilesional (right) hemi-field that is so strong that the contralesional (left) hemi-field is entirely neglected. As a consequence, a neglect patient may eat only from one half of his/her plate or apply make-up to only one half of the face. Such spatial biases can be measured using a line bisection task. In the bedside version of this task, the subject is presented with horizontal lines and asked to bisect the lines in two equal parts. Patients suffering from visuo-spatial hemineglect underestimate the length of the left side of the line and bisect the line far to the right of the veridical center (e.g. Karnath, 1988).

Subsequent studies have demonstrated that spatial biases, albeit much milder, can also be observed in healthy individuals, who show a preference in directing attention to either the right or left visual hemifield (e.g., Szczepanski & Kastner, 2013). Interestingly, spatial biases measured with a line bisection task can be directly linked to the neural substrates of visuo-spatial attention control. In the adult brain, visuo-spatial attention function is controlled by a large-scale network that consists of multiple areas in frontal and parietal cortex (Kastner & Ungerleider, 2000; Corbetta & Shulman, 2002; Buschman & Kastner, 2015). Within the fronto-parietal attention network, each hemisphere generates attentional weights towards the contralateral visual hemi-field (Szczepanski, Konen, & Kastner, 2010). The attentional weights generated by the two hemispheres are in balance through reciprocal inhibition such that visuo-spatial attention can be allocated across the entire visual field (interhemispheric competition theory; Kinsbourne, 1977). Perturbation in the balance within the fronto-parietal attention network can result in biases in spatial attention. For example, in healthy adults, when the fronto-parietal areas in one hemisphere are perturbed by transcranial magnetic stimulation (TMS), spatial attention is temporarily biased toward the side ipsilateral to the TMS interference (Szczepanski & Kastner, 2013). As a result, the perceived midpoint of a bisected line will shift away from the veridical point into the ipsilateral space. Together, these studies provide a robust neural model of spatial attention control that can be linked to a simple behavioral measure, that is, line bisection.

Despite the extensive literature on visuo-spatial attention and the fronto-parietal attention network in adults, it remains unclear how the network develops across childhood to acquire adult-level visuo-spatial attention function (Kim & Kastner, 2019). For example, children with attention deficit/hyperactivity disorder (ADHD) that were not medicated had a visuo-spatial bias significantly rightward compared to controls and children with ADHD who were medicated (Sheppard, Bradshaw, Mattingley, & Lee, 1999). Children with dyslexia showed less of a leftward bias than age-matched controls (Sireteanu, Goertz, Bachert, & Wandert, 2005). However, many of the previous studies in pediatric populations either lacked a neurotypical control group or had small sample sizes that were not robust enough to characterize the neurotypical development of visuo-spatial attention biases. Thus, it remains unclear whether such visuo-spatial attention bias in ADHD or dyslexia populations is part of neurotypical development, or alternatively associated with the disorder. Converging evidence supports that the fronto-parietal network undergoes significant maturation in childhood and adolescence (e.g., Casey, Tottenham, Liston, & Durston, 2005). However, when and how the fronto-parietal network achieves an equilibrium in spatial attention control between left and right hemispheres across development is largely unknown.

In this study, we used a perceptual, computerized version of the line bisection task similar to the task used in Szczepanski and Kastner (2013) and often referred to as a landmark task. The perceptual version of the line bisection task has been shown to provide a robust measure of spatial attention bias (Milner et al., 1992; Bjoertomt et al., 2002; Bisiach et al, 1998). In our version, participants were presented with pre-bisected horizontal lines and asked to judge which side was shorter or longer by pressing buttons corresponding to the left or right. An important advantage of this version of the task is that, unlike manual line bisection tasks used in previous studies (Dellatolas, Coutin, & Agostini, 1996; Bradshaw et al., 1987; van Vugt et al., 2000; Hausmann et al., 2003; Chokron & De Agostini, 1995; Bowers & Heilman, 1980; Chokron & Imbert, 1993), it does not require hand-eye coordination. This avoids any confounds due to manual actions, which is even more critical for children who are still developing their motor skills through adolescence (Gidley Larson et al., 2007; Cole et al., 2008; Schenkenburg et al., 1980; Brodie and Pettigrew, 1995), and for clinical populations such as ADHD and dyslexia, who have a high rate of motor difficulties as co-morbidities (Kaplan et al., 1998; Suskauer et al., 2008). The developmental trajectory of spatial biases using a perceptual version of the line bisection task has not yet been explored.

In Experiment 1, we used the line bisection task as a behavioral measure of spatial biases generated by the fronto-parietal attention network to probe the development of spatial attention function in school-aged children from grades 1 through 8 (equivalent to ages 6 to 14) in comparison to young adults. Rather than dividing the groups by age, we defined groups based on their grade level in order to reflect the child's educational background. We found that children in early elementary grades have a significant leftward bias that gradually diminishes as they advance through school grades. In Experiment 2, we tested the hypothesis that the significant leftward bias observed in children of early elementary grades may be related to the acquisition of reading skills. As reading is first introduced during early elementary grades, the leftward spatial bias may reflect an interaction between the attention network and the emerging reading network. We tested the line bisection task and a rapid automatized naming (RAN) test, a predictor of current and future reading ability (for a review, see Siddaiah & Padakannaya, 2015) in an independent cohort of early elementary school children. We found that the degree of leftward bias predicted RAN performance. Our findings suggest that the acquisition of reading skills may influence the development of visuo-spatial attention function.

Methods

Participants: In Experiment 1, a total of 397 subjects (336 children in grades 1 to 8 and 61 college freshmen) gave informed consent (Table 1) to participate, which was approved by the Institutional Review Board (IRB) of Princeton University. Children were recruited from two venues: a local summer camp (n = 208) and a local school (n = 128; see Figure S5 for details). Adults (n = 61) were undergraduate freshmen at Princeton University. In Experiment 2, a total of 123 children in grades 1 to 3 gave informed consent to participate, which was also approved by Princeton University's IRB. Children were tested in 5 venues: two local summer camps (n = 63), two public libraries (n = 50), and in the laboratory (n = 10). All participants were native English speakers. Each participant's handedness, gender, and age were obtained in both Experiments 1 and 2.

