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EMPIRICAL ARTICLE

CHILD DEVELOPMENT

Visual and cognitive processes contribute to age-related improvements in visual selective attention

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Abstract
Children (N = 103, 4–9 years, 59 females, 84% White, c. 2019) completed visual processing, visual feature integration (color, luminance, motion), and visual search tasks. Contrast sensitivity and feature search improved with age similarly for luminance and color-defined targets. Incidental feature integration improved more with age for color-motion than luminance-motion. Individual differences in feature search (β = .11) and incidental feature integration (β = .06) mediated age-related changes in conjunction visual search, an index of visual selective attention. These findings suggest that visual selective attention is best conceptualized as a series of developmental trajectories, within an individual, that vary by an object's defining features. These data have implications for design of educational and interventional strategies intended to maximize attention for learning and memory.

The ability to selectively attend to visual information that is relevant for a behavioral goal while ignoring competing irrelevant information improves across infancy, through childhood, and into adolescence (Hendry et al., 2019; Plude et al., 1994). This developmental change in visual selective attention ability in turn supports learning and memory at a time when children transition to formal schooling and are expected to acquire immense amounts of knowledge (Markant & Amso, 2022; Merkley et al., 2018; Stevens & Bavelier, 2012). Indeed, children's visual selective attention is challenged by classrooms full of colorful artwork, posters, and talkative peers, and their academic success hinges on their ability to focus their attention on the teacher and lesson while ignoring these distractions, especially for neurodiverse children (Fisher et al., 2014; Hanley et al., 2017). Thus, understanding how visual selective attention develops is key to understanding its role in academic performance, as well as developing interventions for children struggling with learning and/or neurodevelopmental disorders. However, despite extensive research on the developmental timing and neural pathways involved in visual selective attention, we still know little about the mechanisms supporting these developmental changes.

A recent model, grounded in neuroanatomy and the development of the visual system, conceptualizes visual selective attention as a neural computation operating over converging visual inputs (Amso & Scerif, 2015). In previous work, researchers have found that 6- to 7-year-old children are the fastest to detect target items defined by color, followed by orientation, and then by size (Donnelly et al., 2007). The ability to selectively attend to a specific visual feature dimension to support visual search improves across childhood (Lookadoo et al., 2017; Merrill & Lookadoo, 2004). Moreover, the ability to ignore visually salient distractors is still developing in early childhood (5–6 years old; Blakley et al., 2022). Researchers generally argue that these developmental changes are driven by improvements in top-down attentional control. However, another plausible explanation is that children's changing ability to process individual visual features (e.g., color, luminance, motion)

Abbreviations: ER, error rate; ITI, intertrial interval; IQR, interquartile range; RT, reaction time.

and integrate them into a coherent object may be foundational to the development of visual selective attention efficiency (Lynn & Amso, 2021).

In the present study, we leverage methods and task designs from vision science to examine how age-related changes in visual processing and feature integration are related to changes in visual selective attention ability across childhood. If lower level visual abilities are related to visual selective attention development, we may begin to develop curricular and clinical interventions that leverage visual features to cue attention to bolster learning and memory for struggling children.

The development of visual feature processing competence across childhood

Visual feature processing is the ability to detect and discriminate between feature values (e.g., color: red from green). We focused on two measures of visual processing competence measured across two different tasks. One common method for measuring visual feature processing competence is a contrast sensitivity task, where the contrast of a visual object (i.e., a Gabor patch) is systematically manipulated to estimate the minimum amount of contrast needed for the participant to perform the task successfully (Figure 1a). Luminance contrast sensitivity (the ability to detect differences in the lightness of a target against its background) is evident in infancy (Atkinson et al., 1977) and continues to improve into childhood, reaching adult-like levels around 8 years of age (Bertone et al., 2008; Bradley & Freeman, 1982; Ellemberg et al., 1999; Gwiazda et al., 1997; Leat et al., 2009; Silvestre et al., 2020). Color contrast sensitivity is also evident in infancy (Teller, 1998), but improves protractedly across childhood, through adolescence, and peaks around 20 years of age (Knoblauch et al., 2001; for recent reviews, see Maule et al., 2023; Skelton et al., 2022), with red-green (L- or M-cone) sensitivity developing faster than blue-yellow (S-cone) sensitivity (Ling & Dain, 2018). Moreover, orientation sensitivity is still developing in childhood, with the amount of contrast between orientation being about 4–5 times larger in 5-year-olds relative to adults (Lewis et al., 2007). Together, these findings suggest that developmental changes in the ability to process local deviations in one's visual field of view may depend on the visual features present. We predict that contrast sensitivity will improve with age across childhood, but sensitivity will be weaker for color relative to luminance in this age range (Prediction 1).

A second common method for measuring visual feature processing competence across the visual field is a feature search task. In this task, which was originally established to test feature integration theory (Treisman & Gelade, 1980), participants search for a target object (e.g., red circle) presented among a varying number of spatial distractors (e.g., green circles) that differ in one visual feature dimension (e.g., color; Figure 1a). Feature integration theory argues that there are two stages to attending to an object, the first of which is the early and automatic parallel processing of visual features across the visual field. Because visual features are extracted in parallel, the target "pops out" and performance is typically unaffected by the number of distractors. Feature search performance for simple color- or luminance-defined shapes/objects (i.e., dark circle) among spatial distractors (i.e., circles and squares) is generally unaffected by the number of distractors by early childhood and continues to improve across childhood and into adulthood (Gerhardstein & Rovee-Collier, 2002; Hommel et al., 2004; Thompson & Massaro, 1989; Trick & Enns, 1998). However, developmental improvements in feature search may follow multiple trajectories, depending on the visual feature tested. For example, Donnelly et al. (2007) found that younger children (6- to 7-year-olds) were slower to detect an orientation-defined target (e.g., oblique bar) relative to a color-defined target (e.g., red bar) among spatial distractors (e.g., vertical bars or purple bars, respectively), but older children (9- to 10-year-olds) are equally fast to detect either target. This finding suggests that processing color information across the visual field may develop earlier in childhood than processing orientation information. Like contrast sensitivity, we predict that visual feature search competence will improve with age but will be poorer for color than luminance (Prediction 2). Moreover, how these age-related differences in visual processing relate to visual selective attention development remains unclear.

The development of visual feature integration and neurobiological considerations

The second stage of attention according to feature integration theory is the integration of an object's constituent visual features into a coherent whole at a specific location in space (Treisman & Gelade, 1980; Wolfe, 1994). We note that the guided search model (Wolfe, 1994, 2021), which builds on feature integration theory, conceptualizes parallel visual processing (measured by a feature search task) and feature integration stages (measured by a conjunction search task) as existing along a continuum, where attentional selection involves top-down guidance to a relevant visual feature. Visual feature integration is traditionally measured with a conjunction visual search task, where participants search for a target object defined by the conjunction of two or more visual features (e.g., red square) among a varying number of spatial distractors that share one visual feature with the target (e.g., green squares and red circles). These skills/tasks reflect complex visual selective attention processes. In this section, we review multiple processing demands that may result in differences in visual feature integration, and as such in visual selective attention performance, in childhood.

