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What underlies visual selective attention development? Evidence that age-related improvements in visual feature integration influence visual selective attention performance

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A B S T R A C T

Visual selective attention (VSA) improves across childhood. Conjunction search tasks require integrating multiple visual features in order to find a target among distractors and are often used to measure VSA. Motivated by the visual system's architecture and developmental changes in neural connectivity, we predicted that feature integration across separate visual pathways (e.g., color and motion) should develop later than feature integration within the same visual pathways (e.g., luminance and motion). A total of 89 4- to 10-year-old children completed a visual search task that manipulated whether feature integration was between separate parallel visual pathways or within the same visual pathway. We first examined whether color–motion integration was associated with a performance cost relative to luminance–motion integration across childhood. We found that color–motion integration was worse than luminance–motion integration in early childhood but that this difference decreased with age. We also examined whether luminance–motion and color–motion visual search performance developed differently across childhood. Reaction time (RT) visual search slopes for the luminance–motion condition were both stable across childhood and steeper overall than those for the color–motion condition. In contrast, RT search slopes for the color–motion condition became steeperincrease across childhood. Finally, we found that age-related improvements in color–motion integration, relative to luminance–motion integration, were associated with longer color–motion search rates across childhood. These

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data suggest that age-related improvements in color–motion feature integration may increase competition between color–motion targets and distractors, thereby increasing the amount of time needed to process distractors as nontargets during the selection process.

Introduction

Visual selective attention (VSA), in which certain visual objects or locations are selected in the presence of competing others (Desimone & Duncan, 1995; Treisman & Gelade, 1980), typically improves in childhood and through adolescence before peaking in early adulthood (e.g., Hommel, Li, & Li, 2004; Trick & Enns, 1998). VSA has been found to be a critical component of effective learning and memory in both infants (Markant, Ackerman, Nussenbaum, & Amso, 2016; Markant & Amso, 2013) and children (Markant & Amso, 2014). Yet, the mechanisms underlying the development of this key process are not well understood. Here, we asked whether age-related changes in visual feature integration shape VSA.

Visual search tasks, often used to study VSA, require participants to search for a target among competing distractors (e.g., Treisman & Gelade, 1980). Targets and distractors vary along one or more visual feature dimensions (e.g., color, orientation). During a "conjunction search," a target defined by two or more visual features (e.g., a red bar oriented at 60°) is presented among distractors that share one value along one feature dimension but differ in value along a second feature dimension (e.g., red bars oriented at 90° and green bars oriented at 60°). Thus, participants must *integrate multiple visual features* as they search among targets and distractors. Typically, the reaction time (RT) to find conjunction targets increases linearly as distractor number increases (RT slope), reflecting attentional engagement and visual search rate (e.g., Treisman & Gelade, 1980; Wolfe, 1994).

Developmental studies of VSA that employ visual search tasks reveal general improvements in processing speed but also nuances in VSA as a function of task demands (Lobaugh, Cole, & Rovet, 1998; Trick & Enns, 1998). Beginning in infancy and toddlerhood, conjunction visual search performance shows patterns consistent with adult patterns in corresponding visual search tasks, but children's search rates (RT slope) become faster across toddlerhood (Gerhardstein & Rovee-Collier, 2002). Similarly, studies have found that, whereas conjunction search rates for color-defined oriented bars are slower in children relative to adults, search rates became faster from middle childhood (7 years) to late childhood (10 years) (Donnelly et al., 2007). Similarly, the conjunction search rate for a luminance-defined shape (e.g., black circle) was slower in middle childhood relative to late childhood, which was slower than in adulthood (Merrill & Lookadoo, 2004). However, search rates became adult-like by late childhood when researchers varied the amount of distractor competition by holding one distractor type constant (e.g., black square) while increasing only the second distractor type (e.g., gray circle). Here we asked whether developmental improvements in feature integration are an agent of change in conjunction visual search performance from early childhood, across middle childhood, and into late childhood (4–10 years).

