Published in final edited form as:

Dev Sci. 2018 March ; 21(2): . doi:10.1111/desc.12512.

Adults Blink More Deeply: A comparative study of the attentional blink across different age groups

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Abstract

The attentional blink (AB) is thought to help the visual system parse and categorize rapidly changing information by segmenting it into temporal chunks, and is elicited using Rapid Serial Visual Presentation. It is reflected in a decrease in accuracy at detecting the second of two targets presented within 200–500ms of the first, and its development appears to be protracted on tasks that require set-shifting. Here, younger ($M = 8.5$ years) and older ($M = 12.8$ years) children and adults ($M = 19.13$ years) completed a simple AB task with no set-shift requirement in which participants detected 2 letters in a stream of numbers presented at a rate of 135ms/item. In addition to assessing the developmental course of the AB on this simple task, we also assessed temporal order errors, or swaps. The AB and its associated characteristics are present in both groups but developmental differences were noted in the depth of the AB, and the presence or absence of lag 1 sparing. These developmental changes were explained by changes in a single parameter, inhibition, using the eTST model, which suggests that the AB is an adaptive function of visual system.

One of the major challenges for the human visual system is to learn how to categorize and remember the important elements from the stream of information that is delivered by the eyes. Children in particular have the challenging task of building a visual lexicon by learning to attach specific meanings to specific visual patterns (e.g. Carey & Bartlett, 1978) and to rapidly filter important information from less important information (Enns, & Akhtar, 1989). For both children and adults, visual input is fleeting by nature since the eyes saccade rapidly

and remain in one location for only several hundred milliseconds at a time, a behavior which starts in infancy, and reaches adult-like levels within the first few months of life (Hainline, Turkel, Abramov, Lemerise, & Harris, 1984).

The abilities of adults to detect rapidly presented targets has been well characterized using techniques such as Rapid Serial Visual Presentation (RSVP), in which stimuli are presented rapidly in sequence at the center of a display typically at rates of 10 items per second (Forster, 1970; Potter, 1984). RSVP tasks typically require participants to classify a sequence of rapidly appearing stimuli as either targets or non-targets, and to report the target(s) at the end of the stream. The stimuli in such paradigms can be characters, words, or even pictures and the targets can be specified by a feature (e.g. color), or a category (e.g., letters, or dinner foods). The visual system is remarkably successful at rapidly detecting targets for even quite complex stimuli such as natural images that had never been viewed before (Potter, 1976).

However, while performance at detecting a single target is remarkably robust in RSVP, if two targets are presented in sequence, the second target is often completely missed; a finding known as the Attentional Blink or AB (Broadbent & Broadbent 1987; Raymond, Shapiro & Arnell 1992). The AB occurs when subjects are searching for two targets (referred to hereafter as T1 and T2) presented in rapid succession and refers to the large impairment in the ability to spot the second target (T2) if the separation between T1 and T2 is in the range of 200–500ms (Broadbent & Broadbent 1987; Raymond, Shapiro & Arnell 1992). This metaphorical blink of attention can be observed for many kinds of target selection, and is thought to reflect either a limitation of visual processing speed, or cognitive mechanisms that limit the rate at which information is processed (Dux & Marois 2009; Martens & Wyble 2010). For example, the resource theory proposes that processing a single target consumes resources that must be freed before a second target can be encoded into memory. This theory stems from observations that making the first target easier to process through a variety of manipulations reduces the size of the AB (Chun & Potter 1995).