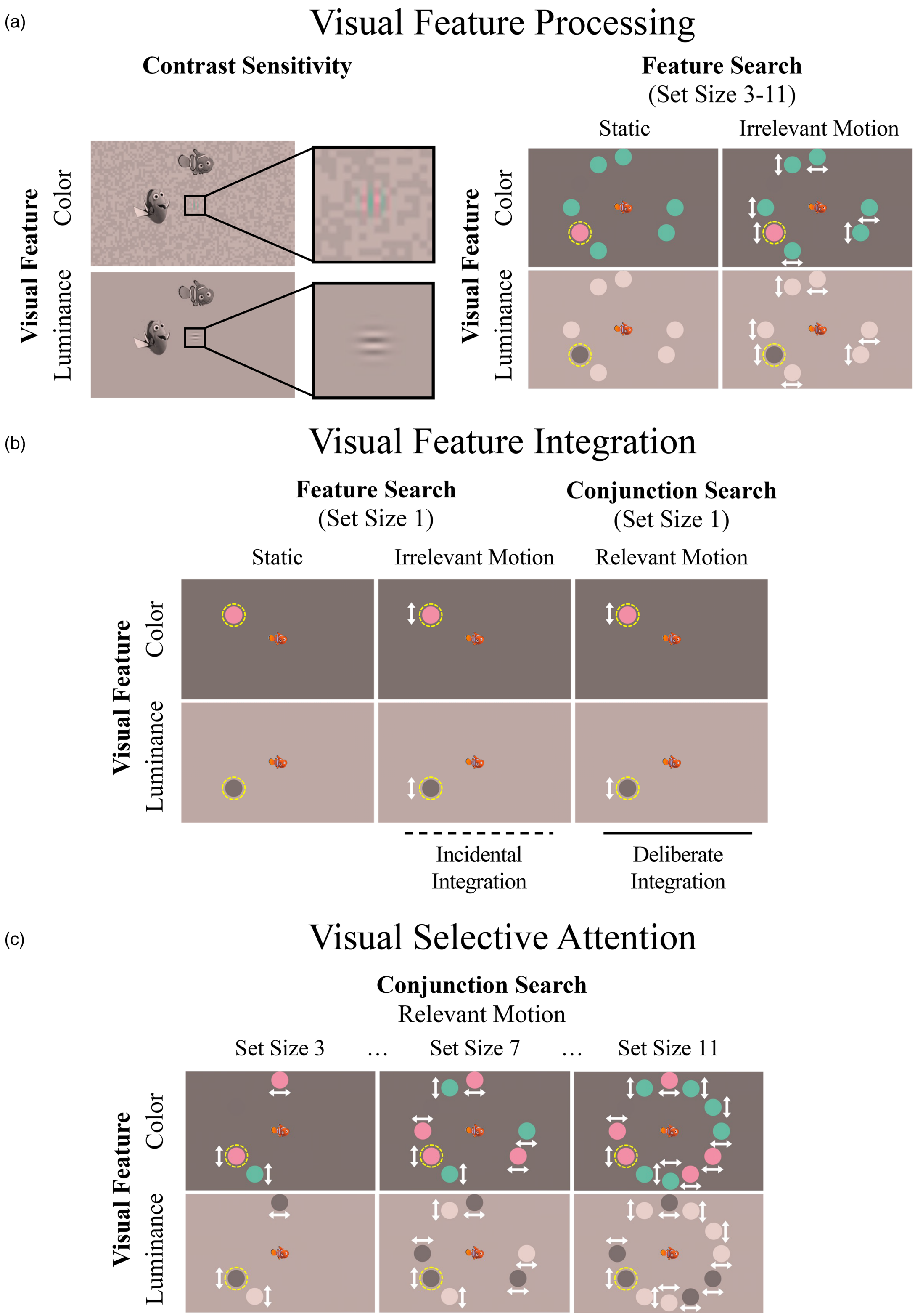

FIGURE 1 Illustration of task conditions and measured constructs. (a) Illustration of tasks measuring visual feature processing. Left, contrast sensitivity trials. Luminance probe trials were presented without noise. Color-r/g probe trial presented with luminance noise. Not depicted: Color-b/y trials and the 5 Hz temporal noise masks presented between each probe to disrupt the respective feature channel. Children completed 64 trials for each Visual Feature condition. (b) Illustration of tasks measuring visual feature integration. Only one target or distractor (Set Size 1) was presented on each trial. No spatial distractors were presented. During feature search, participants searched for a red or black circle. During conjunction search, participants searched for a vertically moving red or black circle. On some feature search trials stimuli were moving, but motion was irrelevant (incidental integration). On all conjunction search trials stimuli were moving, and motion was relevant (deliberate integration). (c) Illustration of task measuring visual selective attention. Only Set Size 3, 7, and 11 trials are depicted. Not depicted: Set Size 5 and 9 trials. Images are for illustrative purposes only. Circles did not overlap during motion. Only target present trials are depicted. Yellow dashed circles = target. White arrows = motion direction.

First, attending to a single complex object, even in the absence of spatial distractors, requires visual feature integration. In the present study, we therefore attempt to distinguish developmental change in visual feature integration without spatial distractors from visual selective attention measured through a conjunction visual search task. To date, little research examines the development of visual feature integration, per se. One study found that both children and adults are slower to identify a single target defined by two visual features (e.g., color and shape) relative to a single target defined by one feature (e.g., color; Trick & Enns, 1998). A recent study found that the ability to integrate color and motion may follow a different developmental trajectory than integrating luminance and motion, with color-motion integration developing more slowly than luminance-motion integration (Lynn et al., 2020). In combination with the findings of protracted age-related color relative to luminance processing reviewed in the previous section, this finding suggests developmental changes in visual feature integration may be related to specific visual feature processing competence. Here we isolated visual feature integration to better examine its developmental course and its ostensible contribution to the development of visual selective attention.

Second, visual feature integration can occur either deliberately or incidentally (Figure 1b). In one case, a child might be instructed to identify whether a black circle is present, regardless of its direction of motion. In another case, a child might be asked to identify whether a *vertically moving black circle* is present. For clarity, the target is only present on some trials, with other trials (target absent) showing variations of feature combinations (e.g., horizontally moving black circle, vertically moving white circle). Across these conditions, the visual experiences are identical, but the demands on feature integration are quite different. For example, detecting a target object (e.g., black circle) that is also defined by a feature that is irrelevant to the selection goal (e.g., motion) may place a greater demand on attentional resources than detecting a target object containing only a single relevant feature (e.g., color), simply because the irrelevant feature may be incidentally integrated with the object's other features (Prediction 3; Markant & Amso, 2022). Moreover, detecting a conjunction of features (e.g., luminance-motion) may be more costly than a detecting a single feature (e.g., luminance only) regardless of the additional cost of distraction incurred by irrelevant features (e.g., motion; Prediction 4). In other words, like irrelevant spatial distractors, a target object's constituent visual features may also act as a distraction and/or additional noise that slows the attentional process via increased processing demands.

Third, neurobiological constraints may further shape the development of feature integration abilities. Visual features are first processed in parallel across multiple visual cortical pathways (e.g., dorsal and ventral; Felleman & Van Essen, 1991; Kravitz et al., 2011, 2013; Ungerleider & Haxby, 1994). Arguably, feature integration demand depends on the need to integrate local neural processing across varying cortical distances. Therefore, integrating some visual feature combinations may be more demanding than others because some features are coded within the same visual pathway (e.g., luminance and motion in the dorsal pathway) and others are coded across more than one visual pathway (e.g., color and motion in the ventral and dorsal pathways, respectively; Gegenfurtner, 2003; Seymour et al., 2009; Shipp & Zeki, 1995; Sincich & Horton, 2005). Evidence from neuropsychology suggests that disconnection of these pathways may contribute to weaker attentional abilities (Festa et al., 2005). Recent developmental neuroimaging work suggests that ventral pathway structural connections are adult-like by 5-years-old, but dorsal pathway and dorsal–ventral pathway connections are not yet adult-like (Vinci-Booher et al., 2022). If the distance between cortical areas processing distinct visual features plays a role in developing feature integration skills, we would predict better performance with age on luminance-defined moving targets than on color-defined moving targets, especially when motion is relevant for the task-at-hand (Prediction 5). Moreover, developmental improvements in visual feature processing competence should support improvements in visual feature integration, depending on the visual feature (Prediction 6).

The development of visual selective attention across childhood

Visual selective attention requires the simultaneous selection of a target object and the suppression of competing spatial distractors (Carrasco, 2011; Desimone & Duncan, 1995; Lynn & Amso, 2021; Treisman & Gelade, 1980). As with visual feature integration, visual selective attention is traditionally measured with a conjunction visual search task (Figure 1c). In contrast to feature search tasks where the target object "pops out" and search time is generally unaffected by the number of spatial distractors, search time increases linearly with the number of spatial distractors in conjunction search tasks (Treisman & Gelade, 1980; Wolfe, 1994). Across childhood, this search rate (RT slope) becomes faster (Donnelly et al., 2007; Gerhardstein & Rovee-Collier, 2002; Merrill & Lookadoo, 2004; Plude et al., 1994). While previous work has examined how top-down cues influence visual selective attention across child development (Lookadoo et al., 2017; Merrill & Lookadoo, 2004), little research examines how other component cognitive processes impact the development of visual selective attention. A recent study shows that younger children (4- to 6-year-olds) are better able to find a moving luminance-defined circle among spatial distractors than a moving color-defined circle, while older children (8- to 10-year-olds) are equally capable of finding moving luminance- and color-defined circles (Lynn et al., 2020). This may be because feature integration of color and motion develops later than integration of luminance and motion. However, studies of how bottom-up visual processing impacts visual selective attention development are scarce. We predict that age-related changes in visual feature processing competence and/or visual feature integration across childhood will account for age-related differences in visual selective attention, depending on the visual feature that is the target of attention (Predictions 8 and 9). Such effects would provide evidence that visual attention emerges across development through cascading changes at increasingly higher processing levels, and that attention may be better understood as a computation limited across development by the inputs over which it operates, rather than a set of processes with a uniform developmental trajectory (Amso & Scerif, 2015; Lynn & Amso, 2021; Werchan & Amso, 2017).