Given that conjunction visual search requires integrating multiple visual features, it is important to consider that visual features are processed in a distributed set of hierarchically organized, parallel neural pathways (e.g., Felleman & Van Essen, 1991; Ungerleider & Haxby, 1994; Zeki, 1978). Whereas some visual features are processed in relatively distinct pathways, others are processes within the same pathway. For example, both color information and motion information are processed in relatively distinct but overlapping layers in cortical areas V1 and V2 and then are routed to separate higher-level extrastriate cortical areas V4 and MT, respectively (Gegenfurtner, 2003; Seymour, Clifford, Logothetis, & Bartels, 2009; Shipp & Zeki, 1995; Sincich & Horton, 2005). However, luminance information proceeds with motion information along the visual hierarchy from V1, through V2, to MT.

Thus, feature integration may occur across separate visual pathways (e.g., color and motion) or within the same visual pathway (e.g., luminance and motion). In this example, both across and within pathway feature integration require motion processing. However, here we asked whether, relative to within-pathway integration, across-pathway integration may incur additional processing costs because color is processed in the ventral stream, whereas motion is processed in the dorsal stream.

Feature integration relies on efficient connectivity between visual processing regions (e.g., Festa et al., 2005). Whereas feature integration within a visual pathway likely relies on short local connections within each region of the visual hierarchy, feature integration across visual pathways also likely relies on more distant distributed connections *between* visual processing regions. Coincidentally, connectivity exhibits dynamic changes, from short to long range, across child development (Cao, Huang, & He, 2017; Fair et al., 2007, 2009; Supekar, Musen, & Menon, 2009; Uddin, Supekar, & Menon, 2010), providing a unique opportunity to examine distinct feature integration across the visual cortical hierarchy. Together, this suggests that, earlier in childhood, integrating features processed in separate pathways (e.g., color and motion) may come with an additional processing cost relative to integrating features processed within the same visual pathway (e.g., luminance and motion). Put another way, the additional processing cost of integrating features across visual pathways may decrease across childhood. Within the same child, an additional cost for color–motion integration, relative to luminance–motion integration, should differentially affect conjunction visual search performance depending on the visual features that define the targets and distractors. This result would strongly suggest that developing visual function is an agent of change in VSA development (Amso & Scerif, 2015). To isolate the change in color–motion feature integration relative to global improvements in information processing, we examine color–motion feature integration performance in *relation* to luminance–motion feature integration.

In the current study, 4- to 10-year-old children performed a visual search task. In two conditions, children were asked to search for a vertically moving target that varied by either color or luminance, placing more or less demand on feature integration across the visual pathways. In both feature conditions, targets were presented with no distractors or with two or four distractors. In the absence of distractors, performance reflects baseline feature integration abilities. In the presence of distractors, performance reflects visual selective attention abilities, specifically, the change in performance with an increase in distractor number (i.e., search slope). We first predicted that color–motion integration would be associated with a performance cost, relative to luminance–motion integration, and that this cost would decrease with age as color–motion integration improves from early to middle childhood. We next predicted that, across early to middle childhood, VSA for color–motion would change more than VSA for luminance–motion. Finally, we predicted that individual differences in developing feature integration may be associated with developmental changes in VSA. Specifically, developmental improvements in feature integration should be associated with *steeper* visual search slopes, and this should be more evident for the color–motion visual search condition than for the luminance–motion visual search condition. As children become better at integrating color and motion, sensitivity to the conjunction of features that define competing distractors should increase. This should result in a greater amount of time needed to resolve visual competition during target selection.

Method

Participants

A total of 89 4- to 10-year-old children (overall: M_{age} = 7.17 years, *SD* = 1.82, range = 4.14–10.75, 39 girls; girls: M_{age} = 7.44 years, *SD* = 1.99, range = 4.14–10.75; boys: M_{age} = 6.96 years, *SD* = 1.66, range = 4.18–10.26) comprised the final sample. Children were normally distributed across age (skewness *z* = 0.62). An additional 12 children were tested but excluded due to noncompliance (*n* = 4), experimenter or technical error (*n* = 3), or color blindness (*n* = 5). We removed 5 children as multivariate outliers and 4 children as univariate outliers as well as 10 children who did not contribute data for selective attention trials (e.g., no correct Set Size 3 or 5 trials; see below). Children and their parents were recruited through advertisements, and all were local community members. Children provided assent and adults provided consent in accordance with the university's institutional review board. Families were compensated $15 (U.S.) for their time.