Task design: To assess spatial attention bias in individual participants, we used a perceptual version of a line bisection task, also known as the landmark task (Milner et al., 1992; Bjoertomt et al., 2002; Bisiach et al, 1998), that was modified for use in pediatric populations (Szczepanski & Kastner, 2013). In adults, this perceptual task is a robust measure for the hemispheric balance of spatial attention control signals produced by the fronto-parietal attention network

(Szczepanski & Kastner, 2010). The task was administered on a laptop using MATLAB software (MathWorks) and Psychophysics Toolbox functions (Brainard, 1997).

Participants were seated 30 to 40 centimeters away from the laptop screen. On each trial, a bisected line was presented in the center of the display (see Figure 1). Each stimulus consisted of a horizontal line bisected by a short vertical line (roughly 2° visual angle in length). The horizontal line was presented in four different lengths (20, 21, 22, 23° visual angle) in random order. Each participant made a judgment based on the stimulus, as to whether one side of the bisected line was shorter or longer. Specifically, each participant was assigned to answer one of the following two questions based on each stimulus: "Which side is longer, right or left?" or "Which side is shorter, right or left?". Participants were instructed to make a response by pressing one of two buttons on the keyboard. They pressed the 'A' button on the keyboard with their left index finger to answer "left" and pressed the 'L' button with their right index finger to answer "right." We placed colored stickers on the 'A' and 'L' buttons and used color names to refer to the buttons (e.g., the blue button for "left" and the yellow button for "right") so that children could find the buttons easily on the keyboard. The use of hands for the two buttons was kept consistent across all participants in order to avoid confusion in using the right hand to answer "left" and the left hand to answer "right." Practice trials were provided at the start of testing. In order to avoid confusion, particularly with the pediatric population, the type of question remained the same throughout the entire session including practice trials. The type of question was counterbalanced across participants.

As shown in Figure 1, each trial started with a 1.5 s preparation period, in which participants maintained fixation at a smiley face in the middle of the screen. A pre-bisected line stimulus was then presented for 200 ms, followed by the presentation of a visual mask for 2 s. The stimulus duration was chosen to minimize the confounding effects of eye movements during display presentation. However, the stimulus duration was extended to 225-700 ms for 40 children, who were unable to perform the task with the short presentation time. We ruled out the possibility that the spatial bias measures in those children were systematically influenced by the extended stimulus duration by assessing the correlation between the stimulus presentation time and estimated spatial bias across all participants as well as the significance of stimulus duration as a variable in the statistical model (see Results). Participants indicated which side of the bisected line was longer (or shorter) by pressing a button on the keyboard. Each participant was asked to complete 4 blocks of the task. Each block consisted of 20 bisected horizontal lines for a total of 80 trials per participant. The task, including the practice trials, lasted roughly 10 minutes per participant.

The location of the bisecting vertical line was manipulated based on a staircase procedure. Each block began with a vertical bisecting line located 1° away to either the left or the right from the veridical midpoint of the horizontal line. The vertical bisecting line was shifted in a two-down, one-up manner. That is, each horizontal line was presented twice at a certain distance away from the veridical midpoint. If a participant responded correctly to both presentations of a stimulus with a certain offset, the vertical line was shifted closer to the veridical midpoint by setting the new offset to 80% of the previous offset. If the participant responded incorrectly, the vertical line was shifted away from the midpoint. Trials with bisecting vertical lines on the right and the left sides were randomly intermixed.

Estimating spatial bias: We estimated spatial attention bias in each participant by fitting a psychometric function and finding the point of subjective equality. Figure 2 illustrates this approach for two example participants. Trials from all four blocks were organized into bins based on the distance between the veridical midpoint and bisecting vertical line. In each participant, the proportion of the "the right side is shorter" response was calculated for each bin. The location of vertical lines was plotted on the x-axis (in degrees of visual angle) and the proportion of the participant's "right is shorter" response was plotted on the y-axis. A psychometric curve was estimated from each participant's data by using a general linear model with a logit link function [ln(pi/(1-pi) = β • Xi]. We used MATLAB's *glmfit* function, which received multiple inputs: the locations of the vertical line (x-value), the participant's "the right side is shorter" responses (y-value), and the total number of trials for each data point (weight). The function used a weighted fit because the number of trials was different for each vertical line offset due to the staircase procedures. Thus, the function gave more weight to data points with more trials (i.e. more reliable data points) and less weight to data points with fewer trials (i.e. less reliable data points). The point of subjective equality refers to the midpoint of the psychometric curve where the y-value is 0.5 (indicated by the blue solid line). The participant's leftward or rightward bias was determined based on the direction in which the x-value of the point of subjective equality deviated from the veridical midpoint, which is described as zero on the x-axis. The degree of the spatial attention bias was determined by the deviation from the veridical midpoint in degrees of visual angle, where a leftward spatial attention bias is described as a negative value (Figure 2A) and a rightward spatial attention bias a positive value (Figure 2B).

Data analyses: We used grade, instead of age, as our independent variable because grade is a better reflection of each child's educational background.

For Experiment 1, we identified outliers from each grade and the adult population. Outliers were defined within each grade distribution as any data points that fell three standard deviations outside of the mean. A total of four participants were identified as outliers from the pediatric population (number of outliers for each grade indicated in Table 2) and one participant was identified as an outlier from the adult population. Outliers were removed from subsequent analyses. For Experiment 2, two participants were excluded from analysis for failure to meet the criterion of achieving spatial biases within the range of three standard deviations from the mean of all subjects on the line bisection task.

We performed additional bootstrap hypothesis tests to compare the distributions of spatial attention biases and control for different sample sizes (e.g., when divided by handedness, gender, and grade level). We performed bootstrap tests using the following procedures (Efron & Tibshirani, 1993). First, we calculated t-statistics comparing the original distributions. Then, we removed the mean difference between the two groups and generated 10,000 bootstrap samples from each group. We obtained a null distribution of t-statistics from the bootstrap samples. We then calculated the p-value based on where the t-statistic obtained from the original samples is located in the null distribution.

To model the relationship between a participant's grade and his or her behavioral spatial attention bias measure in the pediatric population, a linear regression model was applied to the data. Spatial bias was the dependent variable and grade the independent variable. The independent variable was log transformed to model a gradual shift in spatial attention bias towards an asymptote of zero, or the veridical equality point. This was based on previous findings suggesting that adults have a spatial attention bias that is normally distributed around zero (Szczepanski & Kastner, 2013; Bio, Webb, & Graziano, 2018). T-test results of each grade coefficient for comparison with 0 were analyzed using the same fitted linear regression model to avoid multiple comparisons. Residuals from the model were examined to ensure that deviations between the actual data and model estimates were consistent. In addition, we performed another linear regression analysis, which included control variables describing the location where the data was acquired, stimulus duration, handedness, and gender, in addition to the same dependent and independent variables. This was done to control for possible variability induced by the variables.