The current study

We present a fully within-subjects comprehensive developmental investigation of the hypothesis that visual processing and visual feature integration support age-related change in visual selective attention (see Table 1 for all predictions). First, we tested how visual feature processing changes with age depending on visual feature dimension (e.g., color, luminance). Then, we examined how visual feature integration changes with age depending on feature relevance (i.e., incidental vs. deliberate integration) and integration demand (e.g., color-motion vs. luminance-motion). Next, we examined how visual selective attention changes with age depending on integration demand. Finally, we tested our working model of visual selective attention development, which posits that age-related changes in visual processing and feature integration may account for improvements in visual selective attention across childhood.

METHODS

Participants

The present sample included one hundred three 4- to 9-year-old children (M=6.60 years, SD=1.39 years; 59 female). Children's race make-up included 83.5% White, 2.9% Black/African American, 2.9% Asian or Pacific Islander, 1% Native American/American Indian, 4.9% Multi-racial, 3.9% "other", and 1% declined to answer. Children's ethnic make-up included 87% non-Hispanic, 12% Hispanic, and 1% declined to answer. Children and their parents were recruited through advertisements and were all local Providence, RI community members. Children were screened for neurodevelopmental disorders (e.g., autism), learning disabilities (e.g., dyslexia), neurological disorder (e.g., seizure disorder) or injury, and color blindness (Ishihara tests for color-deficiency). Children provided assent and adults provided consent in accordance with the University IRB. Families were compensated $15.

TABLE 1 A list of key predictions.

	Visual processing
Prediction 1	Contrast sensitivity will improve with age, but sensitivity will be lower for color than luminance
Prediction 2	Feature search performance will improve with age, but performance will be poorer for color than luminance
Prediction 3	Feature search performance will be poorer for irrelevant motion Set Size 3–11 trials relative to static Set Size 3–11 trials and this difference will be larger for color than luminance
	Visual feature integration
Prediction 4	Target detection will be poorer for irrelevant motion Set Size 1 visual search trials relative to static Set Size 1 trials and this difference will be larger for color than luminance
Prediction 5	Target detection will be poorer for irrelevant motion Set Size 1 visual search trials relative to relevant motion Set Size 1 trials and this difference will be larger for color than luminance
Prediction 6	Individual differences in color contrast sensitivity will be positively correlated with color-motion feature integration for color+motion. Such an effect will not be evident for luminance because luminance-motion feature integration will not change with age.
	Visual selective attention
Prediction 7	Conjunction search performance will be poorer with increasing distractors and this effect will be larger for color than luminance, but this difference will decrease with age
Prediction 8	Better contrast sensitivity and feature search performance will be associated with more efficient conjunction search across age
Prediction 9	Better incidental and deliberate feature integration performance will be associated with more efficient conjunction search across age

General procedure

Children first completed a contrast sensitivity task, followed by a feature search task, and then a conjunction visual search task. We counterbalanced the order of the Visual Feature condition (i.e., color or luminance) and maintained this order across tasks. For example, if a child began the feature search task searching for a color-defined target and ended with searching for a luminance-defined target, they also began the conjunction search task by searching for a color-defined target. See subsequent sections for details about task conditions and counterbalancing. Together with the experimenter, children tracked their progress across all tasks, regardless of performance, with a "sticker chart". Following the completion of each task, children chose a sticker, and the experimenter oriented them to their progress toward session completion.

Equipment and calibration

Children completed all tasks on a desktop computer using PsychToolbox and MATLAB software. We used a NVIDIA Quadro FX 1800 and EIZO CG2420 ColorEdge monitor to obtain 10-bits-per-channel color resolution to allow for presentation of much finer grain color differences than would be possible under standard 8-bit rendering and therefore greater precision in the psychophysical measurements. Briefly, we first measured the chromaticities and gamma functions of the red, green, and blue monitor primaries using a ColorCal MkII and Minolta CS-200. Chromaticities for each color primary (R, G, and B) were converted to tristimulus (CIE XYZ) values. We calculated the tristimulus-RGB conversion matrix—a 3×3 matrix which when matrix-multiplied by a tristimulus triplet returns an RGB triplet. Since this conversion assumes a linear relationship between the RGB value and the output (luminance, Y, in cd/m^2), we applied a gamma correction based on a look-up table. The equations from Macleod and Boynton (1979) footnote 2, p. 1186) were used to identify the cone-opponent axes in tristimulus space and enable calibration of the chromatic stimuli.

Contrast sensitivity task

Stimuli

Stimuli were either color- or luminance contrast-modulated Gabor patches (Figure 1a). Color contrast-modulated Gabor patches varied along either the L/(L+M) (red-green, hereafter color-r/g) or S/(L+M) (blue-yellow, hereafter color-b/y) axes of Macleod and Boynton (1979) chromaticity space. This space models the cone-opponent retinogeniculate pathways which encode color early in visual processing. The mean luminance of each stimulus was about $50\,cd/m^2$ (10-pixel squares, 45 and $55\,cd/m^2$). We used the QUEST+ adaptive psychometric procedure to modulate Gabor patch contrast at the trial level (Watson, 2017). On each trial, the algorithm updated with children's previous trial accuracy to determine the contrast level to be presented on the following trial to maximize the ability to estimate children's psychometric function. Generally, a higher contrast Gabor patch was more likely to be presented following error, and a lower contrast patch was more likely to be presented following a correct response.

Procedure

We asked children to complete an orientation discrimination task across three counterbalanced Visual Feature conditions (luminance, color-r/g, and color-b/y). Children rested their heads in a chin rest to reduce motion. During breaks, we reminded children to hold still as needed. We asked children to indicate the orientation of a centrally presented, contrast-modulated Gabor patch via button press. We held spatial frequency (2 cpd) and phase constant.

Children first completed the instruction phase in which an illustration of a centrally presented Gabor patch was oriented toward one of two cartoon fish reference images. During the instruction phase, the experimenter explained that vertical lines were "going up and down" and horizontal lines were "going side to side" to ensure children understood orientation differences. Then, children viewed a series of vertical and horizontal Gabor patch illustrations and were asked to verbally indicate whether the lines were "going up-and-down" or "going size-to-side." Next, we provided children with two blue buttons (xKeys Orby Switch, ~6.3 cm) attached to a response pad with cartoon reference images presented directly below the corresponding button to serve as a reminder. Children then saw a series of vertical and horizontal Gabor patch illustrations with luminance-normalized cartoon fish reference images (e.g., "Nemo" and "Dory") on the computer screen. We then asked children to indicate which cartoon character the "lines are pointing to" by pressing the button corresponding to the cartoon reference image.

Following the instruction phase, children completed six randomly ordered practice trials. Practice trials were presented at 25%, 50%, and 100% contrast to demonstrate to children that the contrast would vary. The experimenter repeated the practice phase if the child was unsure of what they were supposed to do or responded incorrectly for all practice trials. Then, children completed 64 experimental trials. Each trial began with a fixation cross embedded in a full-screen 5 Hz temporal noise mask matching the target feature (e.g., luminance, color-r/g, color-b/y) to disrupt visual feature processing and reduce possible after-image effects. Next, children viewed a contrast-modulated Gabor patch and then indicated its orientation via button press. To isolate the color, and ensure that any residual luminance signal was masked, both color-r/g and color-b/y contrast-modulated Gabor patches were embedded in luminance noise across the entire screen (~10-pixel squares) that approximated the Gabor patch spatial frequency (2 cpd; see Figure 1a).

Dependent measures

We estimated the threshold and slope of the contrast sensitivity function, and proportion of attentional lapses using the QUEST+ adaptive psychometric procedure with the following parameters: contrast = −40-0 dB; slope = 2–5, guess rate: 0.5, lapse rate = 0–0.04. We converted children's contrast threshold (dB) to Michelson contrast and then calculated log contrast sensitivity (1/Michelson contrast threshold).

Visual feature integration and search task

Stimuli

Stimuli consisted of red, green, black, and white circles (approximately 0.5° in diameter). Circles were either static (static feature search) or oscillated approximately 0.5° in either direction around their initial starting point at a speed of approximately $1° \times s^{-1}$ (moving feature search, conjunction search). Circles were presented in one of 12 concentric locations equidistant from the screen center (approximately 8°), where an orange cartoon clown fish ("Nemo") served as a fixation point. Stimulus color values were extracted from the look-up table created during monitor calibration. Red and green colors were matched for luminance, and black and white colors were matched for chromaticity. The luminance contrast between the background and the stimuli were equated for each Visual Feature condition.

Procedure

We asked children to complete both a feature search and a conjunction search task. During the instruction phase, we showed children pairs of stimuli and asked them to point to the one that had a specific feature (e.g., red) to verify that children could distinguish between red and green, between black and white, and between vertical and horizontal motion. Children then completed six practice trials (three target present and three target absent), randomly selected across Set Size conditions. If children did not understand the task, the experimenter repeated this instruction and practice phase.

