Paying Attention to Development:
Understanding Developmental Differences in Selectivity

THESIS

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Abstract

Selective attention is a critical component of cognitive development and learning. Despite, the importance of selective attention, past research has demonstrated that children’s early patterns of attention are typically limited by immature selectivity. To this extent, children often fail to prioritize goal- or task-relevant information, and allocate their attention or encode information more indiscriminately than adults. In a series of studies, we identified differences in children’s and adult’s patterns of attention allocation and explored filtering and distracter suppression as the possible mechanisms responsible for developmental changes in selectivity. In Chapter 2, we used two tasks with cued and uncued streams of information to establish differences in patterns of early and mature attention. These experiments revealed that children had more diffused patterns of attention than adults, even when relevant information was selectively cued. In Chapter 3, we used a series of visual search tasks to explore developmental differences in distracter interference and target selection. While performance with minimal distracting information was successful, the presence of extraneous information interfered with target processing even at six years of age. These results indicate that delayed filtering development may be a key factor in the protracted development of selective attention. In Chapter 4, we examined individual and developmental differences in the development of filtering and working memory, revealing filtering as one of the prominent mechanisms of information processing and attention allocation.
Acknowledgments

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notice what adults miss. *Psychological Science.*


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CHAPTER 1: INTRODUCTION

Efficient allocation of attention plays a critical role in many cognitive and learning tasks as well as our daily lives. For example, in order to drive to work, comprehend a book, search for a friend at a crowded bar, or learn an abstract rule, an individual must focus on some aspects of the present input while ignoring others. Broadly speaking, efficiently allocating one’s attention allows said individual to prioritize task- or goal-relevant information, while simultaneously inhibiting or ignoring information that is extraneous. To this extent, selective attention typically implies a contrast between information that relevant and irrelevant. Therefore, in most cases, the goal of the individual is to extract the subset of relevant information for the overall input. This selection can occur due to multiple factors. In some cases, selection is the results of observable or physical stimuli properties. In these instances, attention is referred to as bottom-up or stimuli-driven. However, in the research described here, we will focus predominately on the role of goals or task-relevance in attention allocation (see Awh, Belopolsky, & Theeuwes, 2012 for a review of factors influencing attentional guidance). This ability is sometimes referred to as goal-driven attention, top-down selective attention, or simply selective attention. In the remainder of this introduction, we discuss the developmental trajectory of selective attention, consider potential theories of the
development of selective attention, and examine the broader implications of selective attention in learning and cognitive development.

The Development of Selective Attention

Past research has demonstrated that selective attention undergoes a protracted development (see Plude, Enns, & Brodeur, 1994 and Hanania & Smith, 2010 for reviews). Early in development, selectivity manifests as an inability to extract relevant dimensions as well as an inability to resist distractions. When selective attention improves, we see parallel changes in several other cognitive processes including visual search (Plude et al., 1994), inhibitory control (Rueda, Posner, & Rothbart, 2005), classification (Smith & Kemler, 1977), categorization (Best, Yim, & Sloutsky, 2013; Deng & Sloutsky, 2015;2016), and more formal acquisition of math and science concepts (Kaminski & Sloutsky, 2013; Fisher, Godwin, & Seltman, 2014).

For example, Deng and Sloutsky (2015;2016) presented participants with a task that combined both category learning and memory as measures of selective attention. In this experiment, four-year-olds, six-year-olds, and adults were tasked with learning categories that had a rule-plus-similarity structure. Therefore, each item could be categorized by relying on a single, deterministic feature (indicative of selective attention) or the overall similarity of the items (indicative of distributed attention). Under normal conditions, six-year-olds and adults learned the rule-based categories, whereas four-year-olds formed similarity-based categories. Participants’ memory for the items’ features converged with their categorization. Specifically, four-year-olds did not demonstrate differential memory for deterministic and probabilistic feature, whereas six-year-olds and
adults demonstrated selective memory for deterministic features only. Moreover, even when participants’ attention was directed towards the category-relevant feature, four-year-old children still demonstrated equivalent memory for deterministic and probabilistic features. Thus, these results demonstrate indirect evidence of developmental differences in attention allocation, as well as the relative stability of these attentional patterns.

Similar evidence of attentional distribution come from research focusing on inhibitory control in flanker tasks (Eriksen & Eriksen, 1974). In the flanker task, participants need to identify a property of a target (e.g., the direction of an arrow) that is flanked by distracters. The flankers can point the same direction as the arrow (i.e., congruent trials) or point opposite directions (i.e., incongruent trials). The effect of these manipulations precipitates as either facilitation (faster responding) on the congruent condition or as interference (delayed responding) in the incongruent condition. However, if the individual is successful in selecting only relevant information, these effects should be attenuated. Therefore, efficient selection and filtering may reduce these effects. Developmental evidence from Rueda, Posner, & Rothbart (2005) and Enns and Akhtar (1989) found that flankers had greater effects in 4- and 5-year-olds than in 7-year-olds and adults. Thus, it appears that filtering and selective attention undergoes substantial improvements by late childhood.
A Component Processes Approach to Selective Attention

The ability to attend selectively requires the extraction of relevant information from a larger set of noisy input. However, it is unknown whether the mechanisms by which information is selected is a single, unified process or two separable components. Furthermore, it is unknown what undergoes development to support selectivity.

Across development, there has been indirect evidence that target selection and distracter processing are not a single, unified process. For example, even young children seem to perform well in tasks that require minimal filtering or suppression. For example, manipulations of Dimension Change Card Sort (DCCS; Zelazo, 2006) task have illustrated how varying filtering demands can disrupt or enhance cognitive flexibility (see Buss & Spencer, 2014 for review). In the DCCS, children must sort bivalent cards by one of their features (e.g. shape). After some time, the rule switches and children must sort the cards by the other dimension (e.g. color). Thus, children must select only the relevant sorting dimension while inhibiting their attention to the other dimension.

Traditionally, three-year-old children fail to switch sorting dimension whereas four-year-old children switch dimensions more reliably. However, Kirkham, Cruess, and Diamond (2003) tested how increasing the distracter suppression demands could induce failure in four-year-old children. To do so, the experimenters had the children place the cards face-up so that the card’s values were visible –increasing the need to inhibit attention to those pre-potent values. Under these conditions, even four-year-old children perseverated on the initial sorting rule, demonstrating that even a minor increase in suppression demands can negatively impact behavior. Similarly, decreasing the inhibitory
demands have been shown to promote passing the task in younger children (Diamond, Carlson, & Beck, 2005). By separating the card’s two dimensions, the attentional conflict is reduced. Under these conditions, children reliably switched sorting dimensions by three-and-a-half years of age. Thus, these results demonstrate the fragility of early attentional control and the means by which changes to target and distracter dimensions can differentially impact attention—although there are still open questions regarding the independence of the processes.

Recent data from event-related potentials (ERPs) have suggested that attentional selection is comprised of two distinct components: (1) a component that enhances target selection and (2) a component that supports suppression of distracting information (Hickey, Di Lollo, & McDonald, 2008; Burra & Kerzel 2014). Specifically, these ERP experiments have suggested that the N2pc—contralateral negativity that is typically associated with attentional selection—may reflect the summation of multiple attentional components. Target negativity (NT) reflected target elevation whereas distracter positivity (PD) reflected increased processing of distracting information.

Despite these findings, other research has disputed the role of N2pc in distracter suppression. Mazza, Turatto, and Caramazza (2009) measure electrocortical correlates of suppression under various degrees of distraction. If the N2pc reflects a distracter suppression mechanism, then distracter features such as quantity, spatial proximity to the target, and heterogeneity of the distracters should elicit greater N2pc responses. However, Mazza et al. (2009) found that none of these factors impacted the N2pc, suggesting that the N2pc does not index distracter processing. Instead, they propose the N2pc only
measures the selection of relevant stimulus features. Contrary to other ERP findings, these results suggest that attentional selection may not be composed of two distinct components, and that target processing is the key mechanism of selection. Despite this disagreement, we may be able to better understand the relationship of these processes by examining them as they develop.

*Implications of Separate Components*

Why is it important if focusing and filtering are independent mechanisms of attentional control? It may be that this distinction between component processes yields some explanation for evidence regarding different patterns of attention under varying demands. For example, Vales and Smith (2015) conducted a series of visual search experiments with three-year-olds. They found that under conditions with highly discriminable arrays, three-year-olds were more efficient at identifying the target. Similarly, hearing the label of the target prior to search sped up reaction times. These effects reflect how altering the attentional demands (target enhancement and distracter suppression) of the task can independently alter visual search performance. Specifically, supporting the representation of the target via labeling decreases the reaction times, but the slopes remain indicative of inefficient search. On the other hand, decreasing suppression demands only flattened the search slopes (suggesting greater efficiency of search), but did not change intercepts. Thus, these results are important indicators that target and distractor demands may differentially affect attention allocation.