Children's race makeup was 78% White, 7% multiracial, 8% Black/African American, and 6% other (2% declined to answer). Ethnicity makeup was 84% non-Hispanic and 14% Hispanic (2% declined to answer). Participants' average IQ, as determined by the Woodcock–Johnson Brief Intelligence Assessment (Woodcock, McGrew, & Mather, 2007), was $M = 109.53$ ($SD = 16.08$). One child did not complete IQ testing.

Stimuli and apparatus

Stimuli consisted of red, green, white, and black circles (approximately 1.25° in diameter) that moved either vertically or horizontally in phase synchrony. Circles oscillated approximately 1.25° in either direction around their initial starting point at a speed of approximately $3^\circ\ s^{-1}$. Using a ColorCal MKII colorimeter (Cambridge Research Systems, Rochester, Kent, UK), we measured the luminance (Y) and Commission Internationale de l'Eclairage (CIE) coordinates (x, y) of the stimuli. Luminance-matched red circles ($Y = 19$ cd/m^2; $x = .60$, $y = .34$) and green circles ($Y = 19$ cd/m^2; $x = .32$, $y = .51$) appeared on a black background ($Y = 0.25$ cd/m^2; $x = .26$, $y = .26$). Chromaticity-matched black circles ($Y = 0.25$ cd/m^2; $x = .26$, $y = .26$) and white circles ($Y = 185$ cd/m^2; $x = .33$, $y = .32$) appeared on a gray background ($Y = 16.10$ cd/m^2; $x = .314$, $y = .342$). Circles were presented in one of six concentric locations equidistant from the screen center (approximately 6°), where an orange cartoon clown fish ("Nemo") served as a fixation point. Children were allowed to move their eyes freely throughout the trials. Within a given trial, children saw a search display (Fig. 1) for up to 3500 ms. If a response was recorded, the search display was removed. Following each search display, a cartoon fish was presented for 1000 ms to direct children's attention to the center of the screen.

Procedure

Children were first screened for color blindness using the Ishihara tests for color deficiency. All children in the final sample passed these tests and showed no evidence of color blindness. Prior to the tri-

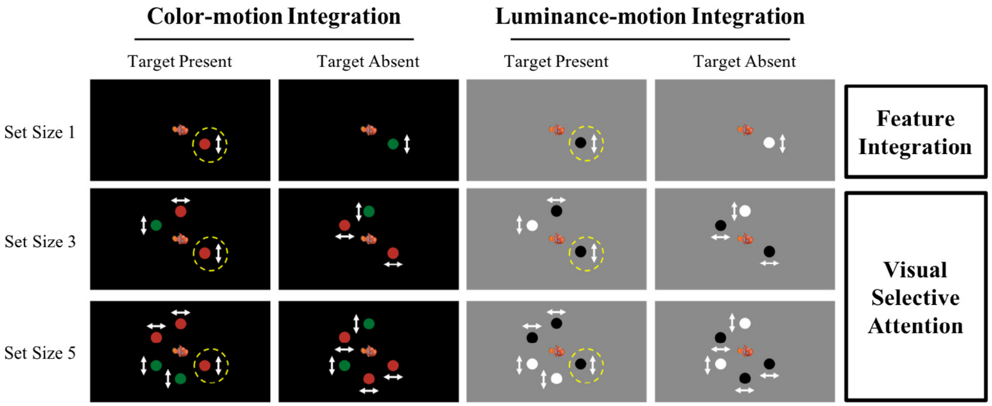

Fig. 1. Illustrations of search displays for feature and set size conditions for both target-present and target-absent trials. The left-most columns depict target-present and target-absent color–motion integration trials. The right-most columns depict target-present and target-absent luminance–motion integration trials. Rows depict set size trials, with an increase in distractors from top to bottom. The top row depicts feature integration trials. The bottom two rows depict visual selective attention trials. Target stimuli are highlighted by a dashed yellow circle. White arrows were not presented to participants but instead represent motion direction. Distractors could differ from the target in either color or luminance but share vertical motion. Or, distractors could differ in motion direction but share either color or luminance value. Each display was presented until children responded (up to 3500 ms) and was followed by a fixation display (1000 ms). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