We instructed children to "press the button as fast as you can when you see" a target and "don't press the button if you don't see" a target. We presented targets on half of all trials. Across both search tasks, we randomly selected the target location from 12 possible locations. We pseudorandomly assigned distractors to the remaining locations, with the requirement that one distractor be adjacent to the target. We allowed children to move their eyes freely throughout trials.

For both search tasks, we manipulated Visual Feature and Set Size. In the color condition, stimuli were red and green. In the luminance condition, stimuli were black and white. The Set Size condition ranged from 1 to 11, in increments of 2. On target present trials, we presented only one target item. For Set Size 1, we presented either a target or a distractor (no spatial distractors). We terminated trials when a response was recorded. We then added the remaining trial duration time to the subsequent ITI (min 1.5 s). Following each search display, a cartoon fish was presented for 1 s to direct children's attention to the center of the screen. We offered children a break between each block of trials.

Feature search

Across two Visual Feature conditions (color and luminance), we asked children to complete a feature search task in which they search for a red or black target circle presented among distractors for up to 2 s. Across all blocks, we randomly ordered Set Size trials, with the constraint that no more than three of the same Set Size conditions were presented consecutively. We equally distributed Set Size trials across all conditions. We presented Visual Feature conditions in counterbalanced blocks of 96 trials. Within each Visual Feature condition, we manipulated motion information in two counterbalanced Motion condition (static, moving) blocks of 48 trials each. Within the moving condition only, we also manipulated stimuli motion direction across all stimuli (heterogeneous, homogeneous). In the homogeneous condition, we allowed all items to move in phase synchrony in the same direction. In the heterogeneous condition, we allowed about half the items to move vertically while the other half moved horizontally. We randomly ordered homogeneous and heterogeneous trials within each Motion Present block. Critically, motion information was not relevant for detecting the color- or luminance-defined target. Overall, performance was near ceiling on the feature search task (Accuracy: $M = 96.6\%$, SD = 4.0%; RT: $M = 884.21$ ms, SD = 174.91 ms).

Conjunction search task

Across two Visual Feature conditions (color-motion, luminance-motion), we asked children to complete a conjunction search task in which they search for a *vertically moving* color- or luminance-defined target presented among vertically and horizontally moving color- or luminance-defined distractors for up to 3 s. We randomly ordered Set Sizes trials and counterbalanced Visual Feature conditions. We presented each Visual Feature condition in four blocks of 24 trials. Critically, motion information was relevant for target selection. The adjacent distractor type (e.g., vertically moving green circle, horizontally moving red circle) was counterbalanced across all trials. Overall, performance was good on the conjunction search task (Accuracy: M=77.6%, SD=12.7%; RT: M=1766.85 ms, SD=209.47 ms).

Dependent measures

We measured children's performance, P=RT(1+2ER), as reported by Lyons et al. (2014), where RT is reaction time (ms) and ER is error rate. P is like the more common inverse efficiency score (I=RT/Accuracy), but P linearly weights accuracy whereas the inverse efficiency score nonlinearly weights accuracy. P can essentially be interpreted as RT (ms) with higher scores interpreted as overall slower performance. We then took the log of this measure because P distributions were slightly negatively skewed. We used performance (P) for Set Size 1 trials as our visual feature integration measure and performance for Set Size 3 through 11 trials as our visual selective attention measures.

RESULTS

We first systematically examined children's contrast sensitivity, feature search performance with spatial distractors (Set Size 3–11), visual search without spatial distractors (feature and conjunction search Set Size 1), and conjunction search performance with distractors (Set Size 3–11) for both luminance and color tasks. Then we examined our working model of visual selective attention development using a structural equation model, where we specifically tested whether each of the previously examined visual and cognitive factors accounts for age-related changes in conjunction search efficiency, our strongest measure of visual selective attention. In this way, our analyses are confirmatory of the several predictions for each task and the overall working model of visual selective attention development.

Age-related changes in luminance and color contrast sensitivity (Prediction 1)

During a contrast sensitivity task (Figure 1a), children saw a centrally presented, vertically or horizontally oriented 2 cpd Gabor patch across three Visual Feature conditions (luminance, color-r/g, color-b/y). Using the QUEST+ function, we systematically manipulated stimulus contrast to estimate contrast sensitivity threshold for each Visual Feature condition. We converted children's dB to Michelson contrast and then calculated log contrast sensitivity [log(1/Michelson contrast threshold)]. Contrast sensitivity threshold measures the minimum amount of contrast needed to reliably distinguish between feature values (e.g., red and green) within a given feature dimension (e.g., color). We removed 15 univariate outliers (1.5×interquartile range, IQR) across at least one Visual Feature condition. We did not identify any multivariate outliers (Mahalanobis distance χ^2, df=2) across Visual Feature conditions and Age. An additional two children did not complete the contrast sensitivity task. This subsample included 86 children. We also conducted a sensitivity power analysis, using G*Power (Faul et al., 2007), which indicated the current sample size provided the power to detect large effects (η_p^2>.1545).

We submitted log contrast sensitivity values to a linear mixed-effects model with Visual Feature (luminance, color-r/g, color-b/y) condition as a within-subjects factor, Age as a continuous variable, and Participant intercept as a random factor. We found a main effect of Visual Feature, $F_{(2,168)}$=974.76, p=2.2×10^{-16}, η_p^2=.92, and a main effect of Age, $F_{(1,84)}$=24.06, p=4.5×10^{-6}, η_p^2=.22. However, we found no Visual Feature×Age interaction (p=.63). These findings suggest that contrast sensitivity improves with age across childhood similarly for luminance and color feature channels, but that luminance sensitivity is higher than color sensitivity across the tested age range (Prediction 1, Figure 2a).

Age-related changes in feature search performance (Predictions 2 and 3)

Recall that during feature search children searched for a color- or luminance-defined target across two Motion conditions, one when motion was absent (static) and one when motion was present but irrelevant (irrelevant motion) to target detection (Figure 1a). We also varied the number of concurrent spatial distractors across several Set Size conditions (3–11). The canonical feature search finding is that the target stimulus "pops-out" among any number of homogenous distractors (Treisman & Gelade, 1980). The static motion condition served as a control to establish the canonical feature search finding relative to the irrelevant motion manipulation. We reasoned that if children also process motion across the visual field, then feature search performance should be poorer for the irrelevant motion relative to static condition. We first removed nine univariate outliers (1.5×IQR) across one or more Visual Feature conditions. We also removed two additional multivariate outliers (Mahalanobis distance χ^2, df=4) across Visual Feature conditions and Age. This subsample included 92