We also examined the developmental trajectory using age as the independent variable. Participants of ages 6 to 13 were included in the analyses based on age while participants age 5 (1 child) and age 14 (5 children) were excluded due to the small sample sizes. Outliers were defined within each age group as spatial bias measures that fell three standard deviations outside of the mean.

Finally, we identified additional outliers based on the precision of line bisection judgments to ensure that less precise judgments did not affect the results. As a measure of the precision of line bisection judgments, we estimated the width of each participant's psychometric curve, which was measured by the difference between the vertical line offsets corresponding to the y-values of 0.25 and 0.5 (Figure S1). A control analysis was conducted after excluding additional outliers with curve widths exceeding three standard deviations from the mean.

Rapid Automatized Naming (RAN) test: In Experiment 2, each participant was administered a RAN test (Wolf & Denckla, 2005) in addition to the line bisection task. RAN has been shown to be a robust predictor of reading ability in children (for a review, see Siddaiah & Padakannaya, 2015). The test assesses the speed at which individuals can name visual stimuli (e.g., letters or numerical digits) presented in serial, left-to-right row order. This acts as a measure of reading ability by requiring participants to exercise many of the same processes involved in reading, including saccadic eye movements, left-to-right serial processing of visual information, and the rapid conversion of visual stimuli to a verbal output (Manis, Seidenberg, & Doi, 1999; Wimmer et al., 1998). Performance on the RAN test is a robust predictor of current and future reading ability in children (Siddaiah & Padakannaya, 2015) and is also predictive of children's performance on word- and pseudoword-reading tests (Warmington & Hulme, 2012).

The RAN test consisted of the RAN Letters and the RAN Numbers subtests designed by Wolf and Denckla (2005). Each subtest consists of a stimulus card containing 5 rows of 10 stimuli each. The Letters subtest uses letters as stimuli, and the Numbers subtest uses numerical digits as stimuli. During each subtest, the experimenter first pointed in random order to each of the items in a set of practice stimuli to ensure that participants were familiar with the stimuli that they would be exposed to during the test phase. During the test phase, participants were then instructed to name the stimuli on the stimulus card (5 rows of 10 stimuli each) as quickly as they could, in row order. Subjects were given raw scores based on the number of seconds they took to finish naming all the test stimuli. These raw scores were then adjusted for age and standardized to a mean of 100 and standard deviation of 15 by using scoring procedures given by Wolf and Denckla (2005), who normed the RAN subtests using a large, nationally representative sample of school-aged children in the United States. The average of the standard scores on each subtest was then taken to derive a single composite RAN score for each participant. The entire experiment, including the line bisection task, lasted approximately 20 minutes per child.

Results

Experiment 1 aimed to examine spatial attention bias in children from grades 1-8 (Table 1). Experiment 2 was intended to probe the relationship between the degree of spatial bias and performance on a rapid automatized naming (RAN) test, a predictor of reading ability. A perceptual version of a line bisection task was used in both Experiments 1 and 2. In this task, participants viewed bisected horizontal lines and indicated whether the bisected lines were shorter (or longer) to the left or right of a bisecting vertical line (Figure 1). The location of the bisecting vertical line was manipulated by using a staircase procedure such that a psychometric curve could be obtained from each participant's responses by fitting a logistic function with a range of 0 to 1. The participant's leftward or rightward bias was determined based on the direction in which the x-value of the point of subjective equality (y = 0.5) deviated from the veridical midpoint (x = 0). The deviation from the veridical midpoint in degrees of visual angle indicated the degree of spatial attention bias. Negative values of spatial bias indicate leftward bias (Figure 2A), positive values indicate rightward bias (Figure 2B), and zero, no spatial bias.

Distribution of spatial attention bias in school children and adults

In Experiment 1, we studied the developmental trajectory of spatial biases amongst the general population of school children. As a first step, we examined the overall distribution of spatial attention biases in school children in grades 1 to 8 and in the adult control group (college freshmen), excluding four outliers from the pediatric group and one outlier from the adult group (see Table 1 for demographics). One-sample t-tests against zero revealed that the children's spatial attention bias was skewed to the left of the veridical midpoint (M = -0.13°, SD = 0.29°; $t(331) = -8.28$, $p < 0.0001$). Adults also showed a leftward attention bias, albeit milder

(M = -0.087°, SD = 0.19°; $t(59) = -3.48$, $p < 0.001$). Adults' average leftward bias was numerically closer to zero than children's, although the distributions of spatial biases did not significantly differ between children and adults [$F(1, 390) = 1.29$, $p = 0.26$].

In order to investigate whether our measures of spatial attention biases were affected by handedness, we examined the distributions of spatial biases separately for right- and left-handed participants (Figure 3A and 3B). Among children, the spatial biases in right-handed participants (n = 299, M = -0.13°, SD = 0.3°) did not differ from left-handed participants (n = 32, M = -0.15°, SD = 0.18°) [$F(2, 329) = 0.11$, $p = 0.9$]. One ambidextrous child was not included in this analysis. Likewise, right-handed adult participants (n = 45, M = -0.092°, SD = 0.19°) showed a similar distribution of spatial biases as compared to left-handed participants (n = 15, M = -0.072°, SD = 0.21°) [$F(1, 58) = 0.084$, $p = 0.77$].

The distributions of spatial biases were also examined separately by gender (Figure 3C and 3D). Among children, the spatial biases in male participants (n = 165, M = -0.11°, SD = 0.35°) did not differ from female participants (n = 167, M = -0.15°, SD = 0.22°) [$F(1, 330) = 1.13$, $p = 0.28$]. Likewise, male adult participants (n = 19, M = -0.098°, SD = 0.19°) showed a similar distribution of spatial biases as compared to female participants (n = 41, -0.082°, SD = 0.2°) [$F(1, 58) = 0.084$, $p = 0.77$].

A series of bootstrap analyses confirmed that there were no significant differences in spatial bias between children and adults ($p = 0.15$), or by handedness amongst children ($p = 0.50$), handedness amongst adults ($p = 0.76$), gender amongst children ($p = 0.33$), and gender amongst adults ($p = 0.80$).