als of interest, children were also asked to point to, or verbally discriminate between, red and green circles and black and white circles as well as vertical (or ''jumping'') and horizontal (or ''sideways'') motion. Children were instructed to ''press the button as quickly as you can'' once they found the target on target-present trials and were instructed to ''not press the button'' on target-absent trials. Next, children completed two practice trials to ensure that they understood the instructions. This procedure was repeated if children failed to correctly indicate a color or motion direction or if they incorrectly responded to either practice trial. Children were then asked to verbally indicate the target stimulus identity (''a jumping red/black circle'') to the experimenter. Children then searched for a vertically moving target circle among distractor circles. Across two feature conditions, we manipulated which visual feature required integration with motion. In the luminance–motion feature condition, the target was a vertically moving black circle, and distractors were vertically moving white circles and horizontally moving black circles. In the color–motion feature condition, the target was a vertically moving red circle, and distractors were vertically moving green circles and horizontally moving red circles. Thus, children were required to integrate motion with either luminance or color information. We also manipulated the number of stimuli presented within each feature condition. Across three set size conditions, stimuli were presented in sets of 1, 3, or 5. Target circles were present in 50% of trials and absent in 50% of trials. Target locations were randomly selected. Feature conditions (luminance–motion and color–motion) were blocked and counterbalanced. Set size conditions (1, 3, and 5) were pseudorandomly ordered. In total, children completed 96 trials, 48 for each feature condition (luminance–motion and color–motion) and 16 (8 target-present and 8 target-absent) for each set size within each feature condition. Each child was offered a short break every 24 trials. Fig. 1 illustrates sample search displays for each feature, set size, and trial type (target-present or target-absent).

Dependent measures

For each feature and set size condition, we recorded RTs on target-present trials and calculated target detection sensitivity (d') across target-present and target-absent trials. Initial data inspections revealed that accuracy was at ceiling in many cases across many conditions. Thus, we applied a log-linear correction to the calculation of d' (Hautus, 1995; Stanislaw & Todorov, 1999). Briefly, 0.5 was added to both hit rates and false alarm rates and 1 was added to both the number of target-present trials and the number of target-absent trials. We then calculated d' by subtracting the normalized false alarm rate from the normalized hit rate.

Feature integration performance

We define feature integration as the detection sensitivity for a target defined by multiple visual features (e.g., Treisman, 1998) *without spatially competing distractors.* Children were instructed to press a button when they found the target stimulus. Targets were either present (e.g., vertically moving red circle) or absent (e.g., horizontally moving red circle or vertically moving green circle). We generated a target detection sensitivity value (d') for each feature condition when targets were presented without distractors (Set Size 1).

We also created a feature integration index to measure the added cost of integrating color and motion features relative to luminance and motion features. To do this, we subtracted each participant's luminance–motion integration performance value from that participant's color–motion integration performance value. A larger negative feature integration index reflects greater performance cost for color–motion relative to luminance–motion feature integration, whereas a positive feature integration index reflects greater performance cost for luminance–motion relative to color–motion feature integration. Thus, a value of zero reflects no performance cost for either color–motion or luminance–motion feature integration. Because this index was significantly skewed ($z = -2.95$), we rank-transformed this measure to reduce skewness ($z = -0.65$).

Visual selective attention performance

We measure VSA performance as the change in children's performance as a function of distractor number (i.e., search slope). Thus, we calculated the performance slope for both reaction time and target detection sensitivity as the ratio of change in performance across set size over the change in set size. We then control for age-related differences in manual dexterity across our wide age range by dividing this performance slope value by performance on Set Size 1 trials. This estimates the visual search rate (i.e., RT slope) proportional to each individual child's baseline performance. Thus, *larger* RT search slope values reflect *slower* visual search rates, whereas *smaller* RT search slope values reflect *faster* visual search rates. In contrast, *smaller d'* search slope values reflect *greater* influence of distractors on accuracy, whereas *larger d'* search slope values reflect *smaller* influence of distractors on accuracy.

Results

Feature integration performance

Following the removal of outliers, additional outliers were revealed and feature integration measures remained skewed (color–motion d': $z = -7.79$; luminance–motion d': $z = -8.69$; color–motion RT: $z = 3.90$; luminance–motion RT: $z = 5.55$). To reduce the potential influence of outliers and skewness, we first collapsed across feature conditions and then rank-transformed each feature integration measure, resulting in less skewed distributions (color–motion d': $z = -2.39$; luminance–motion d': $z = -3.54$, color–motion RT: $z = -0.11$; luminance–motion RT: $z = 0.10$).