Why might we see this difference? One possibility is that if distinct, the components of selective attention may develop at different rates. For example, Garon,
Bryson, & Smith (2008) conducted a review of the development and integration of several core executive functions. This review found different developmental trajectories for the different processes. For example, working memory starts to develop early infancy, whereas attentional shifting and response inhibition appear to have more protracted developmental timescales. Thus, it is possible that these different executive functions correspond to the components of selective attention. Moreover, working memory could reflect processing demands related to focusing on goal-relevant information while inhibitory demands relate to filtering. Therefore, it is possible that the attentional components related to these processes develop at similar rates. To this extent, it is possible that the ability to focus reaches maturity sooner than the ability to filter out irrelevant information. Therefore, slow filtering and suppression development would be the main cause of the protracted development of selectivity.

The reported experiments were designed to address the following issues in the development of selective attention. First, we attempted to understand how mature and immature patterns of attention differed from one another, as well as the larger impact that these developmental differences may have on processing information. Thus, in Experiments 1 and 2, we examined how children and adults differentially process cued (or more goal-relevant) and uncued information as indications of their patterns of attention allocation. We then explored potentially distinct components of selective attention to uncover a potential asynchrony in the development of said components. Thus, in Experiments 3 – 5, we utilized multiple visual search task with varying focusing (target relevant) and filtering (search-irrelevant) demands. If focusing and filtering are
independent components of selective attention, then (a) the developmental trajectories of these processes should differ; and (b) one of these attentional components should reach maturity sooner than the other. Finally, in Experiment 6, we examined filtering development and distracter suppression in greater depth to understand their relationship to selective attention. Overall, our results converge with previous research demonstrating the protracted development of selective attention. In addition, however, our results propose distracter processing or filtering as the prominent mechanism behind this delay.
CHAPTER 2: ESTABLISHING DEVELOPMENTAL DIFFERENCES IN SELECTIVE AND DIFFUSED ATTENTION

As reviewed previously, the development of attention between 4 and 7 years of age seems to produce greater selectivity. This results in the increased ability on a few, relevant dimensions while filtering out dimensions that are irrelevant. Despite these benefits, it is also known that selective attention comes with some costs. For example, the processing of non-selective dimensions may be attenuated despite their importance at a later time point (Coch, Sanders, & Neville, 2005). On the other hand, diffused (or distributed) attention should present neither the costs nor benefits of selectivity, and should result in comparable processing of information regardless of relevance.

The goal of this chapter is to examine whether children have greater processing of irrelevant information due to their broader patterns of attention. To this extent, do tasks that require selective attention results in greater costs of inattention in adults than young children? We explored this question in Plebanek and Sloutsky (2017) using 2 tasks: a change-detection task (Experiment 1) and a visual search task (Experiment 2).
EXPERIMENT 1

Method

Participants

Thirty-five adults (mean age = 19.59 years, SD = 1.33 years; 18 women) and 34 children ages 4 to 5 (mean age = 57.1 months, range = 48.5-68.0 months; 19 girls) participated in this experiment. Data from 4 additional adults and 7 additional children were excluded because of poor test performance (i.e., greater false alarms on old or unchanged items than hits).

The adults were undergraduate students at The Ohio State University and received course credit for participating in this experiment. The children were typically developing children, with no reported vision or hearing impairments. Children were recruited from the greater Columbus, Ohio, area and were tested either in the lab or in a quiet room in their childcare center.

Materials and design

The materials consisted of 52 shape outlines, half of which were red and half of which were green (see Figure 1). These shapes were combined into red-green pairs, with one shape overlaying the other. Participants were asked to make familiarity judgments about the red (i.e., cued) shapes, but not the green (i.e., uncued) shapes.
Procedure

The experimenter started with a short warm-up phase designed to teach the children to pay attention to the screen and respond to the questions. On each of the 10 warm-up trials, participants saw a picture of a cat that had a semitransparent flower garden laid on top of it. Participants were told to pay close attention to the cat because they would need to say if it changes into a frog. The first picture was shown for 1 s and then covered with a mask for 500 ms. After the mask was removed, participants made their response to whether the cat changed and received feedback for their answer.

Following the warm-up phase, participants continued directly into the experiment proper.

The main experiment started with a cuing phase (Figure 2). The cuing phase consisted of five trials and was designed to focus participants’ attention on the shapes of the cued stream. On each cuing trial, participants were asked to pay attention the red shape because they would need to make a familiarity judgment about it. The target shape pair was presented for 1,000 ms. It was then followed by a 500 ms mask. After the mask, the test pair was presented for an addition 1,000 ms. Participants then made the familiarity judgment (‘Did the red shape look familiar?’). This familiarity judgment was
followed by the change detection question (“Did the picture change?”). To induce attention to the red shapes, the red shape changed on every trial in the cuing phase, whereas the green shape always remained the same. No feedback was given on cuing trials.

Figure 2. Sequence of the change detection task.

After the cuing phase, participants went into the testing phase. The testing phase consisted of 15 trials presented in a randomized order. The test trials were similar to the
cuing trials with one critical difference. Specifically, we wanted to examine attention allocation to cued and uncued streams. This change required the inclusion of three trial types (see Figure 3): On cue-change trials, the cued shape was replaced by a different shape; on uncued-change trials, the uncued shape was replaced by a different shape, and on no-change trials, neither shape changed. The experiment was presented on either a Dell desktop (adults) or a Dell laptop (children) and controlled by the Psychophysics Toolbox (Brainard, 1997). Adults recorded their responses using the keyboard, whereas the children made verbal responses which were then recorded by the experimenter.

Figure 3. This figure depicts examples of the three trial types in the test phase of Experiment. Relevant Change trials were trials where the judged shaped also change. Irrelevant Change trials were trials where the unjudged shaped changed. No change occurred on no change trials.
Results and Discussion

We focused our analyses on change detection during the testing phase (see Table 1 for the proportions of “changed” responses). We measured change detection accuracy using $A'$, a nonparametric analogue of the signal detection statistic $d'$ (Snodgrass & Corwin, 1988). We calculated $A'$ separately for cued and uncued streams defining hits as the proportion of “changed” responses on each stream and false alarms as “changed” responses on no-change trials.

<table>
<thead>
<tr>
<th>Age group</th>
<th>Trial Type</th>
<th>Cued-Changed (Hits)</th>
<th>Uncued-Changed (Hits)</th>
<th>No-Change (FA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adults</td>
<td></td>
<td>.92</td>
<td>.34</td>
<td>.15</td>
</tr>
<tr>
<td>Children</td>
<td></td>
<td>.82</td>
<td>.67</td>
<td>.27</td>
</tr>
</tbody>
</table>

Table 1. Proportion of "changed" responses in Experiment 1.

A 2 (shape type: cued vs. uncued) × 2 (age group: adults vs. children) mixed analysis of variance (ANOVA) was performed on the $A'$ data (see Figure 4). There was a significant interaction, $F(1, 56) = 15.44, p < .001$, $\eta^2 = .216$. Specifically, the adults outperformed the children in change detection for relevant information (.915 vs. .846), $t(56) = 3.23, p = .001, d = .864, 95\%$ confidence interval (CI) = [0.31, 1.39], whereas they lagged behind children in detecting changes in irrelevant information (.624 vs. .756), $t(56) = -2.39, p = .020, d = -.631, 95\%$ CI = [-1.16, -0.10]. Net accuracy (i.e., $A'$ averaged across the cued and uncued shapes) did not differ significantly between the adults and
children (.768 vs. .801 respectively, \( p > .250 \)), although the children exhibited numerically greater net accuracy.

**Figure 4.** Change detection accuracies (A') by shape type and age group. Error bars represent ±1SEM.

These results reveal important consequences of the development of selective attention, and they confirm the hypothesis that young children (who attend diffusely) exhibit better change detection for uncued shapes than do adults (who attend selectively). Specifically, the adults exhibited both benefits and costs of selectivity, processing important information more efficiently than the children while missing less relevant information. In contrast, attending diffusely allowed the children to process information regardless of its relevance. To examine the generality of these findings, we conducted
Experiment 2, in which the hypothesized developmental reversal in attention was tested using a visual search task.