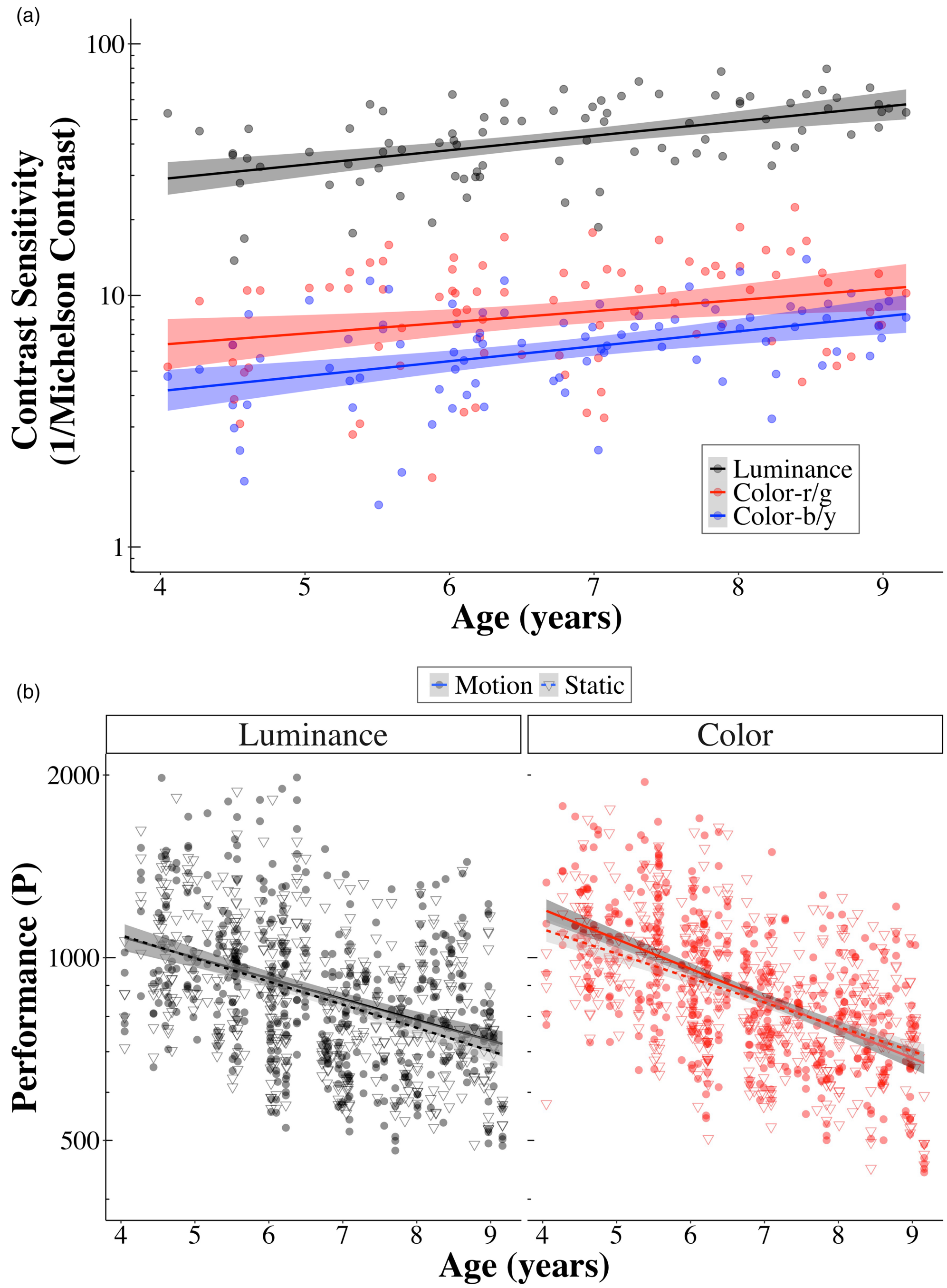

FIGURE 2 Age-related change in visual feature processing. (a) Contrast sensitivity increased with age similarly for luminance and color. Sensitivity was greater for luminance than color, but not different between color -r/g and b/y. (b) Feature search performance, collapsed across Set Size 3 through 11 trials. Color-motion search is slightly slower for younger children relative to color-static and luminance conditions. Note that this effect size is very small. *Y* axes are in $\log_{10}$ scale. Shaded areas surrounding best-fit lines indicate 95% confidence intervals. Darker datapoints indicate datapoint overlap.

children. We also conducted a sensitivity power analysis using G*Power (Faul et al., 2007), which indicated the current sample size provided the power to detect large effects ($\eta_p^2 > .2486$).

Consistent with our previous analyses, we submitted participant's log *P* values for feature search trials to a linear mixed-effects model with Visual Feature (luminance, color) and Motion (static, irrelevant motion) conditions as fixed within-subject factors, Set Size (3, 5, 7, 9, 11) and Age as continuous variables, and Participant intercept as a random factor. We found main effects of Age, $F_{(1,91)} = 60.20$, $p = 1.2 \times 10^{-11}$, $\eta_p^2 = .40$, and Motion, $F_{(1,1753)} = 5.88$, $p = .01$, $\eta_p^2 = .003$. We also found a Visual Feature × Age interaction, $F_{(1,1753)} = 10.48$, $p = .001$, $\eta_p^2 = .006$, and a Visual Feature × Motion × Age interaction, $F_{(1,1753)} = 5.90$, $p = .01$, $\eta_p^2 = .003$ (all other *p*s > .12).

To follow-up with the three-way interaction, we tested for a Motion × Age interaction in each Feature condition separately. We found a Motion × Age interaction in the color, $F_{(1,835)} = 6.92$, $p = .009$, $\eta^2_p = .008$, but not the luminance condition ($p = .28$). The three-way interaction therefore demonstrates that performance was more strongly correlated with Age in the color-irrelevant motion condition, $r_{(463)} = -.58$, $p < 2.2 \times 10^{-16}$, relative to the color-static condition $r_{(463)} = -.50$, $p < 2.2 \times 10^{-16}$. However, such a motion-related developmental difference was not evident across the luminance-irrelevant motion, $r_{(468)} = -.40$, $p < 2.2 \times 10^{-16}$, and luminance-static conditions, $r_{(468)} = -.45$, $p < 2.2 \times 10^{-16}$.

Figure 2b shows that feature search performance for the color condition (especially with irrelevant motion) may be slower than the luminance condition in younger children but catches up by middle childhood, consistent with our predictions (Prediction 2). Importantly, these findings also show that the target stimulus "popped-out" among distractors regardless of Set Size, and that performance improved with age. These findings also suggest that irrelevant motion information may be automatically processed in parallel across the visual field (Prediction 3). However, the interaction effect sizes are very small and should be interpreted with caution.

Age-related changes in visual feature integration (Predictions 4–6)

During the feature search tasks, children searched for a single color or luminance-defined circle that was either static or moving (Figure 1b). During conjunction search tasks, children searched for a color-motion or luminance-motion-defined circle, again in the absence of distractors. Critically, motion was only *relevant* for accurate target detection during conjunction search but was *irrelevant* for target detection during feature search. Any difference in detection of targets across these otherwise visually identical trials can only be attributed to differences in demands on feature integration, whether it was incidental versus deliberate (Figure 1b). We note again that these trials were taken directly from the Set Size 1 stimuli in the visual search tasks.

First, we tested whether *irrelevant* motion impacts target detection performance. We removed three univariate outliers (1.5 × IQR) across at least one Visual Feature conditions. We did not identify any multivariate outliers (Mahalanobis distance χ^2, $df = 3$) across Age, Visual Feature or Motion conditions. An additional two children did not complete the feature search task. This subsample included 98 children. We also conducted a sensitivity power analysis using G*Power (Faul et al., 2007), which indicated the current sample size provided the power to detect large effects ($\eta^2_p > .1510$).

We submitted participants log P values for single target trials (Set Size 1, Figure 1b) to a linear mixed-effects model with Visual Feature (luminance, color) and Motion (static, irrelevant motion) conditions as within-subject factors, Age as a continuous variable, and Participant intercept as a random factor. We found a main effect of Age, $F_{(1,96)} = 58.91$, $p = 1.37 \times 10^{-11}$, $\eta^2_p = .38$, a Feature × Motion condition interaction, $F_{(1,288)} = 4.98$, $p = .03$, $\eta^2_p = .02$, a Motion × Age condition interaction, $F_{(1,288)} = 5.59$, $p = .02$, $\eta^2_p = .02$, and a Feature × Motion × Age interaction, $F_{(1,288)} = 4.35$, $p = .04$, $\eta^2_p = .01$. All other effects and interactions were not significant (all p's > .19).

To understand the three-way interaction, we followed up with a repeated measures ANCOVA in each Visual Feature condition (color, luminance) separately, with Motion condition (static, irrelevant motion) as a within-subject factor and Age as a continuous variable. We found a main effect of Age in both the color, $F_{(1,96)} = 53.00$, $p = 9.18 \times 10^{-11}$, $\eta^2_p = .36$, and the luminance conditions, $F_{(1,96)} = 37.14$, $p = 2.28 \times 10^{-8}$, $\eta^2_p = .28$. This effect confirms that overall performance for target detection improved with age regardless of Visual Feature and Motion conditions. We also found a main effect of Motion in the color condition, $F_{(1,96)} = 7.81$, $p = .006$, $\eta^2_p = .08$, but not the luminance condition ($p = .5$), as well as a Motion × Age interaction in the color condition, $F_{(1,96)} = 12.38$, $p = .0006$, $\eta^2_p = .11$, but not the luminance condition ($p = .84$), suggesting that the performance difference between Motion conditions for the color condition changed with Age, but not for the luminance condition.

Within the color condition, performance was more strongly correlated with Age during the irrelevant motion condition, $r_{(96)} = -.61$, $p = 3.168 \times 10^{-11}$, relative to the static condition, $r_{(96)} = -.42$, $p = 1.51 \times 10^{-5}$. However, during the luminance condition, performance was similarly correlated with Age during both the irrelevant motion, $r_{(96)} = -.49$, $p = 3.73 \times 10^{-7}$, and static conditions, $r_{(96)} = -.47$, $p = 1.30 \times 10^{-6}$. These data indicate that the presence of motion, albeit *irrelevant*, impacted detection of single color-defined target objects but not luminance-defined targets in the same children, and this effect was the largest in younger children. Figure 3a shows that, while children became faster for all conditions, younger children were slower to correctly detect moving color-defined targets than static color-defined targets.

These findings are consistent with our prediction (Prediction 4) that color-motion incidental integration would be poorer than luminance-motion. This effect may be due to color being more difficult to detect and/or motion posing an additive processing demand that is costly. We therefore correlated contrast sensitivity with incidental feature integration performance but found that contrast sensitivity was *not* significantly correlated with feature integration (irrelevant motion-static performance) in either Visual Feature condition when controlling for age (p's > .127). This effect is not consistent with our prediction (Prediction 6).