We predicted that color–motion feature integration would be associated with a performance cost, relative to luminance–motion integration, and that this cost would decrease with age as color–motion integration improves from early to middle childhood. To test this prediction, we submitted both feature integration performance measures (Set Size 1 ranked RT for correct target-present trials only and Set Size 1 ranked target detection sensitivity) to separate repeated-measures analyses of covariance (ANCOVAs) with feature condition (color–motion or luminance–motion) as a within-participant variable and age (in years) as a continuous variable. See Table 1 for dependent variable descriptive statistics collapsed across age.

For correct target-present RTs, we only found a main effect of age, $F(1, 87) = 57.073$, $p < .001$, partial eta (η_p) = .396, all other *ps* > .865. Thus, we submitted the unranked (raw) mean RTs, collapsed across feature conditions, to Spearman's ranked correlations and found that that RTs decreased with age, $r_s(89) = -.608$, $p < .001$. This indicates that children became faster to correctly detect a target across childhood.

For d', there was a main effect of feature condition, $F(1, 87) = 9.454$, $p = .003$, $\eta_p = .098$, where color–motion integration was worse than luminance–motion integration (Table 1). There was also a main effect of age, $F(1, 87) = 27.112$, $p < .000$, $\eta_p = .238$, where overall target detection sensitivity improved across early to middle childhood, $r_s(89) = .564$, $p < .001$. As predicted, there was also an age by feature condition interaction, $F(1, 87) = 6.362$, $p = .013$, $\eta_p = .068$. To understand the interaction, we submitted raw (unranked) d' measures to Spearman's ranked correlations and found that, whereas both feature conditions show age-related improvement, age was correlated with color–motion integration, $r_s(89) = .529$, $p < .001$, to a greater extent than luminance–motion integration, $r_s(89) = .255$, $p = .016$.

Table 1
Summary of behavioral performance measures.

	Color–motion				Luminance–motion			
	Feature integration		Visual selective attention		Feature integration		Visual selective attention	
	d'	RT	d'	RT	d'	RT	d'	RT
N	89	89	87	89	89	89	89	89
Mean	2.70	1141.90	−0.04	0.11	2.95	1152.75	−0.05	0.12
Median	3.19	1080.13	0.00	0.10	3.19	1084.00	−0.06	0.10
Standard deviation	0.79	279.14	0.15	0.13	0.45	311.21	0.11	0.13
Minimum	−0.31	692.75	−0.50	−0.25	1.00	722.00	−0.43	−0.21
Maximum	3.19	2123.83	0.36	0.46	3.19	2475.00	0.16	0.46

Note. RT, reaction time.

Fig. 2 shows that color–motion integration is worse than luminance–motion integration in early childhood but that feature integration becomes equivalent by middle childhood. This finding is consistent with our prediction that color–motion feature integration would be associated with a performance cost relative to luminance–motion integration. However, the added cost of binding color and motion across visual pathways decreases across childhood. In other words, color–motion integration, relative to luminance–motion integration, improves across childhood.

Visual selective attention performance

Age-related changes

We predicted that, across childhood, visual search performance for color–motion targets would change more than visual search performance for luminance–motion target. To test this prediction, we submitted baseline-corrected search slopes for each dependent variable (RT and d') to separate repeated-measures ANCOVAs with feature condition (luminance–motion or color–motion) as a within-participant variable and age (in years) as a continuous variable. We found no effects for the baseline-corrected d' search slopes (all $ps > .06$).

For baseline-corrected RT search slopes, we found a main effect of feature condition, $F(1, 87) = 5.236$, $p = .025$, $\eta_p = .057$, where search rates were slower for the luminance–motion condition relative to the color–motion condition. There was also a main effect of age, $F(1, 87) = 13.315$, $p < .001$, $\eta_p = .133$. Pearson correlations showed that an increase in distractor number was associated with *greater* slowing for search with age, $r(89) = .364$, $p < .001$. Critically, there was also an age by feature condition interaction, $F(1, 87) = 4.917$, $p = .029$, $\eta_p = .053$, suggesting that luminance–motion and color–motion visual search change with age differently across childhood. Fig. 3A shows that color–motion visual search performance, $r(89) = .432$, $p < .001$, but not luminance–motion visual search performance, $r(89) = .125$, $p = .242$, changed across early to middle childhood. These data suggest that, as predicted, luminance–motion visual search is stable earlier than color–motion visual search. Moreover, the pattern of results shows that children have steeper color–motion RT slopes with age, indicating that they become more sensitive to additional distractors with age in the color–motion search condition only.