Developmental trajectory of spatial bias in school children

Next, we examined whether spatial biases changed, or remained relatively stable, as a function of grade by comparing spatial biases in younger children (grades 1 to 3; n = 122), older children (grades 6 to 8; n = 147), and adults (college freshmen; n = 60) (Figure 4). We found that leftward biases were most expressed in younger children (M = -0.2°), whereas the leftward spatial biases of older children were less expressed (M = -0.098°) and not different from those observed in adults (M = -0.087°). An ANOVA confirmed a main effect of Grade (grades 1-3 vs. grades 6-8 vs. adults), $F(2, 326) = 5.6$, $p = 0.004$. Tukey's HSD test revealed that the mean spatial biases differed between grades 1-3 and grades 6-8 (adjusted $p = 0.007$) and between grades 1-3 and adults (adjusted $p = 0.026$), but there was no difference in spatial bias between grades 6-8 and adults (adjusted $p = 0.97$). Thus, younger children (grades 1 to 3) showed greater leftward bias than older children (grades 6 to 8) and adults, while spatial biases of older children were similar to those of adults. Age-based analyses yielded similar results (Figure S2A). There was a main effect of Age (ages 6-8 vs. ages 11-13 vs. adults, $F(2, 310) = 5.0$, $p = 0.007$). And younger children (ages 6-8) showed greater leftward biases compared to older children (ages 11-13; adjusted $p = 0.01$) and adults (adjusted $p = 0.04$).

Given that younger children showed a prominent leftward bias that was decreased in older children and adults, we hypothesized that the leftward bias in grades 1 to 3 gradually decreased towards a normal distribution around 0, typically observed in adults (Sczcepanski & Kastner, 2013) and indicative of a more balanced spatial attention system. In addition, since the older children's spatial bias was similar to that of the adults, it is possible that spatial bias reaches adult-level before grade 8. In order to test for a grade-related change in spatial bias, we used a linear regression model with a log-transformed independent variable (i.e., grade) that takes into account a possible asymptote in the grade-related trend.

As shown in Figure 5, the linear regression model demonstrated that the log-transformed independent variable grade had a significant relationship with the dependent variable spatial bias ($F = 17.88$, $p < 0.0001$, multiple $R^2 = 0.05$, adjusted $R^2 = 0.05$). That is, there was a more prominent leftward bias in children in grades 1 to 3 in comparison to children in older grades, and the estimate of the spatial bias approached zero as children get older. Additionally, we obtained a model estimate for each grade and determined how the estimated spatial bias was different from zero (Table 2). These results from the regression model were consistent with our previous observations from the comparison among younger children, older children, and adults. We further demonstrated that a linear regression with log-transformed age as the independent variable (instead of grade) revealed a developmental trajectory of spatial biases that is consistent with the analyses based on the grade ($F = 14.7$, $p < 0.001$, multiple $R^2 = 0.04$, adjusted $R^2 = 0.04$; Figure S2B). A model estimate and a t-statistic comparing the model estimate to zero were also calculated for each age (Table S1).

One may ask whether the large variance among younger children may have driven the significance of the regression model by introducing greater leftward bias measures in younger grades relative to older grades. To address this issue, we probed whether the residuals (deviations between actual data points and estimated values) were particularly larger for younger grades that presented an overall greater leftward bias. We found that residuals from the regression model were not particularly greater for younger grades than older grades, except for five outliers (Figure S3). We confirmed that the developmental trajectory of spatial biases across grades remained the same, even when the outliers were excluded from the regression model such that residuals were consistent across different bias measures ($F = 34.73$, $p < 0.0001$, multiple $R^2 = 0.1$, adjusted $R^2 = 0.1$). The consistency in the residuals across model-estimated bias values for all grades indicates that the larger variance among younger children does not drive model estimates to be greater leftward biases.

Finally, we examined the distributions of spatial biases in each grade. Because each grade had a different number of participants, we obtained a distribution of bootstrapped sampling means (5000 iterations) and a 95% confidence interval for each grade (Figure S4). The estimated distribution was shifted to the left of zero in all grades and adults, confirming the leftward bias in school children and adults, except the distribution in grade 4, which was only marginally different from zero. Based on the confidence intervals across grades, the distributions of spatial biases indeed trended closer to zero in higher grades and became more similar to the adult group.

Control analyses

For Experiment 1, the children's data were collected in two different locations outside the laboratory, a summer camp and a school. We checked whether the experiment venues affected data distributions (Figure S5). The table in Figure S5 contains the number of participants that were recruited in each location by grade. We compared spatial bias measures in children of grades 2, 3, and 7 because the number of participants from each location was comparable for those grades. We found that the distributions of the data did not differ depending on whether they were acquired in the camp or the school (Mann-Whitney-Wilcoxon Test; W = 2063, p = 0.23).

As mentioned in the Methods section, the stimulus presentation time was adjusted to be longer (225-700 ms) for a total of 40 children in grade 1 (n = 9), grade 2 (n = 18), grade 3 (n = 5), grade 4 (n = 3), grade 5 (n = 2), and grade 6 (n = 3). These children were not able to perform the task with our standard presentation time of 200 ms. There was no significant correlation between the stimulus presentation time and estimated spatial bias across all participants (Pearson's $r = -0.09$, $p = 0.1$).

In order to verify that handedness, gender, location of data acquisition, and stimulus duration did not significantly predict spatial bias, those measures were added to a linear model with grade as a log-transformed independent variable and spatial bias as the dependent variable ($F = 3.2$, $p < 0.001$, multiple $R^2 = 0.06$, adjusted $R^2 = 0.04$). Only grade significantly predicted spatial bias ($p < 0.001$). Handedness, gender, location of data acquisition, and stimulus duration did not significantly predict spatial bias. Thus, grade was the only variable that significantly predicted spatial bias.

Lastly, we examined the linear regression model with an additional exclusion of outliers based on curve width in order to ensure that differences in the precision of line bisection judgments across different grade levels did not drive the results. We identified 2 additional outliers from the pediatric group based on the curve width estimations (> 3 SDs), which served as a measure of the precision of line bisection judgments. No additional outliers were identified from the adult group. Even after excluding these additional outliers, the results from the linear regression model with grade as a log-transformed independent variable and spatial bias as the dependent variable remained consistent ($F = 24.6$, $p < 0.0001$, multiple $R^2 = 0.07$, adjusted $R^2 = 0.07$).