**EXPERIMENT 2**

Experiment 2 used a visual search task in which stimuli had a task-relevant dimension and multiple task-irrelevant dimensions. The relevant dimension was the one over which participants performed their search, whereas the irrelevant dimensions were the ones that could be ignored during search. Participants’ memory was later tested for their ability to detect changes in the relevant and irrelevant dimensions. Because children should attend diffusely, we expected that they would process both relevant and irrelevant dimensions, whereas because adults attend selectively, we expected that they would process primarily the relevant dimension. Therefore, we expected to again observe the developmental reversal, with children exhibiting better processing of irrelevant dimensions than adults.

**Method**

**Participants**

The same participants who completed Experiment 1 completed Experiment 2.

**Stimuli and Design**

The stimuli for the visual search task were arrays that contained six drawings of artificial creatures (Figure 5). There were four sets of creatures; each set had seven different binary feature dimensions. Participants were instructed to search for a target value on one of the dimensions, which was considered, the *relevant* dimension; all other
dimensions were considered *irrelevant*. The target value was unique, as it was included in only one object in the search array.

![Figure 5. Sequence of the visual search task in Experiment 2.](image)

The stimuli for the recognition phase were of three types (see Figure 6). The *old* items were stimuli that had been presented in the search arrays (targets or nontargets). *New-relevant* items were created by taking an old item and replacing the feature on the relevant dimension with a completely new feature on that dimension. *New-irrelevant* items were created by taking an old item and replacing a feature on an irrelevant dimension with a new feature on that dimension.
Figure 6. These objects are examples of test items used in the recognition task of Experiment 1. Targets were present in the search array. New-Relevant items have a new feature where the cued feature was located. New-Irrelevant items have a new feature that was unrelated to the search task.

Procedure

The experiment consisted of a warm-up phase, a visual search phase, and a recognition phase. The goal of the warm-up was to teach participants the rules of the visual search task. Participants were first shown a smiley face and told that only one person in the upcoming search array would be smiling, and everyone else in the array would be frowning. They were then shown an array with six stick figures and asked to find the smiling person as fast as possible. The array remained displayed until participants selected an item. There were four trials in the warm-up phase, and participants received feedback as to whether their responses were correct.

The visual search phase consisted of eight trials using novel stimuli. Each search set was used on two trials, and the order of the search sets was randomized across participants. Each trial started by presenting the trial-specific target feature in the center of the screen, to attract attention to that feature (Fig. 5). Participants were then shown a
set of six objects and asked to find the object that contained the target feature. The adults selected the target object using a computer mouse, whereas the children pointed, and the experimenter entered their responses. No feedback was presented during visual search.

After completing all the visual search trials, participants received 18 recognition trials (6 old, 6 new relevant-feature, and 6 new irrelevant-feature items) for the stimuli in their final search array. Different participants were tested on items from different search sets, and the order of the 18 recognition trials was randomized across participants. On each trial, participants were shown an object and asked if it was a part of the search game or if it was a new item that they had never seen before. As in Experiment 1, we measured accuracy using $A'$. $A'$ for relevant features was calculated by defining hits as “old” responses to old items and false alarms as “old” responses to new relevant items. $A'$ for irrelevant features was calculated by defining hits as “old” responses to old items and false alarms as “old” responses to new irrelevant items.

High recognition accuracy for new-relevant items but not for new-irrelevant items suggested that the individual was selectively focusing on only relevant information. Equivalently high memory accuracy for new relevant and new irrelevant items suggested that the individual was distributing his or her attention across both relevant and irrelevant information.

Results

Visual search accuracy.

Both the children and the adults performed well in the visual search task and successfully identified the items with the target feature. Although accuracy in both age
groups was high (74.5% for the children and 89.2% for the adults) and above the chance level of 16.6% (ps < .001, d*s > 6.47), the adults were better at finding the target feature, t(56) = 3.37, p = .001, d = 0.91, 95% CI = [0.38, 1.47]. Therefore, both groups were able to perform the task, though the adults exhibited greater search accuracy than the young children.

**Memory for features.**

Proportions of “old” responses are presented in Table 2. A 2 (feature type: relevant vs. irrelevant) × 2 (age group: adults vs. children) mixed ANOVA on the A’ data (see Fig. 7) revealed a significant interaction, F(1, 56) = 9.29, p = .004, η² = .142. Specifically, although the adults and children demonstrated comparable recognition accuracy for relevant features (.812 vs. .804) independent-samples t(56) = .335, p > .250, d = .089, 95% CI = [-.43, .61], the adults had lower accuracy for irrelevant features (.574 vs. .683), t(56) = -2.41, p = .019, d = -.644, 95% CI = [-1.18, -0.12]. As in Experiment 1, the children exhibited numerically greater net accuracy than adults (.743 vs. .693) independent-samples t(56) = -1.64, p = .105, d = -.44, 95% CI = [-0.97, 0.073].

<table>
<thead>
<tr>
<th>Age group</th>
<th>Trial Type</th>
<th>Old (Hits)</th>
<th>New-R (FA-R)</th>
<th>New-I (FA-I)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adults</td>
<td></td>
<td>.67</td>
<td>.18</td>
<td>.55</td>
</tr>
<tr>
<td>Children</td>
<td></td>
<td>.67</td>
<td>.18</td>
<td>.39</td>
</tr>
</tbody>
</table>

*Table 2. Proportion of old responses in Experiment 2.*
Figure 7. Accuracy ($A'$) for recognition is presented by feature relevance and age. Error bars represent ±1 SEM.

**Discussion**

The results from both experiments demonstrate differences in the distribution of attention between children and adults. Specifically, children are more likely to spread their attention across both relevant and irrelevant information, whereas adults are more likely to engage in selective attention and extract only information that goal-relevant. Thus, while mature selectivity provides an advantage in prioritizing task-relevant information, it also impedes the processing of information that is not specified by the individual’s current motivation. On the other hand, more diffused allocation of attention
allows for more comparable processing of information, and perhaps greater learning or exploration as well.

While these findings are critical in establishing developmental differences in patterns of attention allocation, we still do not understand the trajectory by which individuals transition from diffused attention to being capable of selective attention. Posner and Rothbart (2007) hypothesized that early distributed attention stems from immaturities of attentional control circuits. These immaturities result in less efficient information processing. In addition, children tend to fail in to avoid processing completely irrelevant information, whereas adults tend to filter out extraneous information (Enns & Akhtar, 1989; Rueda, Posner, & Rothbart, 2005). However, under more simplified or salient conditions, children demonstrate some selectivity (Trick & Enns, 1988 and Merill & Connors, 2013). Thus, it is possible that the protracted development of selective attention can be linked exclusively to a specific component of attention. In the next chapter, we discuss a potential separation of different components of attention across development.
CHAPTER 3: ASYNCHRONOUS DEVELOPMENT OF TARGET AND DISTRACTER PROCESSING

As demonstrated in Chapter 2, there are observable differences in mature and immature attentional patterns. While these patterns may illuminate what is encoded, they do not explain how the mechanisms behind attention allocation operate.

Past research has demonstrated that adults are capable of extracting relevant subsets of information almost instantly. For example, Egeth, Virzi, & Garbart (1984) had adults complete a visual search task in which the ratio of the distracter kinds varied. On half of the trials, the arrays contained a clearly identifiable subset (three red items) that participants could utilize to expedite their search. On the other half, the distractor ratio (red items to black items) remained 50:50 as the overall display size increased. The researchers found that when the subset was present, reaction times remained constant. This indicates that the subset is aiding in efficient selection and visual search. Similar findings were obtained in studies that examined guided visual search in 7- and 10-year-olds (Merill & Lookadoo, 2004). However, it is important to note 7-years-of age appears to be relatively late in development and may be after the changes in attentional distribution discussed earlier. Furthermore, it is difficult to say whether the efficient
visual search demonstrated in both of these studies is the result of goal-driven (top-down) selectivity, or bottom-up salience.

To parse these questions, we devised a series of experiments to examine the development of visual search by comparing 4- and 6-year-olds, and adults. The goals of the research described in this chapter were twofold. First, we sought to identify differential effects of increased relevant and irrelevant processing demands. Second, we sought to identify the developmental trajectories of these attentional components to link the protracted trajectory of selective attention to the development of one component.

To meet these goals, we implemented a series of visual search tasks based on the design of Egeth et al. (1984). In Experiment 3, we extended the original findings of Egeth et al. (1984) to younger age groups and compared the standard task to a task that also contained irrelevant information. In Experiment 4, we added focusing demands by adding more values to the color dimension –decreasing the salience of the target value. Finally, in Experiment 5, we sought to better understand filtering demands by altering the quantity and variability of extraneous information presented to the participants.