A competing theory to this resource-depletion account is that the visual system has a built-in mechanism to inhibit attention while information is being encoded, which results in the AB (Wyble, Bowman & Nieuwenstein, 2009; Lagroix, Spalek, Wyble, Jannati & Di Lollo 2012). In this account, the AB is actually a useful adaptation of the visual system, which segments multiple pieces of information into discrete chunks that can be more easily stored in memory in the correct temporal order. This episodic segmentation theory was inspired by the intriguing finding that the AB starts after a delay, that is, if the T2 appears directly after T1, it is often quite easy to see (Raymond Shapiro & Arnell 1992; Chun & Potter 1995). Furthermore, when T2 escapes the AB at lag-1, T1 and T2 are often reported in the wrong order (Chun & Potter 1997) which suggests that the two targets are being encoded together as part of single representation or episode (Akyurek & Hommel 2005; Bowman & Wyble 2007; Wyble Bowman & Nieuwenstein 2009). This finding of preserved T2 accuracy for immediately sequential targets has been named lag-1 sparing due to the fact that lag-1 T2 is “spared” from the AB. Further, the temporal order errors are often referred to by the term “swaps” due to their order being swapped at the time of report (Chun & Potter, 1995).

Measurements of the AB across development

With these competing theories in mind, it is important to determine how the AB changes over the course of development, since, with increasing maturity, the depth of the AB might diminish, or alternatively, grow even deeper. Either finding would be informative about how visual processing changes over development, and would also provide evidence in support of or against certain theories of the AB. For example, if the aforementioned resource theory is correct, then over the course of years, visual experience with characters such as letters and numbers should reduce the AB for these increasingly familiar stimuli.

There have already been several studies on the developmental course of the AB and the results of these studies suggest that the typical AB pattern observed in adults develops slowly over the course of childhood, with a gradual reduction in duration until age 15 (Dye and Bavelier, 2010; Garrad-Cole, Shapiro & Thierry 2011; Heim, Benasich, Wirth, & Keil, 2013, 2015). However, it is important to note that differences between task requirements affect the characteristics of the AB and presumably the appearance of its developmental course. Most developmental studies of the AB use a task in which the two targets, T1 and T2 are defined by different criteria, (e.g. Heim, Wirth, & Keil, 2011, exp.1; Heim, Wirth, Benasich and Keil, 2015) or tasks that are complicated by the conjunction of targets and distractors (Dye and Bavelier, 2010; Garrad-Cole, Shapiro and Thierry, 2011). For example, Heim, Wirth and Keil (2011) asked participants to first detect a green mode of transportation (e.g. an airplane) and then a green shape (e.g. a circle) among other shape distractors (and recall the identity of both targets at the end of the stream). In a similar vein, Dye and Bavelier, (2010) and Garrad-Cole, Shapiro, & Thierry (2011) asked participants to first detect a red triangle that could be oriented to the left or the right, and then, switch mental sets to detect a blue triangle which could be oriented up or down, among distractors of different shapes and colors (e.g. green triangles, blue circles and yellow squares). At the end of the trial, participants had to report the orientation of both the red and blue triangles. This task was complicated not only by the need to shift mental sets to a different color, but also by the conjunction of color and shape features between the targets and the distractors. Examining the development of the AB in the absence of set-shifting requirements is important as Dale, Dux, & Arnell (2013) suggest that although different types of tasks that measure the AB seem to share common variance, tasks that include a set-shifting component also have unshared variance that cannot be attributed to the AB.

The AB paradigms used in these studies are optimized toward the abilities of very young children by making the two targets clearly distinct from another, however, using distinct criteria for T1 and T2 places some limits on the conclusions that can be drawn from the observed AB. First, when two targets require different attentional sets, participants may solve the task by switching from one mental set to another as soon as the first target is detected in a form of task-switch. This might produce an additional task-switching cost in addition to the attentional blink, and therefore any differences between age groups might be attributable to age-related differences in the ability to rapidly change mental sets or the reliance on a set-switching strategy. In addition, since the T1 and T2 were always from distinct categories presented in the same order, participants would always know the order of the targets, which makes it impossible for participants to make temporal order errors. Recent

attempts to understand the perception of temporally contiguous events have focused on the interaction of the AB and temporal order errors (swaps), and such errors have also been found to be exaggerated in atypical populations (Hommel & Akyürek, 2005; Spalek, Lagroix, Yanko, & Di Lollo, 2012; Wyble, Bowman & Nieuwenstein, 2009; Su et al. 2015). Thus, the task presented here allows us to add a developmental component to the growing literature on this topic in adults.