Relationship between spatial bias and reading skills in children

In Experiment 1, we found that the significant leftward bias in early elementary grades gradually and significantly attenuated with advancing grade. This led to the question of whether the significant developmental correlation between spatial bias and advancing grade can be attributable to learning a new cognitive task during early elementary school years: reading. The leftward spatial bias may reflect the experience of learning to read a left-to-right language like English. If the leftward spatial bias in early elementary school children is related to the acquisition of reading skills, we hypothesized that the degree of leftward bias may correlate with individual reading ability. Therefore, in Experiment 2, we tested the line bisection task in an independent sample of elementary school children attending grades 1-3 and measured their performance on a rapid automatized naming (RAN) test, a predictor of reading ability. We hypothesized that the degree of leftward spatial bias in early elementary grades might predict performance on the RAN test.

First, we examined the distribution of spatial biases, as measured in the line bisection task. We found an overall leftward distribution of spatial attention biases amongst children in grades 1 to

3 (n = 121) as shown in Figure 6A [M = -0.182°, SD = 0.311°; $t(120) = -6.45$, $p < 0.0001$], thereby replicating the significant leftward biases in grades 1 to 3 found in Experiment 1 with this independent sample (Mann-Whitney-Wilcoxon Test; $p = 0.73$). Second, we examined the distribution of RAN scores in this group of children. Figure 6B displays the children's composite RAN scores, which were standardized for age with a mean of 100 and standard deviation of 15. The average RAN score of our sample [M = 104.2, SD = 13.3] was close to the national average (i.e., 100), and the scores ranged from 74 to 139.5, which would be evaluated to be 'poor' to 'very superior' based on the score cutoffs (Wolf & Denckla, 2005). In order to investigate the relationship between spatial biases and performance on the RAN test, we conducted a regression analysis using spatial bias to predict composite RAN scores, while controlling for grade, handedness, testing location, and gender. We found that spatial bias significantly predicted the composite RAN score [$F(9, 111) = 1.971$, $p = 0.0087$, *multiple R2* = 0.138, *adjusted R2* = 0.068] (Figure 6C). Thus, as hypothesized, the degree of leftward spatial bias in early elementary grades was predictive of children's performance on our reading measure.

Discussion

The current study examined the development of spatial attention biases in school children by using a perceptual, computerized line bisection task. We found that children in early elementary grades showed a greater leftward bias that gradually diminished with advancing grade level. In contrast, the distribution of spatial biases among children in middle school was not different from that of adults. The developmental trajectory was gradual and started with a significant leftward bias in first graders that incrementally diminished with increasing grade, independent of gender or handedness. We hypothesized that the significant leftward bias observed in early elementary school children reflects an interaction of attention function and first reading experience. In order to test this idea, we recruited an independent sample of children attending early elementary grades and measured their spatial biases as well as their performance on a rapid automatized naming (RAN) test, a predictor of current and future reading ability. We replicated the leftward spatial bias in this independent study sample and further showed that the degree of leftward bias predicted better performance on the RAN test. These results suggest an interaction between visuo-spatial attention function and the acquisition of reading skills; leftward spatial biases may reflect the experience of novice readers to scan text from left-to-right in the English language, thereby generating a stronger bias towards left-hand space. As children gain reading expertise, spatial biases may return to an equilibrium and a more even distribution, reflecting balanced attentional control across visual hemifields.

Our findings on behavioral spatial biases have implications for the development of the underlying neural mechanisms. In adults, neural attentional weights in the fronto-parietal network predict the behavioral spatial attention bias of an individual, as measured in the line bisection task (Szczepanski & Kastner, 2013). For example, if an individual has a leftward spatial bias, there are greater attentional weights produced by the right hemisphere, which controls spatial attention control in the left hemifield, than by the left hemisphere, which controls spatial attention in the right hemifield. Based on previous studies conducted in adults, we hypothesize that the right hemisphere produces greater attentional weights than the left hemisphere in younger children, thereby exerting greater control over the left than the right hemifield and resulting in greater leftward bias. As children get older, the attention network may achieve a better equilibrium such that the attentional weights produced by the two hemispheres become more similar and thereby control visual space in a more balanced fashion. It will be an exciting future direction to test this neural attention model across development.

Our results on the relationship between leftward bias and better performance on the RAN test in early elementary grades suggest an interaction of attention and reading functions. Specifically, learning the left-to-right scanning direction in English may shape the attentional control system of children in lower grade levels so that the left side is prioritized over the right side of visual space. Considering that more leftward biases predict better RAN scores, children may develop these leftward attention biases because these biases offer a perceptual advantage that facilitate the repetitive, left-to-right shifting of attention involved in reading. Then, as children gain reading expertise, this leftward spatial attention bias may become less useful in facilitating reading and thus gradually diminish.

If our interpretation of the relationship between leftward biases and reading is correct, we predict that children learning to read from right to left (e.g., Hebrew, Arabic) will show opposite, that is, rightward attention biases. Indeed, Chokron and colleagues (1995) found that Israeli children of age 4.5 and 8 years had greater rightward biases, compared to French children of the same ages who appeared to have rightward biases yet to a lesser degree. However, this study used a paper-and-pencil version of the line bisection task and could not rule out the confounding effect of handedness and other motor-related issues. Therefore, it remains an open question whether spatial attention biases are initially shaped by the experience of reading direction. Future studies involving pediatric populations from cultures with reading conventions different from the English language will be necessary to explore this important issue further.

The dorsal visual stream plays an important role in visuo-spatial attention (e.g., Buschman & Kastner, 2015; Fiebelkorn & Kastner, 2020), and has also been linked to reading development. For example, it has been found that dorsal visual stream functioning measured by frequency doubling sensitivity can be predictive of early reading skills in first graders. The frequency doubling stimulus involves the counterphase presentation of two low spatial frequency gratings that appear to have twice the spatial frequency when flickered rapidly (Kevan & Pammer, 2009). Previous research indicates that dyslexic participants are significantly less sensitive to the stimulus than controls (Buchholz & McKone, 2004; Pammer & Wheatley, 2001). These and other findings have led to proposals that have linked reading ability to attentional mechanisms controlled by the dorsal visual stream (Franceschini et al., 2012; Livingstone et al., 1991; Vidyasagar & Pammer, 2010; Stein & Walsh, 1997). The idea that visuo-spatial attention and reading function influence each other during development is also reflected in the estimated 25-40% bidirectional comorbidity between ADHD and dyslexia (Willcutt & Pennington, 2000; Bental & Tirosh, 2007). Indeed, a longitudinal study demonstrated that poor performance on visuo-spatial attention tasks in pre-readers predicts later reading deficits, providing compelling evidence for the causal role of attention in the acquisition of reading skills (Franceschini, Gori, Ruffino, Pedrolli, & Facoetti, 2012).