**EXPERIMENT 3**

*Method*

*Participants*

Participants were randomly assigned to one of two conditions –the baseline condition or the distracter condition. 25 adults (11 women), 23 six-year-old children ($M_{age} = 79.05$ months, range = 72 – 83.81 months, 12 girls), and 25 four-year-old children


$(M_{age} = 54.71 \text{ months}, \text{ range} = 48.3 - 59.56 \text{ months}, 13 \text{ girls})$ completed the baseline condition. An additional 25 adults (12 women), 24 six-year-old children $(M_{age} = 78.16 \text{ months}, \text{ range} = 73.12 - 84.06 \text{ months}, 12 \text{ girls})$, and 24 four-year-old children $(M_{age} = 54.85 \text{ months}, \text{ range} = 49.5 - 63.12 \text{ months}, 15 \text{ girls})$ completed the distracter condition. In the baseline condition, data from 2 additional 4-year-olds were excluded for failing to complete the task. In the distracter condition, data from 5 additional 4-year-olds were dropped for failing to complete the task. Data from 1 additional 6-year-old was also dropped for failing to follow the experimenter’s instruction.

Adult participants were students at The Ohio State University and participated in the experiment for course credit. They were tested in a quiet room in our laboratory. Children were recruited for childcare centers and the Columbus Center of Science and Industry (CoSi). Children were individually tested by an experimenter in a quiet room of their preschool or CoSi.

**Materials and Design**

In the baseline condition, the stimuli were red and black letters that were drawn in Calibri font. In the distracter condition, the letters were placed in the center of cartoon “bugs”, so that each stimulus contained task-irrelevant information (e.g., the legs, bodies, and antennae of the bugs) in addition to task-relevant information (e.g., the letters; see figure 8). Only one type of bug was present in the display at a time so that distracter identity was consistent across the display. The stimuli were randomly distributed to the center of a cell in a $5 \times 5$ matrix. On each trial, there were 5, 15, or 25 items in the display.
In keeping with the procedure used by Egeth, et al. (1984), trial types varied by two additional factors. The first major factor was the presence or absence of the target item. On half of the trials, the target was a part of the display. On the other half, the target was not presented. The second major factor was whether the display supported efficient search by minimizing the number of items sharing the relevant target value (i.e., red letters, see Figure 9). On supportive trials, the distribution of distracter types was uneven, so that every supportive display only contained 3 red items including the target. Thus, if the trial type was “target present/display size 15”, the display would consist of the target, 2 red distracters, and 12 black distracters. On unsupportive trials, the numbers of red and black distracter items were equal. Thus, if the trial type was “target present/display size 15,” the display would consist of the target, 7 red distracters, and 7 black distracters.
Set size, target presence, and support were combined to create 12 different trial types. During a short training phase, participants completed 12 trials—one of each display type. After training, participants completed 144 trials (12 of each display type) that were randomly ordered for each participant.

**Procedure**

The experiment started with a short training phase. At the beginning of the training phase, participants were told that the goal of the study was to find the Red “O” as quickly as possible. If the Red “O” was a part of the display, participants were supposed to press 1. If the Red “O” was not a part of the display, participants were told to press 0. For children, the 1 and 0 buttons had stickers with + and − signs fixed to them to make identifying the buttons easier. During training, participants received feedback (smiley faces and frowny faces) for correct and incorrect responses.

Before training, participants were also given a “hint” that they were told would help them complete the task more quickly. They were told that the best way to find the
Red “O” was to concentrate on only the red letters. Thus, attention to the red set of items was cued throughout the experiment. The hint was also repeated if a participant made an incorrect response in training.

The additional features of the stimuli in the distracter condition led to a few small changes in the task’s instruction. Specifically, participants were told that the “bugs have letters on their bellies.” Their goal was to find the bug with the Red “O.” Participants were then given the hint: “The quickest way to find the bug with the Red “O” is to look at only the bugs that have the red letters.” Other than these small changes, the procedures were identical.

Each trial began with a fixation cross being presented in the center of the screen for 150 ms. After this time the display appeared on the screen for 1500 ms. Participants could make their response at point while the display was present. If participants failed to make a response within the time limit, the display would be removed from the screen and replaced with a frowny face and a prompt for their answer.

After training, participants were reminded of the “hint.” They then went immediately into the test phase which followed the same general procedure as the training phase. The only difference between the two phases was that feedback for accuracy was not provided in the testing phase.

Results and Discussion

Results of Experiment 3 are presented in Figure 10. To examine developmental and conditional differences in visual search performance, we first calculated the average slopes for each individual’s accuracies on supportive and unsupportive trials given
increases in set size. As supportive and unsupportive trials at set size 5 had the same display configuration, we collapsed across these trials to form one estimate of performance at the lowest set size. This estimate was then used in conjunction with accuracies on supportive and unsupportive trials at set sizes 15 and 25 (when the target was present) to calculate supportive and unsupportive slopes.

Figure 10. Visual search accuracy in baseline (Top) and distracter condition (Bottom).
To understand developmental differences in filtering and visual search, we performed a 2 (Trial Type: Supportive vs. Unsupportive) × 3 (Age Group: 4-year-olds vs. 6-year-olds vs. Adults) × 2 (Condition: Baseline vs. Distracters) mixed ANOVA. The three-way interaction did not reach significance, \( F(2, 140) = 2.154, p = .119, \eta^2 = .03 \).

However, there were several other significant interactions. First, there was a significant interaction between Trial Type and Condition, \( F(1, 140) = 6.769, p = .010, \eta^2 = .046 \). There was also a significant interaction between Trial Type and Age Group \( F(2, 140) = 14.302, p < .001, \eta^2 = .170 \). There was also a significant interaction between our between-subjects factors –Age Group and Condition, \( F(2, 140) = 4.221, p = .017, \eta^2 = .057 \). We then performed separate 2 (Trial Type: Supportive vs. Unsupportive) × 2 (Condition: Baseline vs. Distracters) repeated measures ANOVAs for each individual age group.

For adults, this interaction was significant, \( F(1, 48) = 13.672, p = .001, \eta^2 = .222 \). There was also a main effect of Trial Type, \( F(1, 48) = 40.351, p < .001, \eta^2 = .457 \). In the baseline condition, follow-up t-tests revealed that although slopes for supportive trials were numerically smaller than unsupportive trials (-.0013 vs. -.0036), this difference did not reach significance, \( t(24) = 1.769, p = .090 \). However, the difference between supportive and unsupportive performance did in fact reach significance in the distracter condition (-.0007 vs -.0096), \( t(24) = 7.604, p < .001 \). Furthermore, there was a main effect of Condition, \( F(1, 48) = 5.135, p = .028, \eta^2 = .097 \). This revealed that there were no differences between unsupportive trials in the baseline and distracter conditions, \( t(48) = -.441, p = .661, d = -.127 \). Thus, adults were unaffected by filtering demands when the
target subset was present. However, differences due to conditions transpired on unsupportive trials, $t(48) = 3.352, p = .002, d = .967$. Thus, when the target subset was not present, the additional filtering demands were detrimental to even the adult’s search performance.

For six-year-olds, the interaction did not reach significance, $F(1, 45) = 3.301, p = .076, \eta^2 = .068$. There was, however, a main effect of Trial Type, $F(1, 45) = 108.13, p < .001, \eta^2 = .706$. Follow-up paired samples t-tests revealed that 6-year-olds performed better on supportive than unsupportive trials in both the baseline condition (-.0012 vs -.0135), $t(22) = 8.128, p < .001$, and the distractor condition (-.0056 vs -.0232), $t(23) = 7.29, p < .001$. Furthermore, there was a main effect of Condition, $F(1, 45) = 16.306, p < .001, \eta^2 = .266$, with performance on both supportive and unsupportive trials being significantly better in the baseline condition, $t_{(45)} > 2.950, p < .01, ds > .879$. Thus, the presence of additional attentional demands impeded children’s selection, but they also demonstrated the emergence of some selectivity to help locate the target.

For four-year-olds, the interaction was not significant, $F(1, 46) = .021, p = .855, \eta^2 = .001$. As with the other age groups, there was a main effect of Trial Type, $F(1, 46) = 69.082, p < .001, \eta^2 = .595$. Follow-up paired samples t-tests revealed that 4-year-olds also performed significantly better on supportive trials in both the baseline (-.0002 vs -.0120), $t(24) = 6.979, p < .001$, and distracter conditions (-.0097 vs -.0211), $t(23) = 5.090, p < .001$. There was also a main effect of condition, $F(1, 46) = 24.305, p < .001, \eta^2 = .341$. Follow-up comparisons revealed that participants in the baseline condition outperformed the distracter condition on both supportive and unsupportive trials, $t_{(47)} >$
3.150, $ps < .01$, $ds > .918$. Thus, like older children, 4-year-olds seem to be demonstrating immature, yet emerging selectivity.