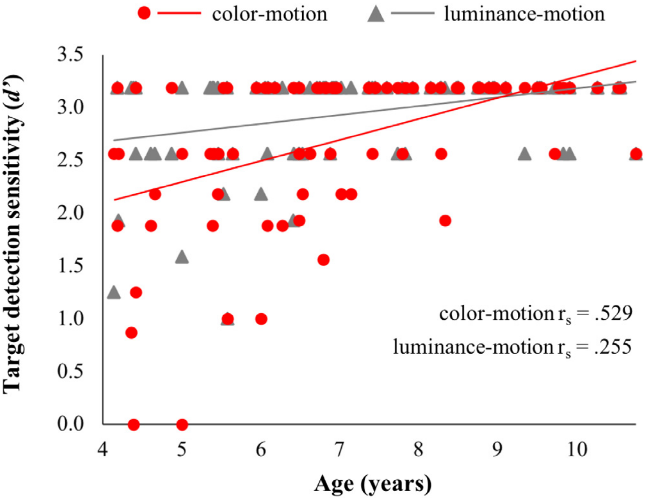

Fig. 2. Age-related changes in feature integration accuracy, as measured by target detection sensitivity (d') for Set Size 1 trials. Color–motion target detection sensitivity increased with age to a greater extent than luminance–motion target detection sensitivity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

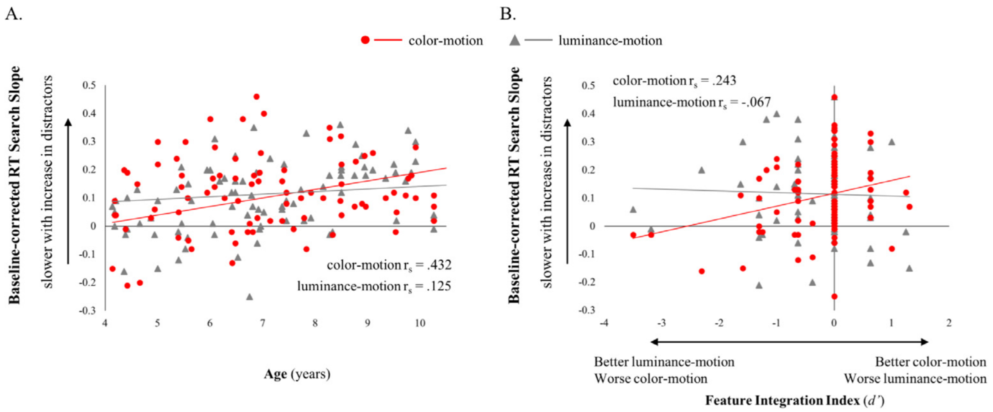

Fig. 3. (A) Age-related changes in visual selective attention performance. Color–motion visual search rates slowed across childhood, but this effect is not evident in luminance–motion visual search. (B) Individual differences in feature integration predict color–motion visual selective attention performance. Worse color–motion integration, relative to luminance–motion integration, is associated with slower color–motion visual search rates. Raw feature binding index is plotted for easier interpretation. RT, reaction time. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Individual differences in feature integration

We predicted that individual differences in feature integration may influence VSA across childhood. In particular, stronger visual feature integration should strengthen both target and distractor processing and, therefore, should increase competition with increasing distractor number. This would result in slower visual search as distractor number increases.

To test this prediction, we submitted baseline-corrected search slopes for each dependent variable (RT and d') to separate repeated-measures ANCOVAs with feature condition (luminance–motion or color–motion) as a within-participant variable and the ranked feature integration index (i.e., difference score between Set Size 1 d' color–motion and Set Size 1 d' luminance–motion) as a continuous variable. See Table 1 for descriptive statistics for each condition. For baseline-corrected d' search slopes, we found no significant effects (all $ps > .169$).