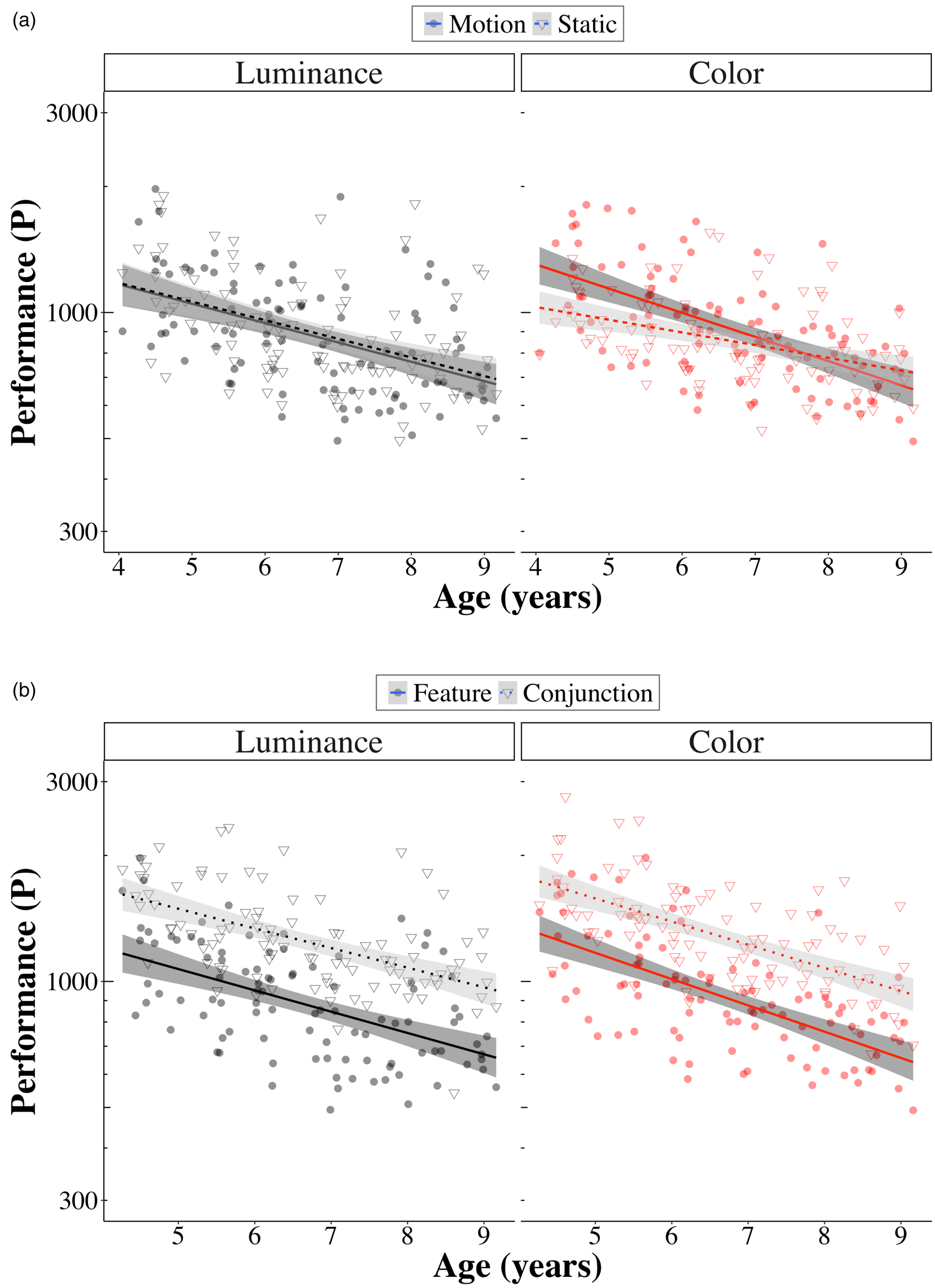

FIGURE 3 Age-related changes in visual feature integration (Set Size 1 trials). (a) Incidental feature integration (irrelevant motion-static) improves with age for color but not luminance. That is, performance for a single target detection improves with age for both luminance and color, but irrelevant motion affects color and not luminance. (b) Deliberate integration (conjunction search-irrelevant motion feature search) does not change with age for either color or luminance. Although performance improves with age across both conjunction and feature search trials for single target detection, target relevance impacts both color and luminance conditions similarly across our age range. Note that the irrelevant motion feature search data (b, solid line) are the same data as the irrelevant motion data (a, solid line). *Y*-axis is in $\log_{10}$ scale. Shaded areas surrounding best-fit lines indicate 95% confidence intervals. Darker datapoints indicate datapoint overlap.

Next, we tested whether relevant relative to irrelevant target motion impacted detection of color- and luminance-defined circles. We removed four univariate outliers (1.5 × IQR) across one or more Visual Feature conditions. We did not identify any multivariate outliers (Mahalanobis distance χ^2, $df = 3$) across Visual Feature conditions and Age. An additional two children did not complete the feature search or conjunction search tasks. This subsample included 97 children.

We submitted log *P* values for single target (Set Size 1, Figure 1b) irrelevant motion feature search and conjunction search trials to a linear mixed-effects model with Visual Feature (luminance, color) and Search Type (feature search irrelevant motion, conjunction search relevant motion) as fixed within-subject factors, Age as a continuous variable, and Participant intercept as a random factor. We found a main effect of Search Type, $F_{(1,285)}=316.90$, $p=2.2\times10^{-16}$, $\eta^2_p=.53$, and Age, $F_{(1,95)}=94.84$, $p=5.98\times10^{-16}$, $\eta^2_p=.50$. We found no other main effects or interactions (all other p's > .06). Figure 3b shows that children became faster with Age, and children were slower to detect targets when motion was relevant compared to when it was irrelevant for accurate target detection, despite holding visual information constant across search conditions. These effects provide partial support for our prediction (Prediction 5).

To summarize, in comparison to static targets, the addition of irrelevant motion resulted in poorer performance in younger children for color-defined targets only. That is, detection of a luminance-defined target improved similarly with Age regardless of whether it was moving or static. Detection of color-defined moving targets when motion was irrelevant was poorer than a color-defined static in younger children relative to older children (Prediction 4). However, regardless of Age, detecting a color- or luminance-defined moving target was more costly when motion was relevant for detection compared to when it was irrelevant (contrary to Prediction 5).

Age-related changes in conjunction search task performance (Prediction 7)

During conjunction search, children searched for a color-motion or luminance-motion defined circle among a varying number of spatial distractors (i.e., Set Sizes 3 through 11, Figure 1c). We reasoned that if feature integration demand affects children's visual selective attention, then search time may increase with distractor number to a greater degree for the color-motion relative to the luminance-motion condition (Lynn et al., 2020). Further, if integration demands affect visual selective attention less with age, then feature-related differences in performance may decrease with age. We removed three univariate outliers (1.5 × IQR) across at least one Visual Feature and/or one Set Size condition. We did not identify any multivariate outliers (Mahalanobis distance χ^2, df = 4) across Visual Feature or Set Size conditions and Age. This subsample included 98 children. We also conducted a sensitivity power analysis using G*Power (Faul et al., 2007), which indicated the current sample size provided the power to detect large effects ($\eta^2_p > .1955$).

We submitted participant's log P conjunction search values to a linear mixed-effects model with Visual Feature (luminance-motion, color-motion) and Set Size (3, 5, 7, 9, 11) as fixed within-subject factors, Age as a continuous variable, and Participant intercept and Set Size slope as random factors. We found that including Set Size slope as a random factor improved the model fit, log likelihood ratio = 853.72, $\chi^2 = 16.13$, $p=3.0\times10^{-4}$. Participant random effects accounted for approximately 47% (intraclass correlation coefficient = .47) of variance in performance values. At the fixed-effects level, we found main effects of Set Size, $F_{(1,94.69)}=174.76$, $p<2.2\times10^{-16}$, $\eta^2_p=.65$, and Age, $F_{(1,96.02)}=73.04$, $p=1.96\times10^{-13}$, $\eta^2_p=.43$. We also found a Set Size × Age interaction, $F_{(1,95.26)}=4.83$, $p=.03$, $\eta^2_p=.05$, and a Visual Feature × Age interaction, $F_{(1,765.35)}=10.27$, $p=.001$, $\eta^2_p=.001$.

We followed up with the Visual Feature × Age interaction by calculating the correlation between age and mean log P across Set Size conditions for each Visual Feature condition separately. We found that performance was more strongly negatively correlated with Age for the color, $r_{(96)}=-.63$, $p<5.6\times10^{-11}$, relative to the luminance condition, $r_{(96)}=-.60$, $p<8.4\times10^{-10}$. However, given the small effect size, this interaction should be interpreted with caution.