If reading experience shapes spatial attention biases in early elementary school grades, as suggested by our findings, it adds a new angle to the current literature on the relationship between attention and reading. Our results offer a hypothesis opposite to the prevailing focus in the literature that visuo-spatial attention function primarily influences reading development (e.g., Vidyasagar & Pammer, 2010; Hari & Renvall, 2001). That is, reading may also have an impact on the development of visuo-spatial attention. Indeed, neuroimaging studies have found that the fronto-parietal attention network is connected to the Visual Word Form Area and that the connectivity strengthens as children gain reading expertise (Moulton et al., 2019; Vogel, Miezin, Petersen, & Schlaggar, 2012), but it remains elusive how such interactions in the brain lead to the developmental changes in spatial attention biases as well as reading behavior. Future research needs to further explore how the evolving reading and the attention networks influence each other during the acquisition of reading skills.

Since the current study aimed to examine the general population of school children, we were agnostic to atypical development in our participants. According to the National Center for Learning Disabilities, it is estimated that 1 in 5 children in the United States have learning and attention difficulties. Studies have suggested that children with ADHD or dyslexia show rightward spatial attention biases relative to age-matched controls (Bellgrove et al., 2008; Chan et al., 2009; Sireteanu et al., 2005). For our study cohort, we assume that participants with an atypical developmental trajectory are normally distributed in the general population and that our findings therefore reflect a population-level development of spatial attention biases in children. As a result, the developmental trajectory of the general population discussed in this paper may provide a useful reference for future studies that aim to explore differences in the development of spatial biases in children with atypical development.

A crucial strength of our experimental design is that it avoids possible confounds of manual actions in bisecting lines. The traditional paper-and-pencil version of the line bisection task requires participants to move their hand across the page and coordinate hand/arm movements with visual information in order to indicate a midpoint. Confounding motor effects may be more critical in children than in adults. For example, it has been shown that children's spatial bias measures varied largely based on which hand they used to indicate the subjective midpoint (Bradshaw, Nettleton, Wilson, & Bradshaw, 1987; Dellatolas, Coutin, & De Agostini, 1996). In particular, children indicated a midpoint to the right side of the veridical midpoint when they used the right hand (Dobler et al., 2001). This deviation was observed to the left of the veridical midpoint when the same children used their left hand. Adults were shown to be more consistent regardless of the hand used to bisect the line. Thus, spatial biases measured in this type of task are prone to motor-related confounds, particularly in younger children. To avoid such confounds, we developed a perceptual, computerized line bisection task that only required simple button presses after the perceptual judgment had been formed. We found that the distribution of spatial biases was consistent regardless of handedness. Therefore, the current study may provide more precise and reliable measures of spatial attention biases in children that are not confounded by motor-related parameters. The perceptual version of the line bisection task used in the current study will be particularly useful to test children with ADHD and/or dyslexia, as motor deficits are frequently observed in those populations (Kaplan et al., 1998; Suskauer et al., 2008).

In summary, the present study probed the development of spatial attention biases in school children from grades 1 through 8 and college freshmen. We found that children in early elementary grades had leftward spatial biases that diminished with advancing grade level, independent of motor abilities, gender, and handedness. We also showed a relationship between leftward spatial biases and reading ability in early elementary grade levels, which suggests that leftward biases among this population may be driven by learning to read in a language system that requires scanning text from left-to-right. Our findings provide a foundation for future research on the development of visuo-spatial attention function and possibly on the interaction of attention and reading function in neurotypical and atypical development.

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Figure Legends

Figure 1. Experimental design. Each participant was prompted with an instruction screen at the beginning of each block. Each trial started with a delay during which a smiley face was

shown to prepare the participant for the trial onset. A pre-bisected horizontal line was presented briefly, followed by a mask. Participants indicated their answer by button press. The location of the bisecting vertical line was varied following a staircase procedure.

Figure 2. Examples of individual participants' psychometric curves. Vertical line offsets are indicated on the x-axis; zero is the veridical midpoint, negative values are offsets to the left, and positive values are offsets to the right. The proportion of responses for each vertical line offset was plotted on the y-axis. A psychometric curve (black solid curve) was estimated for each participant. The midpoint of the psychometric curve, at which y = 0.5, indicates the point where the participant judged the left and right segments to be of equal length (blue solid line). Each participant's spatial attention bias is estimated in degrees of visual angle based on the deviation of the point of subjective equality (i.e., the x-value of the curve's midpoint) from the veridical midpoint. Participant A shows a leftward bias and participant B has a rightward bias.

Figure 3. Spatial attention bias does not depend on handedness or gender. The distribution of spatial attention bias in participants across grades 1 through 8 (Panels A and C) and adults (Panels B and D) showed a leftward bias in Experiment 1. Panels A and B show that such leftward attention bias was not related to participants' handedness. The distribution of attention biases in left-handed (colored in orange) and right-handed participants (colored in green) was similar. Panels C and D show that leftward attention bias was not related to participants' gender. The distribution of attention biases in male (colored in red) and females (colored in orange) was similar.

Figure 4. Children in early elementary school grades show an expressed leftward bias. The distributions of grades 1-3 (top panel; green), grades 6-8 (middle panel; orange), and college students (bottom panel; blue) are plotted for Experiment 1. The veridical midpoint is found at zero, the location of the grey dotted line. The mean is the vertical line in each grade group's respective color. Grades 1-3 showed an expressed leftward bias (mean= -0.2). Grades 6-8 (mean= -0.098) show a distribution similar to that of college freshmen (mean= -0.087).