For RTs, we found a main effect of feature condition, $F(1, 87) = 5.779$, $p = .018$, $\eta_p = .062$, with slower search rates for the luminance–motion condition relative to the color–motion condition. There was no main effect of feature integration index ($p = .294$). However, there was a feature condition by feature integration index interaction, $F(1, 87) = 5.800$, $p = .018$, $\eta_p = .062$. Fig. 3B shows that when luminance–motion feature integration is better than color–motion feature integration, luminance–motion RT visual search slopes are steeper. Within the same child, as color–motion feature integration performance approached luminance–motion feature integration performance, this difference in visual search RT slope values decreased. As color–motion feature integration performance approached luminance–motion feature integration performance, visual search RT slopes increased for the color–motion condition, $r_s(89) = .243$, $p = .022$, but not for the luminance–motion condition, $r_s(89) = -.067$, $p = .533$ (Fig. 3B). Thus, improvements in color–motion feature integration, relative to luminance–motion feature integration, resulted in greater slowing for color–motion search.

So far, we have shown that (a) feature integration performance for color–motion targets improves with age (Fig. 2), (b) VSA performance on color–motion trials reflects increased sensitivity to distractors with age (Fig. 3A), and (c) improvement in color–motion feature integration, relative to luminance–motion feature integration, is associated with greater sensitivity to color–motion distractors during visual search (Fig. 3B). These findings indicate that the relationship among age, feature integration, and VSA in our age range is specific to the color–motion visual search condition. To directly test this claim, we submitted baseline-corrected RT search slopes to a repeated-measures ANCOVA with feature condition (luminance–motion or color–motion) as a within-participant factor and the age by feature integration index interaction as a covariate (or continuous variable). As before, we found a main effect of feature condition, $F(1, 86) = 7.882$, $p = .006$, $\eta_p = .083$, where search rates were slower for luminance–motion search relative to color–motion search. We also found a feature condition by age by feature integration index interaction, $F(1, 86) = 8.475$, $p = .005$, $\eta_p = .089$. These results suggest that, regardless of a child's age, when luminance–motion integration is better than color–motion integration, luminance–motion search rates are slower overall. In contrast, as color–motion feature integration comes to approximate luminance–motion feature integration with age, color–motion search rates become slower. When feature integration is equal, however, both search rates are similar and color–motion search rates slow with age. Thus, age-related changes in color–motion integration may increase children's sensitivity to color–motion distractors, as revealed by steeper visual search RT slopes.

Discussion

We examined whether children's feature integration and visual selective attention abilities for objects in motion change with age. First, we found that whereas feature integration improved with age, this effect was larger for color–motion integration relative to luminance–motion integration. This suggests that whereas color–motion integration was worse than luminance–motion integration in early childhood, the two become equivalent by middle childhood. Second, whereas RT search slopes were, on average, steeper for the luminance–motion condition, slopes increased with age for the color–motion condition. This result revealed that whereas luminance–motion search performance was robust across childhood, older children were more influenced by additional color–motion distractors. Third, when luminance–motion integration was better than color–motion integration, luminance–motion RT search slopes were steeper, indicating that children were more sensitive to the addition of luminance–motion distractors that competed with the to-be-selected target. In contrast, age-related improvements in color–motion feature integration were associated with steeper color-motion RT search slopes.

Our results add to the visual search developmental literature in two important ways. First, we demonstrate that, in the absence of distractors, younger children are worse at integrating multiple visual features relative to older children. This pattern was especially evident for color–motion integration relative to luminance–motion integration. Prior work found that, in the absence of distractors, both children and adults were slower at detecting a target defined by two features compared with a target defined by one feature (Trick & Enns, 1998). Our results are consistent with the interpretation that younger children, relative to older children, are slower to integrate feature information during conjunction visual search. We add that integrating feature information across parallel visual streams may be costlier early in childhood relative to integrating feature information within a visual stream.

Second, the current study examined how differences in feature integration affect visual selective attention. To our knowledge, ours is the first study to examine conjunction visual search performance as a function of variable feature integration demands across or within visual pathways within children. Previous work in adults has shown that visual search performance varies by visual sensitivity (Hunter, Godde, & Olk, 2018; Li, Sampson, & Vidyasagar, 2007). Previous work in children has shown that distractor number (Donnelly et al., 2007; Gerhardstein & Rovee-Collier, 2002) and top-down cues (Lookadoo, Yang, & Merrill, 2017; Merrill & Lookadoo, 2004) affect developmental visual search trajectories. Still other work has shown that basic oculomotor information processing and improvement in visuospatial abilities affect visual search development across adolescence (Burggraaf, van der Geest, Hooge, & Frens, 2019). Our work is also consistent with recent work showing that the ability to track a moving target among distractors improves across late childhood (Wolf et al., 2018). We found that, relative to the color–motion visual search, children were slowed by increasing distractor set size more when searching for luminance–motion targets, but this effect was constant across the 4- to 10-year age range. In contrast, color–motion visual search became slower with additional distractors with age, and this slowing was associated with age-related improvements in color–motion feature integration. Thus, visual search performance depends on many factors that may differentially influence this ability at different times in development. Moreover, together these findings show that there is no single visual search developmental trajectory but rather multiple developmental trajectories that likely interact across development. Future work will consider whether feature integration across and within visual pathways is stable by adolescence and, if so, whether visual search slopes would then show a decline with age, perhaps reflecting general information processing mechanisms.