Figure 4 shows that Set Size slopes, regardless of Feature condition, become steeper between 4 and 7 years of age (contrary to Prediction 7). We therefore followed up with a sensitivity analysis to determine whether 4-year-olds were driving the Set Size × Age interaction. Upon removing children aged 4–4.99 years old, the Set Size × Age interaction was no longer significant ($p=.57$), but all other effects remained. This suggests that the youngest children in our sample were driving the age-related Set Size slope effect. These data also show that regardless of Set Size (distractor number), color-defined targets were more challenging to detect than luminance-defined targets in younger children.

Testing a novel model of visual selective attention development (Predictions 8 and 9)

We developed a structural equation model to test whether contrast sensitivity, feature search performance, and incidental and deliberate feature integration performance independently and/or collectively contribute to age-related changes in conjunction search efficiency, and whether these effects depend on which visual features are the target of attention. This subsample included children that contributed to all previous analyses ($N=74$).

In the full model (Figure 5), we included Visual Feature (luminance, color) as a categorical exogenous variable and Age as a continuous exogenous variable. We also included, as endogenous variables or mediators, contrast sensitivity, feature search performance (mean across Set Sizes 3–11), incidental feature integration (the difference between irrelevant motion and static Set Size 1 feature search trials), and deliberate feature integration (the difference between conjunction search and irrelevant motion Set Size 1 feature search trials). Finally, we included the slope of conjunction search performance across Set Size 3–11 as the endogenous variable.

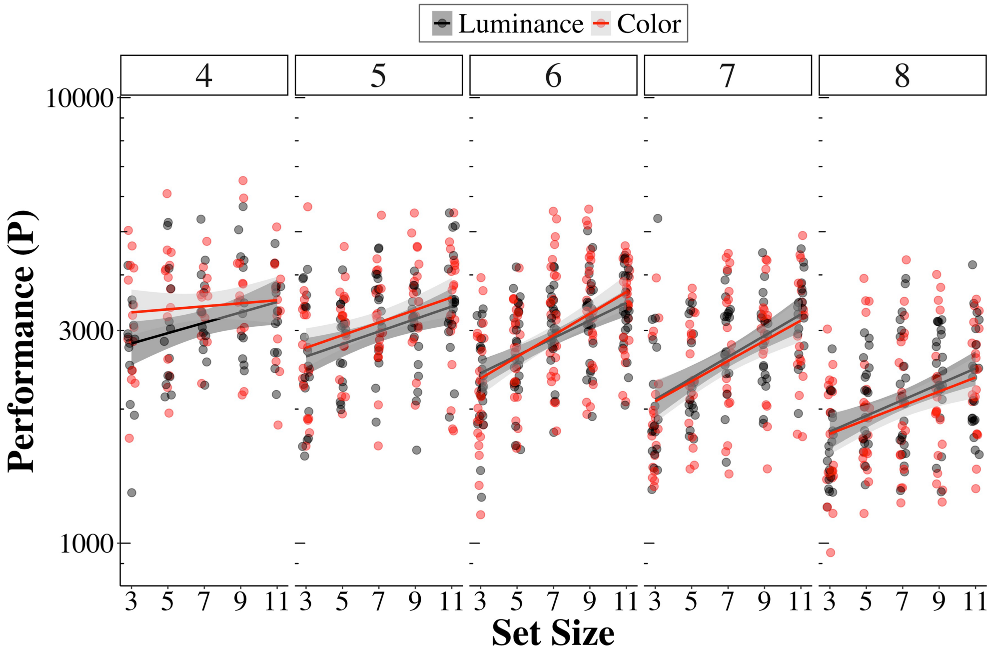

FIGURE 4 Age-related change in conjunction search performance. Conjunction search Set Size slopes change as a function of age but do not differ between Visual Feature conditions. Sensitivity analyses suggest this age-related difference is driven by younger children. *Y*-axis is in $\log_{10}$ scale. Shaded areas surrounding best-fit lines indicate 95% confidence intervals. Darker datapoints indicate datapoint overlap.

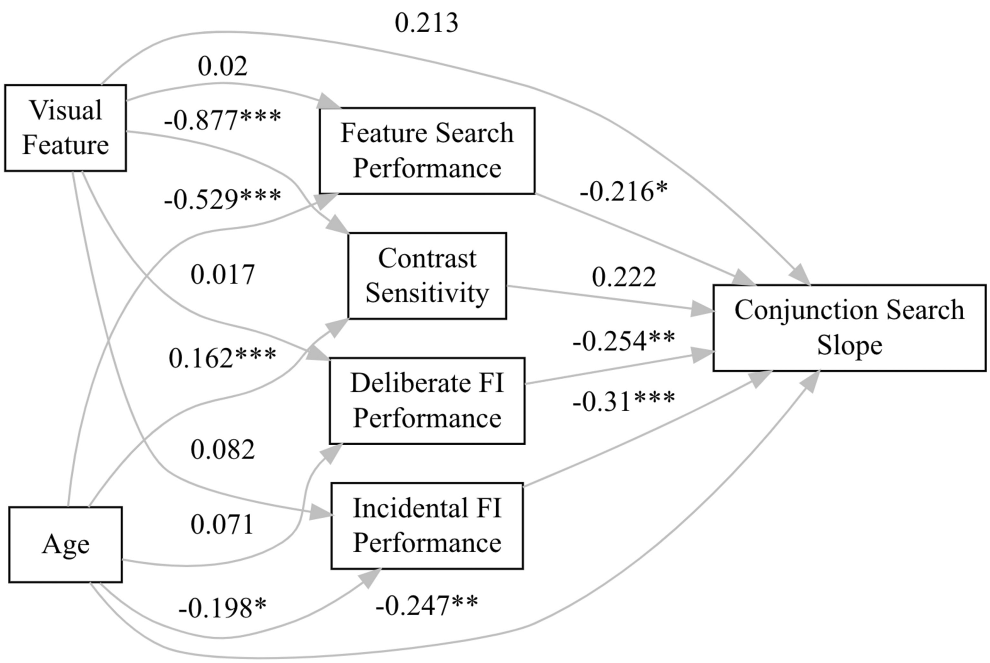

FIGURE 5 Working model of visual selective attention development. Feature search performance and incidental feature integration (FI) partially mediate age-related changes in conjunction search efficiency. Numbers associated with each path are beta values. Gray arrows depict relation between all variables in the full model. *$p<.05$; **$p<.01$; ***$p<.0001$.

We found that both feature search performance ($\beta=.11$, $z=2.04$, $p=.04$, 95% CI [.01, .23]) and incidental feature integration ($\beta=.06$, $z=1.87$, $p=.06$, 95% CI [.01, .14]) partially mediated age-related changes in the conjunction search slope. Collectively, contrast sensitivity, feature search performance, and incidental and deliberate feature integration partially mediated the relation between Age and conjunction search slope ($\beta=.19$, $z=2.94$, $p=.003$, 95% CI [.08, .33]). Overall, Age remained a significant predictor of conjunction search slope ($\beta=-.25$, $z=-2.61$, $p=.01$, 95% CI [−.43, −.06]). Together, these findings provide support for our predictions (Predictions 8 and 9).

DISCUSSION

In the present study, we provide support for a novel model of the development of visual selective attention that posits age-related changes in processing and integration of visual features support the development of visual selective attention. Using a contrast sensitivity task, we found that both luminance and color contrast sensitivity improve similarly with age across childhood (Prediction 1). Using a motion manipulation during a feature search task, we found limited evidence that, while performance improved with age, younger children were slower to detect color than luminance relative to older children (Prediction 2), and younger children were especially slower to detect color relative to luminance in the presence of irrelevant motion (Prediction 3). Using a novel manipulation across feature and conjunction search tasks, we found that children are slower to detect a moving color target relative to a moving luminance target when motion is irrelevant, but not *relevant*, to the task at-hand (Predictions 4 and 5). However, we found no evidence that contrast sensitivity is related to children's feature integration abilities (contrary to Prediction 6). Using a conjunction search task, we also found that the degree to which children's performance is slowed with additional distractors changes across childhood but is not dependent on which visual features are the target of attentional selection (Prediction 7). Finally, we built a structural equation model to show that, within the same child, faster feature search and better incidental feature integration across childhood partially accounts for age-related improvements in conjunction search efficiency (Predictions 8 and 9). These data provide evidence that, while visual processing abilities for multiple individual features (e.g., luminance and color contrast sensitivity) improve across child development, age-related improvements in the ability to process visual information across the visual field and ignore irrelevant target object features (e.g., motion) contribute to variability in visual selective attention efficiency *within an individual child* across development.