Figure 5. Early elementary grades show an expressed leftward spatial attention bias that gradually diminishes with advancing grade. Individual spatial biases were plotted by grade for Experiment 1. Negative values on the x axis indicate leftward attention bias, positive values rightward bias, and zero no bias. Similar to previous findings in adult populations (Szczepanski & Kastner, 2013; Bio et al., 2018), individual participants' spatial biases were widely distributed in each grade level. A linear regression model with a log-transformed independent variable demonstrated that early elementary school grades show an expressed leftward spatial attention bias, which gradually becomes more normally distributed around zero in higher grades. A solid black line represents the model fit. Black asterisks indicate an average spatial bias for each grade.

Figure 6. Degree of leftward spatial bias predicts performance on a Rapid Automatized Naming (RAN) test. (A) The distribution of spatial attention biases in Experiment 2 (grades 1-3) showed an overall leftward bias, thereby replicating Experiment 1 (see Figure 4). (B) The distribution of composite RAN scores of participants in Experiment 2 (grades 1-3). (C) Relationship between individual participants' spatial biases and their composite RAN scores. Participants who showed leftward biases (negative values) tended to have better composite RAN scores. The regression line and a 95% confidence interval are indicated.

Figure S1. Curve width estimations. To control for precision of line bisection judgments, we estimated the width of each participant's psychometric curve. For each participant, spatial bias was measured by the midpoint of the psychometric curve where the y-value is 0.5 (blue solid line). To estimate the curve width, we found the first quartile point where the y-value is 0.25 (pink solid line) and calculated the difference between the vertical line offsets corresponding to the two points. Panel A is an example of a psychometric curve with a smaller curve width. Panel B shows an example of a flatter psychometric curve with a greater curve width. Although these two sample participants' spatial biases were estimated to be similar to each other (A: 0.03°, B: -0.005°), the widths of their psychometric curves differed from each other. As a control analysis, we additionally excluded two participants for curve widths that were greater than three standard deviations from the mean. Even after excluding these additional outliers, the results from the linear regression model with grade as a log-transformed independent variable and spatial bias as the dependent variable remained consistent (see Results for more details). The lower panels compare average psychometric curves between the youngest group (Panel C; grades 1-3; N = 147) and the oldest group (Panel D; grades 6-8; N = 120) in children. In panels C and D, gray lines indicate individual participants' psychometric curves and the blue solid curve indicates the average from each group.

Figure S2. Spatial bias analyses based on age. Younger children ages 6-8 (top panel A; green) showed an expressed leftward bias (mean = -0.2°) in comparison to children ages 11-13 (middle panel A; orange; mean = -0.09°) and college students ages 17-21 (bottom panel A; blue; mean= -0.087°). A linear regression model with a log-transformed independent variable demonstrated that younger children show an expressed leftward spatial attention bias, which gradually becomes more normally distributed around zero as they get older (panel B). A solid black line represents the model fit. Black asterisks indicate an average spatial bias for each age group. The analysis by age yielded similar results as compared to those based on grade.

Figure S3. Residuals for the model estimate for each grade. From the linear regression model with a log-transformed independent variable (log-transformed grade vs. spatial bias), we obtained the residuals from the model estimate for each grade in Experiment 1. The x-axis shows the regression model's estimated biases (indicated by black solid line in Figure 5), and the y-axis shows residuals for individual participants' actual biases versus the model's estimated biases for their grade. As the model's estimates gradually became closer to zero from grade 1 to grade 8, the clustered data points indicate data points for each grade level; Panel A shows grade 1 on the left (x-value = -0.26) to grade 8 on the right (x-value = -0.055). Residuals for early grades (especially grades 1,2, and 3) were not greater than for older grades. In Panel B, five data points with the most extreme residual values are excluded such that the residuals are normally distributed. The model remains significant after this exclusion. This indicates that the larger variance among younger children did not drive more negative model estimates.

Figure S4. Sampling distributions for each of the grade levels and adults. We estimated the distribution of spatial bias for each grade in Experiment 1 by using bootstrapping methods. The whiskers indicate 95% confidence intervals from the bootstrapped distributions. Black dots indicate the sampling means. Distributions of spatial bias were shifted to the left (i.e., negative values) in all grades and in the adult group, except for grade 4, which had a distribution marginally different from zero. Consistent with the findings from group-level comparisons and the regression model, grades 1, 2, and 3 had greater leftward biases that gradually reduce in older grades. Older grades (e.g., grades 7 and 8) showed similar distributions to adults.

Figure S5. Comparison of data acquired from school or summer camp setting. We conducted the Experiment 1 at two different locations for children. The table shows the number of children's data acquired either at the summer camp or the school. In order to assess whether the different settings affected the results, the distributions of individual spatial biases for children in grades 2,3, and 7 (shaded in the table) were compared. Grades 2, 3, and 7 were selected because the number of participants was comparable between the two locations. Variances and means of the two distributions are not significantly different from each other.

Tables

Table 1. Demographics

Children (Experiment 1)

Grade	Number of subjects	Mean Age; Range	Handedness			Gender	
			Right	Left	Ambi	Male	Female
1	38	6.11; 5-7	34	4		12	26
2	44	6.93; 6-8	38	6		29	15
3	42	8.02; 7-9	40	2		19	23
4	30	9.03; 8-10	28	2		13	17
5	34	9.91; 9-11	33	1		20	14
6	56	10.84; 10-12	46	10		34	22
7	53	12.08; 11-13	47	5	1	20	33
8	39	13.08; 12-14	36	3		18	21
Total	336	9.65; 5-14	302	33	1	165	171

Grade	Number of subjects	Mean Age; Range	Handedness			Gender	
			Right	Left	Ambi	Male	Female
College Freshmen	61	18.38; 17-21	46	15		20	41

Adults (Experiment 1)

Children (Experiment 2)

Grade	Number of subjects	Mean Age; Range	Handedness			Gender	
			Right	Left	Ambi	Male	Female
1	38	6.08; 6-7	36	2		21	17
2	42	6.98; 6-8	36	6		20	22
3	43	7.84; 7-8	43	0		25	18
Total	123	7.02; 6-8	115	8	0	66	57

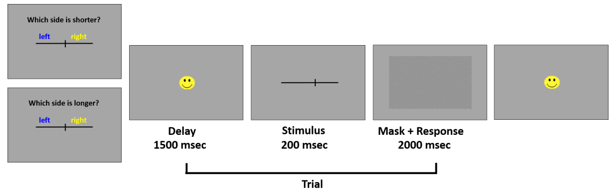
Table 2. Number of participants per grade and distribution of their spatial biases (Experiment 1).