We then broke our analyses down to identify developmental differences for each condition and trial type. In the baseline condition, there were no developmental differences on supportive trials, $F(2, 70) = .464, p = .631$. This indicates that all age groups were able to attend to the subset and optimize search under bare conditions. However, significant developmental differences transpired on unsupportive trials in the baseline condition, $F(2, 70) = 12.158, p < .001$. As expected, adults were less affected by the absence of the subset than four-year-olds, $t(48) = 3.969, p < .001, d = 1.07$, and six-year-olds, $t(46) = 4.520, p < .001, d = 1.30$. There were no differences on unsupportive trials between six- and four-year-olds, $t(46) = -.676, p = .502, d = -.199$.

For the distractor condition, the one-way ANOVA comparing supportive trials revealed significant developmental differences, $F(2, 70) = 15.837, p < .001$. Adults performed better than both six-year-olds, $t(47) = 3.677, p = .001, d = 1.07$, and four-year-olds, $t(47) = 5.822, p < .001, d = 1.70$. Furthermore, six-year-olds performed significantly better than four-year-olds, $t(46) = 2.139, p = .038, d = .630$. The one-way ANOVA comparing unsupportive trials also revealed significant developmental differences, $F(2, 70) = 15.389, p < .001$. On unsupportive trials, adults once again outperformed both six-year-olds, $t(47) = 5.525, p < .001, d = 1.61$, and four-year-olds, $t(47) = 4.354, p < .001, d = 1.20$. However, there were no differences between six- and four-year-old children, $t(46) = -.616, p = .541, d = 1.27$. 
In sum, these results demonstrate the impact of added attentional demands on selecting a relevant target feature during visual search. Under relatively bare conditions (e.g., the baseline) participants of all age groups were capable of extracting the relevant subset and target with ease. This in turn results in steady performance despite increases in the overall size of the display. When this subset is not present (e.g., the unsupportive trials), visual search performance returns to the standard finding—decreases in performance as set size increases.

In the distracting displays, both groups of children struggled with identifying the target even when the number of red items remained small. However, based on the nature of the distracting stimuli, it is unclear what aspect of the attentional demands is causing this interference. One possibility is that selection was impacted by the added variability on the target dimension (i.e., color). This in turn may have added focusing demands by making it harder to identify the relevant target value. However, it is also possible that the additional features increased the complexity of the stimuli, and therefore added filtering demands to the task as well. To this extent, children may have been unable to filter out the extraneous information in order to direct their attention towards the relevant aspect of the stimuli. We probe these possibilities in the next two experiments.
**EXPERIMENT 4**

**Method**

**Participants**

Twenty-five adults (10 women), 24 six-year-old children ($M_{\text{age}} = 77.96$ months, range = 72 – 83.33 months, 14 girls), and 24 four-year-old children ($M_{\text{age}} = 54.43$ months, range = 48.47 – 59.97 months, 11 girls) completed Experiment 4. Participants were recruited from the same locations as Experiment 3. Data from 4 additional 4-year-old children were dropped from analyses, 1 child because they were colorblind, 1 child because of a computer error, and 2 children because they failed to complete the task.

**Materials and Design**

The materials and design of experiment 4 was similar to the baseline condition of Experiment 1 with one critical difference. While the arrays in Experiment 3 contained only black and red letters, this experiment sought to induce additional focusing demands by adding variability to the target dimension (i.e., letter color). Thus, each array contained three colors (red, blue, and green). All other aspects of the stimuli and design of the experiment remained the same.

**Procedure**

The procedure remained the same as Experiment 3. There were no differences in the timing of the trials or the configurations of the displays.
Results and Discussion

Results for Experiment 4 are presented in Figure 11. As with the previous experiment, our primary analyses focused on comparisons of slopes for target present trials across our three age groups. We first performed a 2 (Trial Type: Supportive vs. Unsupportive) × 3 (Age Group: 4-year-olds vs. 6-year-olds vs. Adults) repeated measure ANOVA. This interaction did not reach significance, $F(2, 70) = 2.280, p = .110, \eta^2 = .061$. To probe developmental differences, we performed one-way ANOVAs for supportive and unsupportive trials. There were no developmental differences on supportive trials (adults: -.0021, 6-year-olds: -.0035, 4-year-olds: -.0025), $F(2, 70) = .320, p < .727$. As expected, developmental differences transpired on unsupportive trials, $F(2, 70) = 3.764, p = .028$. Follow-up independent sample t-tests revealed that adults (-.0039) significantly less affected by the color variability than both six-year-olds (-.0089), $t(47) = 2.804, p = .007, d = .818$, and four-year-olds (-.0081), $t(47) = 2.214, p = .032, d = .645$. There were no differences between six-year-olds and four-year-olds, $t(46) = -.357, p > .720, d = -.105$. Thus, it appears that there were minimal developmental differences due to target dimension variability.
Figure 11. Average accuracies at each set size in Experiment 4.

EXPERIMENT 5

Method

Participants

Twenty-five adults (14 women), 24 six-year-old children (M\text{age} = 77.60 \text{ months}, range = 72.06 – 81.41 \text{ months}, 14 girls), and 24 four-year-old children (M\text{age} = 56.43 \text{ months}, range = 50.06 – 60.33 \text{ months}, 15 girls) completed Experiment 5. Participants were recruited from the same locations as the previous experiments.

Materials and Design

The materials and design of Experiment 5 was similar to the distracter condition of Experiment 3 with a few key differences. First, the “bugs” in the display were varied so that each display contained three different kinds of bugs (see Figure 12). In addition, the bugs’ features were no longer made up of individual colors (as in Experiment 3).
Instead, the bugs were a gradient of green and black and made of less discernable features. The letters in the bugs remained either red or black. Data from 2 additional 6-year-old children were dropped for failing to complete the task.

Figure 12. Examples of the stimuli used in Experiment 5.

Procedure

The procedure remained the same as Experiments 3 and 4. There were no differences in the timing of the trials or the configurations of the displays.

Results and Discussion

Performance in Experiment 5 is presented in Figure 13. We first performed a 2 (Trial Type: Supportive vs. Unsupportive) × 3 (Age Group: 4-year-olds vs. 6-year-olds vs. Adults) repeated measures ANOVA on the slopes for each participants visual search accuracy. This revealed a significant Trial Type by Age Group interaction, \( F(2, 70) = 7.158, p = .001, \eta^2 = .170 \). To further understand this interaction, we used one-way ANOVAs to examine developmental differences within supportive and unsupportive trials. For supportive trials, this was not significant, \( F(2, 70) = 2.278, p = .110 \). Follow-up
t-tests revealed that adults (-.0019) and 6-year-olds (-.0038) were not significantly different, $t(47) = 1.163, p = .251, d = .339$. However, the difference between adults and four-year-olds (-.0054) was significant, $t(47) = 2.134, p = .038, d = .623$. On unsupportive trials, the one-way ANOVA revealed significant differences, $F(2, 70) = 17.140, p < .001$. Follow-up tests revealed that adults (-.0041) were significantly less impacted by variable filtering demands on unsupportive trials than 6-year-olds (-.0111), $t(47) = 3.265, p = .002, d = .952$, and 4-year-olds (-.0168), $t(47) = 6.259, p < .001, d = 1.83$. Furthermore, 6-year-olds were significantly less impacted by the filtering demands than four-year-olds, $t(46) = 2.409, p = .020, d = .702$. Thus, there is evidence that filtering extraneous information significantly contributes to selecting and searching through the relevant items in visual search.

![Figure 13](image.png)

*Figure 13. Average performance at each set size in Experiment 5.*
Cross-Experiment Comparisons

To better understand the effects of focusing and filtering demands as well as the possible developmental asynchrony, we performed additional analyses comparing visual search slopes in Experiments 4 and 5. We started by performing a 2 (Trial Type: Supportive vs. Unsupportive) × 3 (Age Group: 4-year-olds vs. 6-year-olds vs. Adults) × 2 (Experiment: Experiment 4 vs. Experiment 5) mixed ANOVA. The three-way interaction did not reach significance, $F(2, 140) = 1.645, p = .197, \eta^2 = .023$.

However, the other potential interactions did reach significance. First, there was a significant interaction between Trial Type and Experiment, $F(1, 140) = 4.412, p = .037, \eta^2 = .031$. There was also a significant interaction between Trial Type and Age Group, $F(2, 140) = 8.852, p < .001, \eta^2 = .112$. Finally, the between-subjects factors, Age Group and Experiment, significantly interacted, $F(2, 140) = 3.958, p = .021, \eta^2 = .054$. To explore this interaction further, we performed follow-up 2 (Trial Type: Supportive vs. Unsupportive) × 2 (Experiment: Experiment 4 vs. Experiment 5) repeated measures ANOVAs for each group.