These data suggest that the development of the attentional mechanisms that support learning and memory (Markant & Amso, 2014; Markant, Worden, & Amso, 2015; Werchan, Lynn, Kirkham, & Amso, 2019) may be affected by the changes in robustness of visual processing across childhood (Amso & Scerif, 2015). The current study provides evidence that, across early to middle childhood, as the ability to integrate color and motion visual features improves, competition between targets and distractors may increase, thereby increasing the time needed to resolve this competition by processing additional distractors during the target selection process. Thus, developmental changes in visual feature integration abilities may be important for developmental changes in VSA. These findings have important implications for developmental work showing that learning and memory for features processed in separate visual pathways may follow distinct developmental trajectories (Lange-Küttner & Küttner, 2015) that may be related to visual processing development (see Braddick & Atkinson, 2011). Indeed, visual acuity, luminance and chromatic contrast sensitivity (e.g., Bradley & Freeman, 1982; Ellemberg, Lewis, Liu, & Maurer, 1999; Knoblauch, Vital-Durand, & Barbur, 2001), and global motion direction sensitivity (e.g., Ellemberg, Lewis, Maurer, Brar, & Brent, 2002; Hadad, Maurer, & Lewis, 2011) all improve across childhood. Moreover, some suggest that luminance thresholds necessary for form perception improve from middle to late childhood (Bertone, Hanck, Guy, & Cornish, 2010). Future work will examine the impact of visual feature processing development on feature integration abilities across early to middle childhood.

Our findings also mirror those from patients with Alzheimer's disease (AD), whose cortical connectivity is disrupted (see Delbeuck, Van der Linden, & Collette, 2003). AD patients exhibit greater age-related slowing for conjunction visual search when compared with healthy elderly adults (Foster, Behrmann, & Stuss, 1999). AD patients are better at detecting global motion that requires feature integration *within* one visual pathway relative to feature integration *between* distinct parallel visual pathways (Festa et al., 2005). Thus, greater improvement in color–motion feature integration across childhood, relative to luminance–motion feature integration, suggests that integration across relatively distinct visual pathways may develop later in childhood than integration features processed within a single visual pathway. This age-related improvement in pathway integration is in line with developmental patterns of network connectivity (Cao et al., 2017; Fair et al., 2007, 2009; Hagmann et al., 2010; Supekar et al., 2009; Uddin et al., 2010) and increasing coherence across visual cortices in childhood (Kipping, Tuan, Fortier, & Qiu, 2017). Future work will also examine whether feature integration reflects underlying functional connectivity within and between visual pathways.

Conclusions

The current study adds to the developmental literature by showing that visual systems development is an agent of change in visual selective attention development (Amso, Haas, & Markant, 2014; Amso & Scerif, 2015). Feature integration within a visual pathway may develop earlier than feature integration between visual pathways and, thus, may differentially affect target–distractor similarity during the VSA process across childhood. Indeed, as color–motion integration improved across childhood, visual search rates slowed, suggesting that competition between color–motion defined targets and distractors increased. Mechanistically, as distractor number increases, robust color–motion feature integration across the visual scene would mean more locations competing for selection. Children with relatively better between-visual pathway integration, therefore, may be more sensitive to color–motion distractors relative to luminance–motion distractors and may need additional time to recognize distractors as nontargets during the selection process. These data suggest that VSA development may be better conceptualized as a biased competition computation (e.g., Desimone & Duncan, 1995) rather than a finite discernible network of attentional processes with a uniform developmental trajectory (Petersen & Posner, 2012).

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jecp.2019.104732.

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