In support of the idea that the developmental trajectory of the AB in these studies reflects developmental changes in set-switching, it is observed that in one of the two experiments reported in Heim, Wirth & Keil (2011), younger and older children were tested on a simple version of an AB task that did not require set-shifting. The authors found that in this case younger and older children showed AB patterns that more closely resembled a typical AB found in adults. Although this finding provides support for the notion that task selection requirements affect our understanding of the development of the AB, the fact that older and younger participants in this study received slightly different versions of the same task, makes direct comparisons difficult.

The present experiment

To provide an assessment of the developmental trajectory of the AB without contamination from set-shifting we have measured the AB using a simple letter detection task that neither requires set shifting nor presents complex conjunctions between targets and distractors. The same task was completed by three sets of individuals: younger children, older children and adults. In addition to assessing the developmental course of the AB on this simple task, we also assess temporal order errors, or swaps. Swaps occur when participants report both targets correctly but in the wrong order (Chun & Potter, 1995). These errors occur almost exclusively at very short temporal separations between the targets (i.e. lag 1 and lag 2) among adults, but have not been studied in children. Understanding the development of temporal order errors is relevant to our understanding of the AB and its cognitive models. For example, in schizophrenia (Su et al., 2015) there is some evidence that there is no AB deficit but there is a deficit in correct temporal order perception, which suggests that there are cases in which there could be impairments in the ability to organize information in time that do not coincide with AB differences. The present experimental design allows us to separately analyze the AB and temporal order errors.

Thus, the goals of this study were to assess the developmental course of the AB, using a very simple task among a) younger and b) older typically developing children and c) adults. In addition, we set out to determine whether developmental changes occur with respect to temporal binding errors by examining swaps in these 3 age groups across middle childhood, adolescence and adulthood. The results of the study will be compared against simulations from a computational model that relates swap errors to the depth of the attentional blink to determine how the developmental changes can be explained by contemporary theories of the AB in adults.

Method

Participants

Child participants were recruited through word of mouth and flyers placed in the community and through school listservs, an application that distributes messages to subscribers on an electronic mailing list. Adults were recruited through the SONA system in which undergraduate students in Psychology participate for credit. Participants were excluded if they had non-corrected vision problems, or other sensory impairments. Child participants were also excluded if they had a history of academic or psychiatric problems, as assessed by a parent history questionnaire. Thirty typically developing children and adolescents (16 females) between the ages of 6 years, 10 months and 14 years, 11 months, and 32 adults (22 females) between the ages of 18 years, 0 months and 21 years 11 months participated in this study ($M = 19.13$, $S.E. = .15$). The child participants were divided into younger ($M = 8.48$, $S.E. = .28$, $n = 15$) and older ($M = 12.1$, $S.E. = .39$, $n = 15$) groups. On the basis of previous research on the AB, in which a semi-mature AB is noted around the age of 10, our younger children were younger than 10.01 and our older children were 10.01 years or older. Participant characteristics, which also include age and IQ as measured by the Wechsler Abbreviated Scale of Intelligence, 2nd Edition (Wechsler, 1999) for the younger and older children can be found in Table 1. All of the child participants were right handed, and all had full scale IQ's in or above the average range. No significant differences were noted between the two child groups for any of the IQ variables.