For adults, there was only a main effect of Trial Type, $F(1, 48) = 5.984, p = .018, \eta^2 = .111$. Follow-up paired samples t-test revealed that although the slopes for supportive trials in both experiments were numerically higher than unsupportive trials, these differences did not reach significance, $t_{24} < 1.80, ps > .080$. Furthermore, there were no differences between either the supportive or unsupportive slopes of Experiments 4 and 5, $t_{48} < .104, ps > .890, ds < .030$. Thus, it appears that adults were relatively
unaffected by both types of attentional demands and that the presence of the target subset did not alter performance under these conditions.

For six-year-olds, there was also only a main effect of Trial Type, $F(1, 46) = 24.151, p < .001, \eta^2 = .344$. Thus, six-year-olds were significantly better at finding the target when the relevant subset was present in both experiments, $t(23) > 3.332, ps < .01$. However, there were no differences stemming from the attentional demands of Experiments 4 and 5 for either supportive or unsupportive trials, $t(46) < 1.00, ps > .330, ds < .295$. Thus, the presence the target subset aided search performance despite either type of attentional demands.

For four-year-olds, the interaction was significant, $F(1, 46) = 5.898, p = .019, \eta^2 = .114$. Furthermore, there were main effects of both Trial Type, $F(1, 46) = 49.00, p < .001, \eta^2 = .516$, and Experiment, $F(1, 46) = 10.562, p = .002, \eta^2 = .187$. Follow-up tests confirmed that four-year-olds performed better on supportive trials in both experiments, $t(23) > 3.658, ps \leq .001$. Furthermore, while the slopes for supportive trials were flatter for Experiment 4 (signifying more efficient selection), this difference did not reach significance, $t(46) = 1.404, p = .167, d = .414$. However, the difference between unsupportive trials did reach significance, with smaller slopes in Experiment 4, $t(46) = 3.847, p < .001, d = 1.13$. Therefore, the presence of variable filtering demands seems to be more detrimental to young children’s selection than variability in relevant features. However, the presence of the target subset helped 4-year-olds compensate somewhat for poor filtering.
Discussion

The experiments reported in this chapter examine the influences of relevant and irrelevant attentional demands on visual search as well as how these influences change over the course of development. Under conditions in which search is largely influenced by perceptually salient features (Experiment 3), all age groups were capable of efficient visual search. However, later experiments suggest that this may have been the result of stimulus-driven processing as opposed to the goal-driven processing usually associated with selective attention (see Yantis and Egeth, 1999 for another viewpoint).

Without perceptual information driving attention, four-year-olds were consistently unable to search efficiently. Thus, any additional focusing or filtering demands lead them to be unable to restrict attention to the subset of target-colored letters. On the other hand, adults were capable of efficiently searching through the subset under all conditions, regardless of the added focusing or filtering demands. Thus, unsurprisingly, adults demonstrated developed selective attention.

Interestingly, separate focusing and filtering variability had little impact on selecting the subset for 6-year-olds. However, the combination of color and distracter variability in Experiment 3 impeded selection. One possibility is that distracter suppression is more strongly influenced by specific dimensions. Recently, Wolfe and Horowitz (2017) conducted a review of the main factors that guide attention in visual search. “Undoubted guiding attributes” included features such as color and orientation, but not form. Perhaps, the features that guide attention are also the features that most influence distraction. In other words, it is possible that despite not containing variability
amongst the distractor identities, the multi-colored features of the distracter arrays in Experiment 3 required filtering while also introducing variability on the target dimension. On the other hand, the Experiment 5 primarily attempted to influence distraction through variability in the object form. Thus, this manipulation may have been less demanding because shape has a less consistent influence on attentional guidance (Wolfe and Horowitz, 2017).
CHAPTER 4: THE DEVELOPMENT OF FILTERING EFFICIENCY AND WORKING MEMORY

In previous chapters we have discussed the implications of developmental differences in attention allocation and proposed an asynchrony in the development of two distinct components of selective attention. The work described in chapter 3 seemed to suggest that filtering has a more delayed developmental trajectory. Thus, in this chapter, we explore filtering efficiency as a major contributor to selective encoding via both developmental and individual differences.

To explore selective attention, we used a variant of the filtering task devised by (Vogel, McCollough, & Machizawa, 2005). Although past research on the development of working memory (WM) has demonstrated substantial increases in capacity during early childhood, there is still much debate over what is developing (Cowan, 2010; Cowan et al., 2006; Riggs, McTaggart, Simpson, & Freeman, 2006; Simmering, 2012). Some researchers have theorized that there is a fixed number of slots that account for one’s capacity limits, whereas others have argued that the limit stems from a more continuous pool of cognitive resources (e.g., selective attention) that influence the ability to encode and maintain multiple items (see Donkin et al., 2013 and Simmering and Perone, 2013 for reviews).
This debate leaves us with three possible explanations for the development of working memory: 1) The discrete-slots model suggests a straight-forward interpretation of development of WM capacity: the number of slots increases, perhaps due to the maturation of the prefrontal cortex. 2) It is also possible that the capacity is determined by the ability to use these slots efficiently. For example, it could be argued that the capacity is determined by the ability to filter out irrelevant information: more efficient filtering results in more available slots (Vogel et al., 2005). This theory links the development of WM with a broader set of cognitive processes, specifically selective attention. 3) It is possible that both “slots” and “cognitive efficiency” undergo development, and together, they influence increases in capacity seen across development. Here, we explore these theories and their implications for attention development.

Experiment 6

Methods

Participants

The sample consisted of 30 adults (17 females), 30 7-year old children ($M = 89.62$ months, range 84.12-95.53 months, 15 girls), and 30 4-year-old children ($M = 54.37$ months, range 49.12-59.41 months; 19 girls). Two additional adults were excluded from analyses for poor performance (i.e., a greater number of false alarms than hits on the majority of trial types). Six additional 4-year-olds were excluded from analyses: two for having a “yes bias” in the task and four for failing to complete the task.
Adults were undergraduate students at The Ohio State University, who participated in the experiment for course credit. Child participants were typically developing children with no reported vision or hearing impairments. These participants were recruited from preschools, daycares, and elementary schools in the greater Columbus, Ohio area.

Materials and Design

The experiment was administered using either a Dell desktop (adults) or a Dell laptop (children) and controlled via PsychToolBox (Brainard, 1997). All stimuli were presented on a black background.

In the memory capacity task, the stimuli were simply violet, rectangular blocks. The number of blocks presented to the participant ranged between one and three for four-year-olds, and one and four for the other age groups.

The materials used in the filtering task contained two sets of items. There were bunnies that were outlined in a red rectangle and chickens that were outlined in a blue rectangle (see Figure 14). Participants were randomly assigned to one set of items as their “target set.” The remaining set served as the “distracting set.”

Figure 14. Stimuli used in the filtering task of Experiment 6.
Targets and Distracters were combined to create five different trial types. Trials without distracters were identified as “pure trials”. Pure trials were separated into “low load” trials (these had the number of target items that was below the average working memory capacity of the given age group) and “high load” trials (these had the number of target items at or above this group’s average capacity). Low and high load trials were combined with distracting information to create three types of filtering trials (see Table 3 for specific information on each trial type.

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*Table 3.* Filtering trial types completed by each age group.

**Procedure**

The task consisted of two phases. The first phase was a standard working memory capacity task (see Figure 15). At the start of this task, participants were told that they would see several purple blocks that would appear on the screen very quickly and then disappear. The blocks would then reappear, but one of the blocks may have rotated. To
demonstrate the concept of the experiment, the participant’s attention was directed a single purple block on the screen. The block then disappeared and returned having been rotated 45 degrees. The experimenter (or computer for adults) then pointed out the rotation to the participant and told the participant that because the block had rotated that it was different. The same sequence of events was then presented for trials in which the block did not rotate, with the emphasis being placed on the block having not changed.

Figure 15. Sequence of the working memory capacity task of Experiment 6.

After the demonstration of the task, participants completed a short block of eight practice trials. Participants were presented with displays containing between one and four purple blocks (between one and three blocks for younger children) presented around a
fixation cross. Stimuli were presented for 500 ms to children and for 100 ms to adults. After the allotted display time, the blocks disappeared for a 900 ms retention interval. The array of items then reappeared on the screen for 1,000 ms. After this time, participants had to say whether one of the purple blocks had rotated or if all the items had stayed the same. Feedback was given for correct and incorrect responses. After the practice block, participants stopped receiving feedback and completed 48 trials (36 trials for younger children) that were balanced for set size and change/no change.