Grade	Total number of subjects	Number of outliers	Distribution		t-statistics (Different from zero?)	Model estimate
			M	SD		
1	38	1	-0.32	0.65	$t(330) = -7.5$ $p < .0001$ ***	-0.27
2	44	1	-0.15	0.25	$t(330) = -8.9$ $p < .0001$ ***	-0.2
3	42	0	-0.15	0.15	$t(330) = -9.5$ $p < .0001$ ***	-0.16
4	30	0	-0.075	0.23	$t(330) = -8.4$ $p < .0001$ ***	-0.13
5	34	1	-0.063	0.16	$t(330) = -6.5$ $p < .0001$ ***	-0.11
6	56	0	-0.12	0.18	$t(330) = -4.8$ $p < .0001$ ***	-0.088
7	53	1	-0.093	0.18	$t(330) = -3.5$ $p < .001$ **	-0.073
8	39	0	-0.07	0.17	$t(330) = -2.6$ $p < .01$*	-0.06
Total	336	4				

***$p < 0.0001$; **$p < 0.001$; *$p < 0.01$

Number of participants per grade and distribution of their spatial biases (Experiment 2).

Grade	Total number of subjects	Number of outliers	Distribution	
			M	SD
1	38	1	-0.13	0.33
2	42	1	-0.16	0.36
3	43	0	-0.24	0.23
Total	123	2		



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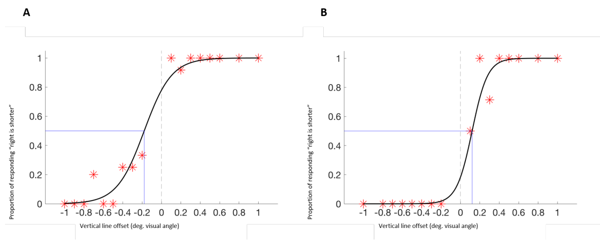

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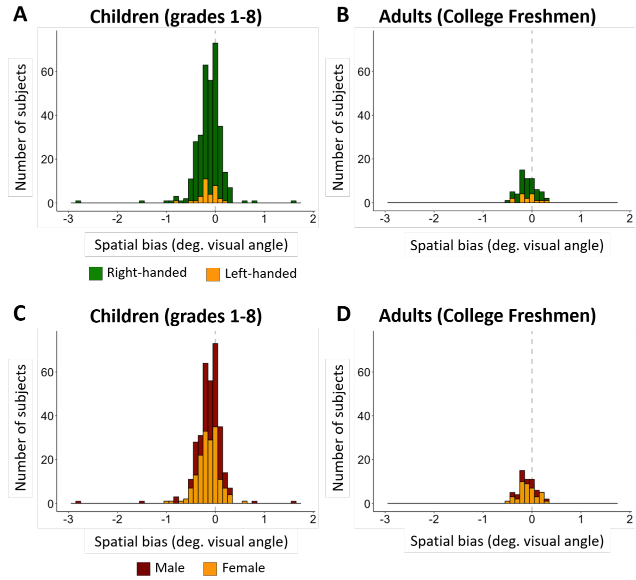

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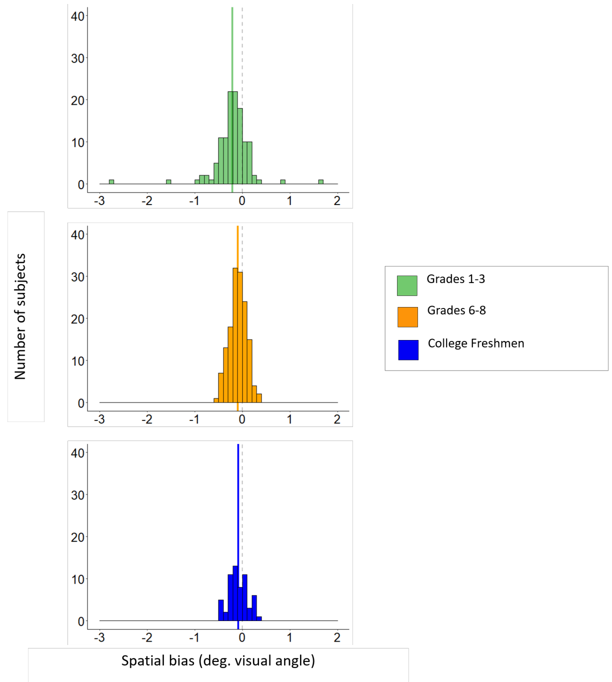

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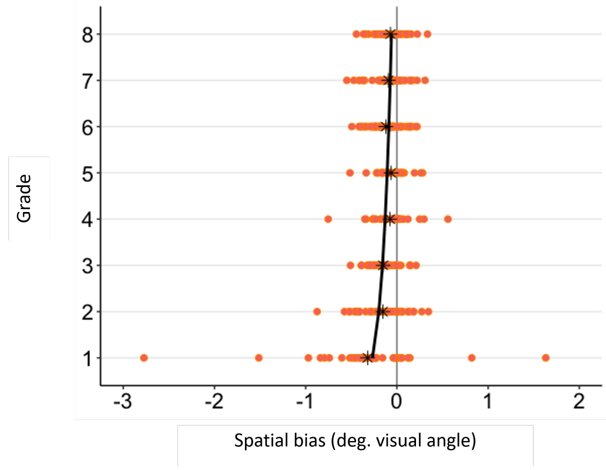

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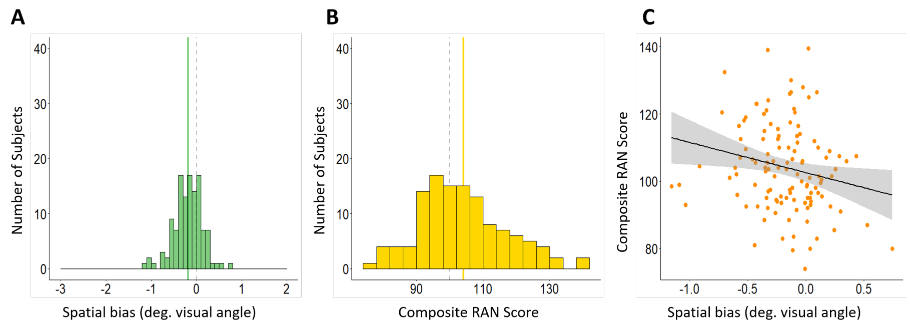

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