Experimental task

All participants completed 234 trials of a categorical AB task. Participants were asked to recognize two letters among number distractors and report them at the end of an RSVP stream. Stimuli were presented using Matlab on either a DELL P2210 with a resolution of 1680 by 1000 pixels with a 60 Hz refresh rate or a Macintosh Mini with a screen resolution of 1680 by 1050 pixels with a 60Hz refresh rate. Despite the slight difference in size between the screen resolutions, the visual angle of all the stimuli were kept constant, subtending 1.2 degrees vertically and 1.3 degrees horizontally from the center of the screen. The experiments were programmed and initiated using Stream, a MATLAB toolbox that uses Psychophysics toolbox (Brainard, 1997) designed by the last author of this paper (BW). Stimuli were presented on a grey background at the center of a screen at a rate of 1 item per 135ms with no inter-stimulus-interval in 48 point Arial font. Although there is variability in methods used to measure the attentional blink and in RSVP more generally, we have followed the method of Chun & Potter (1995) who also used letter/digit stimuli and for which there was no ISI. Stimulus timing was confirmed with timestamps collected for each stimulus. Letter stimuli included uppercase letters A, B, C, D, F, H, J, K while number stimuli included the numbers 2, 3, 4, 5, 6, 7, 8 and 9. Each trial consisted of 30 stimuli, 28 distractors and 2 targets and began with a fixation cross, presented for 200ms followed by the RSVP stream (see Figure 1). The first target (T1) could occur in positions 6 to 18 in the stream. T1 position and T1–T2 lag (which included a no-T2 condition) were counterbalanced in a 13 by 9 design to ensure that these were evenly mixed. The inter-target interval (the time between the presentation of the T1 and T2, heretofore referred to as Lag) varied such that between 0 and 7 distractors could be presented between the T1 and the T2.

This lead to the following target onset asynchronies: lag 1 (135ms), lag 2 (270ms), lag 3 (405ms), lag 4 (540ms), lag 5 (675ms), lag 6 (810ms), lag 7 (945ms), and lag 8 (1080ms). On 11% of trials no T2 was presented (T1 only trials) in order to measure the ability of participants to report a single target and to serve as a baseline. On such trials, the T1 was presented randomly in position 6 to 26 in the RSVP stream. Following stimulus presentation, two identical response screens were presented (one at a time). Both screens contained two rows of possible targets presented on a grey background, as well as the following two statements: 'I saw nothing' and 'I don't know what I saw'. Child participants were asked to indicate verbally which uppercase letters they saw in order, while the adults typed in their responses. After the first response was typed in, the second response screen was presented, prompting participants for their second target response. Recognition rather than recall was selected as a response strategy for the participants. Although this differs from previous work in which participants are asked to recall targets, we believe this strategy minimized the potential confounding effects of memory development, allowing for a purer examination of the development of the AB.

Analysis strategy and results

T1, as well as conditional T2, accuracy scores were calculated for each participant at each lag. Conditional T2 accuracy represents accuracy with which participants correctly identified the T2 when they had correctly reported the T1 (i.e. T2|T1). Repeated Measures (RM) ANOVAs were run to examine the effects of lag and age. It is important to note that trials were included as correct if the order of reporting was reversed, that is, if participants identified the T1 as the T2 and vice versa, a strategy often used in the adult literature (e.g. Chun & Potter, 1995; Dell'Acqua, Doro, Dux, Losier, & Joliceur, 2016), and which also minimizes the effect of potential developmental differences in temporal order memory. Swaps, in which participants reversed the order of T1 and T2, were calculated as a total proportion of the trials in which participants reported both targets correctly but in the opposite order of their presentation. All interactions were probed with tests of simple effects using corrections for multiple comparisons. As is common in studies of the AB, interactions between age and lag for T2|T1 accuracy, specific lag based comparisons that allow for descriptions of the typical AB characteristics were conducted. Specifically, to assess for lag 1 sparing, paired t-tests for each age group were conducted to compare accuracy between lag 1 and lag 2, and lag 1 and lag 8, while, to assess for the presence of recovery of performance, comparisons are made between lag 2 and lag 8. Further, to assess for the presence of an AB, the mean of lags 2 and 3 was compared to the mean of lags 7 and 8 through a mixed model ANOVA. The strategy of examining the AB by combining lags 2 and 3 and comparing these to lag 7 and 8 was based on measures used in other studies on adults (e.g. Colzato, Sape, Pannebakker, & Hommel, 2007; Kelly & Dux, 2011; Martens, & Johnson, 2009) and was determined prior to examining the data.