Participants moved immediately from the capacity task to the filtering task (see Figure 16). They were told a cover story that they were going to see some animals (chickens and bunnies) on a farm and some of these animals liked to move around a lot. Their goal was to say when one of the animals rotated. Participants were then given a hint based on which condition they were assigned to. If participants were assigned to the “chicken condition,” they were told that only the chickens liked to move and to pay close attention to only the chickens. If participants were assigned to the “bunny condition,” they were told that only the bunnies liked to move and to pay close attention to only the bunnies. Participants were only asked about animals from the group that they were assigned to attend to.
Figure 16. Sequence of the filtering task used in Experiment 6.

After instruction, participants were given a demonstration of the possible sequences of events—similar to the demonstration given prior to first phase. Participants were shown two items from the target set. These items then disappeared. When the items returned, one of the items had rotated and the other had remained the same. This difference was pointed out to the participant by either the experimenter or the computer. Participants then saw the same sequence of events for trials that did not include a change.

After the demonstration, participants completed all 80 trials of the filtering task which were balanced by trial type and change/no change. Presentation times and
retention intervals were the same as the capacity task. Participants did not receive feedback.

Results

Working Memory Capacity

Performance in the capacity task is presented in Figure 17. To calculate capacity, we used Cowan’s (2001) formula, \( K = SS \times (H - FA) \), where \( K \) is capacity, \( SS \) is set size, \( H \) is the proportion of hits, and \( FA \) is the proportion of false alarms. As set size increases, the upper limit of the capacity estimate also increases. Thus, an individual’s capacity should continue to increase with set size until it asymptotes at their limit.

To examine the development of WM, we first performed a 3 (Age Group: 4-year-olds vs. 7-year-olds vs. Adults) \( \times \) 3 (Set Size: S1 vs. S2 vs. S3), with \( K \) as the dependent variable. The analysis revealed a significant main effect of age group, \( F(2, 87) = 17.68, MSE = .488, p < .001, \eta^2 = .381 \), with older children and adults having greater capacity than younger children, all \( ts(58) > 2.36, ps < .022, ds > .619 \). There were no significant differences between adults and seven-year-olds, \( ts(58) < 1.40, ps > .10, ds < .370 \). There was also a significant age group by set size interaction, \( F(1, 87) = 14.16, p < .001, \eta^2 = .246 \).

We then performed follow-up t-tests on \( K \)-values across the set sizes for each age group. For adults and seven-year-olds, capacity estimates were significantly higher for S4 (recall that S4 could not be included in the ANOVA because these trials were not presented to 4-year-olds) than all other set sizes, adults: all \( ts(29) > 2.80, ps < .01, 7\)-year-
olds: $t(29) > 3.39, ps < .01$. This indicates that both groups’ WM capacities are likely around four items and that 7-year-olds exhibited adult-like levels of capacity. However, while 4-year-olds capacity at S2 was significantly higher than at S1, $t(29) = 4.55, p < .001$, performance at S3 was not significantly different from that at S1 or S2, both $t(29) < .167, ps > .10$. Thus, 4-year-olds’ WM capacity is likely around 2 items.

Figure 17. Working memory capacity estimates by age group and set size.

The Development of Filtering Efficiency

To compare filtering ability relative to each individual’s pure performance, we created a standardized measure of filtering performance. This transformation was performed using the following formula: Filtering Efficiency ($FE$) = $1 - ((Pure - Filtering)/Pure)$, where “Pure” refers to accuracy ($Hits - False Alarms$) on pure trials and
“Filtering” refers to accuracy on the filtering trials. We used only trials with low loads of relevant information (i.e., S1 for 4-year-olds and S2 for 7-year-olds and adults) to calculate FE because the calculation would have been distorted by poor performance on high load trials in both groups of children. As this method can theoretically give ratios greater than 1, we capped all ratios at 1.

Results of filtering efficiency are presented in Figure 18. To identify developmental differences, we performed a one-way ANOVA on filtering efficiencies and found significant differences across the age groups, $F(2, 87) = 5.58, p < .01$. Follow-up comparisons revealed that adults had the greatest filtering efficiency (.831), being significantly larger than both seven-year-olds (.675) and four-year-olds (.609), both $t(58) > 2.5, ps < .015, ds > .65$. However, there were no differences between seven-year-olds and four-year-olds, $t(58) = .88, p > .35, d = .23$. These results suggest that filtering efficiency continues to develop between 7-years of age and adulthood.

Finally, to behaviorally replicate the findings of Vogel et al. (2005), we examined correlations between filtering efficiency and average WM capacity. We first examined the correlation between filtering efficiency and WM capacity by collapsing across age, and found a significant correlation, $r(88) = .563, p < .001$. Similar correlations transpired in each age group, $r(28) = .632, p < .001$ in adults; $r(28) = .626, p < .001$ in 7-year-olds, and $r(28) = .496, p < .01$ in 4-year-olds, suggesting that filtering efficiency contributes to both age-related differences and individual differences in WM capacity.
In order to behaviorally replicate the findings of Vogel et al. (2005), we examined correlations between filtering efficiency and average WM capacity. We first examined the correlation between filtering efficiency and WM capacity by collapsing across age, and found a significant correlation, $r(88) = .563, p < .001$. Similar correlations transpired in each age group, $r(28) = .632, p < .001$ in adults; $r(28) = .626, p < .001$ in 7-year-olds, and $r(28) = .496, p < .01$ in 4-year-olds, suggesting that filtering efficiency contributes to both age-related differences and individual differences in WM capacity (Figure 19-21).

Figure 18. Estimates of filtering efficiency by age group in Experiment 6.
Figure 19. Relationship between filtering efficiency and working memory capacity in adults.

$r = .632$
Figure 20. Relationship between filtering efficiency and working memory capacity in 7-year-olds.

$r = .626$
Unique Contributions of Filtering

As one of our goals was to examine the unique effects of selective attention on memory capacity, we implemented a hierarchical linear regression to determine whether a significant proportion of variance in capacity could be uniquely explained by filtering (cf. Vogel et al., 2005; see also Cowan, 2012; Cowan & Morey, 2006). If capacity stems from the total number of slots, then there should be no unique contribution of filtering. However, if working memory capacity relies on a more general pool of attentional and cognitive resources, including the ability to use the available slots, then filtering

Figure 21. Relationship between filtering efficiency and working memory capacity in 4-year-olds.
performance should uniquely account for a significant proportion of the variance in WM capacity.

For the regression, we used average accuracy (hits – false alarms) on pure and filtering trials on the filtering task (see Table 1) to predict capacity (as measured by average $K$) on the capacity task. As set size three exceeded 4-year-olds’ capacity, this trial type was excluded from 4-year-old’s average capacity estimate.

The first step of the regression was to examine if age alone predicted average capacity as estimated in the first phase of the experiment. Unsurprisingly, age accounted for a significant proportion of the variance in capacity, $\Delta R^2 = .446$, $F_{\text{Change}} (1, 88) = 70.77$, $p < .001$. The second step was to introduce pure trials to the model. This served as a simple examination of the reliability of WM capacity measures, because these were variants of the same task with different stimuli. As expected, pure trials accounted for a significant proportion of the variance in capacity, $\Delta R^2 = .168$, $F_{\text{Change}} (1, 87) = 37.91$, $p < .001$.

We then added performance on filtering trials to the model. This step uniquely accounted for an additional, significant proportion of variance in capacity, $\Delta R^2 = .076$, $F_{\text{Change}} (1, 86) = 20.94$, $p < .001$. This substantial contribution of filtering trials remained when the analyses were performed separately for each group, all $ps < .01$. Therefore, filtering efficiency accounts for both developmental and individual differences in WM capacity.
Discussion

This study demonstrates that filtering is a key contributor of attention and encoding across development. We found that age, working memory capacity, and filtering ability were all uniquely related to storing relevant information. Moreover, we identified a clear protraction in the development of filtering efficiency. Thus, these results suggest that the interference children are frequently susceptible to when processing or storing information in working memory may be due to poor selection mechanisms as well as fewer resources in capacity.

Furthermore, our results support a hybrid of the two main viewpoints of WM development. First, it is clear from previous research (as well as our own findings here) that working memory is directly impacted by maturation and development. However, our results also demonstrate the critical influence of more general, cognitive processes such as selective attention and filtering. Take for example, the performance of seven-year-olds and adults. While their performance in the first phase’s working memory task was similar, seven-year-old’s filtering efficiency was much lower. Thus, these results suggest that younger individual may be misallocating their attention and encoding irrelevant information that interferes with their goals. However, it is for future research to explore the manner by which delays in the development of filtering efficiency directly influence information processing.