Our contrast sensitivity findings (Figure 2) are consistent with and add to previous work in two important ways. First, ours is the first study to examine both luminance and color visual feature dimensions within the same children, which allowed us to discover that both dimensions improve similarly across childhood. Developmental psychophysical studies show that luminance contrast sensitivity improves across early childhood and may reach adult-like levels as early as 7 years old (Ellemberg et al., 1999) or as late as 12 years old, but may depend on spatial frequency, and stimulus orientation (Almoqbel et al., 2017; Beazley et al., 1980; Mayer, 1977). Knoblauch et al. (2001) found that chromatic sensitivity improved from infancy, through childhood, and into adolescence. Second, our study demonstrates the utility of an adaptive psychometric algorithm (Watson, 2017), validated for use in children (Farahbakhsh et al., 2019), to estimate contrast sensitivity across multiple visual feature channels.

Our feature search findings (Figure 2b) show that children's ability to process color- and luminance-based signals across a visual field of spatial distractors, improves with age similarly across childhood. Previous work by Donnelly et al. (2007) showed that 6- and 7-year-old children detect color targets faster than orientation targets, but 9- and 10-year-old children and adults find color and orientation targets equally fast. Taken together, these findings suggest that distributed luminance and color processing may develop earlier than orientation processing. However, the current study design was such that blocks of trials were grouped by visual feature, which may contribute to a priming effect across trials.

We also built on a novel manipulation to examine the development of feature integration (Lynn et al., 2020). Feature integration refers to the ability to integrate multiple visual features into a single visual field location (Treisman & Gelade, 1980). The current findings suggest that feature integration may occur at multiple processing levels. These are the incidental and deliberate feature integration processes that we suspect occur in an early, feedforward and a later, feedback, manner, respectively. The data indicate that feature integration that occurs incidentally has a longer developmental trajectory than integration that occurs deliberately (Figure 3). Younger children may be more easily distracted by a target object's irrelevant feature and therefore may perform worse when irrelevant features are present, suggesting they may incidentally integrate irrelevant and relevant features. This interpretation is in line with recent developmental work that shows 5-year-olds' attention is captured by irrelevant visual features of spatial distractors, but they can subsequently ignore this distracting feature (Blakley et al., 2022).

Our current feature integration findings also suggest that, in line with our previous work (Lynn et al., 2020), incidental feature integration abilities may depend on the cortical distance between the local encoding of the target features. That is, we found younger children were more likely to incidentally integrate motion with color relative to luminance, in the absence of spatial distractors (Figure 3a). This evidence provides supports for the idea that feature integration is more costly when features must be combined across the dorsal and ventral cortical pathways, rather than within either pathway. The age-related differences in incidental (irrelevant) relative to deliberate (relevant) feature integration for color-motion combinations suggest that, early in childhood, integrating relevant and irrelevant feature information *across* visual pathways may be more costly than integrating *within* a visual pathway.

The extant developmental literature shows that conjunction visual search performance improves across childhood for targets defined by features coded within the ventral visual pathway (i.e., color, orientation, objects; Donnelly et al., 2007; Gerhardstein & Rovee-Collier, 2002; Merrill & Lookadoo, 2004; Trick & Enns, 1998). The present study examines visual search within the same children for targets coded within the dorsal (luminance, motion) or across both the dorsal and ventral visual pathways (color, motion). We found that, while children's conjunction search efficiency changed with age, on average this effect did not differ between Visual Feature conditions (Figure 4). This finding contrasts with our previous study of 4- to 10-year-old children, which used a similar task and showed that color-motion conjunction search efficiency *decreases* with age, but luminance-motion efficiency remains stable (Lynn et al., 2020). One key difference in the present study is that we added set size conditions 7, 9, and 11, whereas the previous study included only Set Size conditions 3 and 5. This manipulation creates a substantially larger demand on visual selective attention for young children. One possibility is that the current task dynamics could have resulted in greater engagement of visual selective attention computations in a manner that obviated the previously found effect. Alternatively, and perhaps relatedly, the increase in the number of set size conditions may have offered us a better estimate of visual selective attention abilities. Future work should explore selective attention in younger children and adolescence as a function of visual feature dimensions to better characterize these developmental trajectories.

Finally, using a structural equation modeling framework, we found support for a recently proposed theoretical model of visual selective attention development (Amso & Scerif, 2015; Lynn & Amso, 2021). Contrast sensitivity, or low level visual processing, *did not alone* mediate age-related improvements in conjunction search efficiency in this age range, nor was it related to feature integration performance. Rather, we found that age-related improvements in feature search performance and incidental feature integration partially mediate age-related changes in conjunction search efficiency, and that this did not differ across feature conditions (Figure 5). Importantly, incidental feature integration mediation was supported by a small effect size and borderline significance, and age remained a significant predictor of visual selective attention, suggesting additional developmental mechanisms are at play that are not examined in the current study. In total, we provide evidence that the developmental mechanisms underlying improvements in visual attention are multifaceted and include selecting relevant visual features and visual field locations as well as suppressing a target object's irrelevant visual features and competing spatial distractors.

Future directions and limitations

The present study is not without its limitations that in turn also provide many opportunities for future research. First, we test only one spatial frequency (2 cpd) of contrast across static luminance and color visual features. Thus, whether these findings generalize to other feature values (e.g., blue and yellow, high spatial frequency, etc) is unknown. Future work should build on this approach to test multiple visual features across a range of spatial and temporal frequencies, which will serve to provide a comprehensive assessment of visual function in childhood. Second, the current study design grouped color and luminance conditions in blocks of trials that were counterbalanced across children. Future work should intersperse Visual Feature condition trials to test whether younger children flexibly process visual features across the visual field, as one study suggests this tendency develops around mid to late childhood (Grubert et al., 2014). Third, the current study design is predicated on the assumption that visual feature integration and selective attention are mediated by brain connectivity between regions coding the constituent features of a target object. Future research examining structural and functional brain connectivity within and between visual pathways while children complete this novel feature integration task is necessary to determine whether these age-related changes are driven by the distributed coordination of local neural processing. Distractor location and feature relevance should receive special consideration, as these factors appear to be important for shaping the developmental trajectories of feature integration abilities during childhood. Fourth, while including both visual feature processing competence (measured using a rigorous psychophysical method) and visual feature integration in the full structural equation model, both processes required that children attend to the stimulus. Future work will determine whether visual processing competence per se impacts visual feature integration and selective attention, or whether other visual and/or cognitive mechanisms not explored in the present study are better predictors of visual selective attention development. For example, a future study might measure visual feature processing competence in the presence and absences of attention, as attention is known to enhance visual feature processing in adults (Carrasco, 2011; Carrasco et al., 2004; Ling & Carrasco, 2006; Pestilli & Carrasco, 2005). Finally, our sample is racially/ethnically homogenous. As such, whether our current findings generalize to the broader population is unknown. Future work must reduce sampling bias and work toward building an equitable and inclusive developmental science (Nketia et al., 2021).

CONCLUSIONS

Here, we present a fully within-subjects comprehensive assessment of children's visual processing and visual attention abilities to test a novel theoretical model of visual selective attention development. Using an adaptive psychometric algorithm and a novel manipulation of visual search tasks, we show that while contrast sensitivity, feature search performance, and visual feature integration performance all improve across childhood, only feature search and incidental feature integration performance explain variance in age-related change in visual selective attention efficiency. Our findings provide insight into the visual, cognitive, and developmental mechanisms underlying improvements in visual attention across childhood. Moreover, our framework provides the foundation for future work to examine the neural computations that contribute to these mechanisms across child development and to leverage these changes in visual and attentional factors to maximize efficiency in age-appropriate educational curricula and clinical interventions.

Taking a developmental lens on the issue, we speculate that our framework can be used to test how to tune children's visual processing abilities in a manner that challenges their visual selective attention and supports improved learning and eventually support educators in crafting visual teaching aides (e.g., books, posters, educational technology) that are age appropriate. For example, might we be able to leverage children's developing color processing abilities to cue attention to lesson-relevant information while simultaneously helping to hone children's selective attention skills (e.g., King et al., 2023). This would be a markedly different strategy than one that might be used to support attention network development without knowledge of underlying agents of change in these networks. In the latter case, children might be asked to exercise the "orienting network" muscle through repeated practice with the same standardized tasks. Instead, future work might explore how curricular and clinical interventions may leverage strong visual feature processing in a particular age group to maximize efficient target selection among competing visual inputs.

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CONFLICT OF INTEREST STATEMENT

We have no known conflicts of interest to disclose.

DATA AVAILABILITY STATEMENT

The data and analytic code necessary to reproduce the analyses presented here are publicly accessable at the following URL: https://osf.io/u5mfa/. Materials necessary to attempt to replicate the findings presented are not publicly accessible but may be shared by the corresponding author. The analyses presented here were not preregistered.

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