It appears that early filtering is inefficient and irrelevant information frequently interferes with encoding goal-related features. However, over development, filtering efficiency increases, and individuals become more capable in restricting their focus to a
relevant subset of information. Thus, it appears that early patterns of encoding are driven by broadly storing as much information as possible, whereas as mature encoding is driven by filtering and selectively encoding information that is pertinent to one’s goal.
CHAPTER 5: GENERAL DISCUSSION

The reported research aimed to address several questions regarding the development of attention. First, we asked whether children’s and adults’ patterns of selectivity differed and whether these patterns had larger implications for their memory. After we identified what factors characterize the difference in attentional patterns, we devised a series of experiments to parse potentially distinct processes involved in selection. Through these experiments, we identified focusing and filtering as developmentally asynchronous components of attention. Furthermore, we presented evidence suggesting that filtering development was the main cause of the protracted development of selective attention.

Summary of Findings

We first established attentional evidence that children allocate their attention in diffused patterns, whereas adults selectively allocate their attention to single dimensions or features (Experiments 1 and 2). In Experiment 1, we tested participants on a change detection task that had cued and uncued information. We found that adults demonstrated greater selectivity towards the cued information whereas children processed both streams comparably. In Experiment 2, we found similar results for participants’ search performance and memory of items after a visual search task. These results corroborate a
number of past findings from the categorization and classification literature which speculate the important role of selective attention in learning as well as a distributed to selective transition in attention development (Smith & Kemler, 1977; Deng & Sloutsky, 2015 and 2016; see Sloutsky, 2010 for review).

We then manipulated filtering and focusing demands in a visual search task by altering relevant and irrelevant properties of the search array. Under simplified conditions (baseline -Experiment 3), all age groups demonstrated efficient search. However, it is highly likely that this was due to a pop-out effect due to the subset greatly increasing the target’s salience. When manipulating target relevant features (Experiment 4), all age groups suffered minor impairments in selection, but there were no developmental differences. In experiments with filtering demands (Experiments 3 and 5) adults were the only age group to remain efficient in both, suggesting that they were able to overcome the filtering demands. Four-year-olds searched inefficiently under both filtering demands, suggesting that they were unable to cope with the extraneous information.

In Experiment 6, we directly examined individual and developmental differences in working memory capacity and filtering efficiency as a case study of processes involved in attention development. We found that both working memory capacity and filtering ability were uniquely related to encoding relevant information. Moreover, we identified a clear protraction in the development of filtering efficiency. Thus, these results suggest that the interference children are frequently susceptible to when processing or storing information in working memory may be due to poor selection mechanisms as well as fewer resources in capacity.
Stimuli-Driven to Goal-Driven Shifts in Selectivity

One consistent finding from the presented studies is that distracting information interfered with children’s goal-directed attentional control, whereas adults were capable of overcoming or filtering out the extraneous information to select goal-relevant information. Although it may seem like 4-year-olds are exhibiting selectivity in Experiment 3, it may also be possible that attentional guidance is driven by the salience of the subset as opposed to the individual’s attentional control setting (see Triesman, 1969 or Friedman-Hill & Wolfe, 1995). Thus, it appears that the development of filtering also coincides with shifts from selective attention being elicited from stimulus properties to selective attention being guided by specified goal-oriented control settings.

Other research has found similar evidence of early, salience-driven processing in visual search tasks. For example, when visual search can proceed in parallel (e.g., searching for targets defined a single feature/singleton-detection), search rates remain consistent for both children and adults despite increases in set size (Trick & Enns, 1988; Gerhardstein & Rovee-Collier, 2002). However, when top-down attentional processes were required to identify the target (e.g., feature search mode in conjunctive visual search), children younger than seven-years-old typically demonstrate steep search slopes (Merrill & Conners, 2013).

Thus, one possibility is that young children are simply unable to modulate their selectivity via top-down control settings as adults can. Support for this possibility stems from several instances where bottom-up manipulations succeed in inducing selection attention while top-down manipulations fail. For example, relating back to the
Dimensional Change Card Sort task, manipulations of saliency of pre- and post-switch dimensions yield changes in set shifting in the task. For instance, Fisher (2011) altered both dimensions by making the dimensions’ values more similar or less similar (thereby decreasing and increasing their salience respectively). Fisher found that children were more successful in shifting from dimensions with less salient differences in targets to the more discriminable dimension. Similarly, Perone, Molitor, Buss, Spencer, and Samuelson (2015) found that experience in selectively attending to the relevant post-switch aided in switching, but only when the past experience left sufficiently salient memory traces of said dimension. On the other hand, manipulations relying on top-down control often show a more protracted developmental trajectory (see Munakata, Snyder, & Chatham, 2012 for review).

*Filtering and Selective Attention*

Based on the research presented here, it appears that filtering may be the mechanism at the heart of this interference in selection. In other words, poor filtering ability may be closely linked to the diffused attentional patterns present in early childhood. It is important to reiterate that the development of filtering appears to follow a similar (and in some cases even more protracted) trajectory to a number of other developmental improvements in cognitive flexibility and inhibitory control (Davidson, Amso, Anderson, & Diamond, 2006), rule-based learning (Sloutsky, 2010; Rabi & Minda, 2014), feature-based visual search (Merill & Conners, 2013) visual orienting (Trick & Enns, 1998).
As is apparent, filtering and inhibitory control have wide reaching consequences for a variety of behaviors and cognitive processes. Despite this apparent utility, the mechanism by which distracter processing is related to selection is less clear (see Cave & Chen, 2016 for review). One possibility is that filtering is simply a byproduct of selection. To this extent, filtering results from the “maintenance of selection.” (Posner, 1980). However, a second possibility is that individuals are actively inhibiting or resisting extraneous information. For example, Fukuda and Vogel (2009) found that individuals with low working memory capacity were more susceptible to attentional capture than high capacity individuals. Thus, it is possible that development allots improvements in attention akin to those seen by increased capacities. However, more research is required to understand the role of filtering in attention and development.

Attention, Cognitive Development, and Learning

Young children’s failure to inhibit attending to irrelevant dimensions has important implications for understanding differences in learning between children and adults. Primarily, this failure to filter results in distributed attention and the processing of a broad set of information. This distribution of attention may allow for greater exploration—which can be a major contributor to early cognitive development (for review see Loewenstein, 1994). On the other hand, adult’s selectivity limits processing to narrow subsets of information, but may limit interference from irrelevant information.

Additionally, children’s tendency to distribute their attention leads to differences in many areas of cognitions. For example, these findings may provide an attentional account for the developmental reversals in memory identified by Brainerd & Reyna
(2007) and Fisher & Sloutsky (2005). To summarize these findings, when children are presented with a set of identified organized around a specific concept or gist, children are impacted less frequently by memory intrusions than adults. In particular, children appear to remember individual examples of the set (e.g., the specific identities of cats that were shown to them), whereas adults only remember the identity of the set and not individual items. Perhaps because of the immaturity in selective attention, children process identity specific information by encoding a wider array of contingencies or features, while adults extract only gist information.

While distributed attention seems to have its fair share of benefits, it too comes with several costs. Primarily, distributed attention may negatively affect learning in formal academic settings that have clear goals to learn specific concepts. For example, Fisher, Godwin, & Seltman (2014) investigated the impact of both sparsely and richly decorated classrooms on children’s ability to sustain attention during instruction and children’s ability to acquire the lesson plan’s content. The researchers found that children in the decorated classroom demonstrated more off-task behaviors and fewer learning gains than children in the undecorated rooms. Similarly, Kaminksi and Sloutsky (2013) examined acquisition of mathematics knowledge under conditions with and without engaging, but extraneous perceptual information (see also Son, Smith, & Golstone, 2011). While kindergarten and first grade students demonstrated the ability to interpret bar graphs under perceptually simple conditions, they were unable to filter the perceptually rich information and failed to interpret the graphs when extraneous
information was present. Thus, learning in formal classroom settings may require finding the appropriate balance of contexts that require selective and distributed attention.

Conclusions

The current research presents extensive evidence in support of the protracted development of selective attention. These differences have widespread implications in learning, memory, and other areas of cognitive development. Moreover, these differences may stem from poor inhibition of attention or filtering, as opposed to simply extracting the target. Over the course of development, we see changes in the ability to suppress processing of irrelevant information. Future research must identify the processes and mechanisms by which filtering undergoes developmental change.
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