Separate RM ANOVAs were conducted for T1, and T2|T1 accuracy measures as well as for the proportion of swaps with the between subjects factor of age (younger children, older children, and adults) and the within subject factor of lag (8). For the T1, there was a main effect of age ($F(2, 59) = 37.92, p = .000$), with accuracy increasing with increasing age. Younger children were significantly less accurate than older children ($M_{\text{younger}} = .62, S.E.$

= .04; $M_{\text{older}} = .87$, $S.E. = .027$; $p = .001$) and adults ($M_{\text{adults}} = .9$, $S.E. = .001$, $p = .001$) but there was no accuracy difference between older children and adults. A main effect of lag was also noted ($F(7, 413) = 8.43$, $p = .000$), which was driven by overall lower accuracy at lag 1 (all p 's, $< .02$) than all other lags, none of which differed from one another. No interactions between age and lag were noted suggesting a similar overall pattern of T1 accuracy between the groups, albeit with younger children having lower accuracy overall.

For T2|T1, there were main effects of age ($F(2, 59) = 5.38$, $p = .007$) and lag ($F(7, 413) = 31.3$, $p < .001$), as well as an interaction between age and lag ($F(14, 413) = 4.17$, $p < .001$). The main effect of age was related to findings that overall, accuracy was significantly lower for the younger children ($M_{\text{younger}} = .67$, $S.E. = .036$), than the older children ($M_{\text{older}} = .81$, $S.E. = .032$, $p = .017$) and the adults ($M_{\text{adults}} = .79$, $S.E. = .024$, $p = .013$), who did not differ significantly from one another. The main effect of lag suggests that the overall pattern of performance was consistent with typical AB findings.

To examine the lag by age interaction, we conducted a RM ANOVA with the factor of lag (mean of lag 2 and 3 vs. means of lag 7 and 8) of T2|T1 accuracy, and the between factor of age group. This analysis led to a main effect of lag ($F(1, 59) = 68.71$, $p < .001$) and an interaction between lags and age group ($F(2, 59) = 7.4$, $p < .001$), but there was no main effect of age, suggesting that the pattern of performance were similar across the different age groups. The mean of lags 7 and 8 ($M = .838$, $S.E. = .017$) was significantly higher than the mean of lags 2 and 3 ($M = .617$, $S.E. = .031$, $p < .001$). Posthoc tests suggest that with age, the accuracy decrement brought on by the AB decreased, however, the AB was significant for all of the groups. For the youngest children, there was an 11.5% reduction in accuracy ($M_{\text{diff}} = -.115$, $S.E. = .034$, $p = .005$), while for the older children, and adults, this decrement was 20% and 34% (both p 's $< .001$) suggesting an increase in the depth of the AB with age (see figure 4).

Paired sample t-tests were conducted separately for each of the groups in order to assess for the presence of lag 1 sparing and recovery from the AB. For the youngest group, only the comparison between lags 4 and 6 ($M_{\text{diff}} = -.124$, $p = .031$) was significant. For both the older children and the adults, there was clear evidence of lag 1 sparing, as there were significant differences between lags 1 and 2 ($p = .007$) and no differences between lags 1 and 8 ($p = 1$). Recovery of performance was also present for both of the older groups, as the comparisons between lag 2 and 8 was also significant ($p = .002$ and $.000$ respectively).

For the swap data (see Fig. 5), there were significant main effects of age ($F(2, 59) = 8.7$, $p = .001$), as well as lag ($F(7, 413) = 49.82$, $p = .000$), but no interaction. The proportion of swaps decreased with increasing age ($M_{\text{younger}} = .095$, $S.E. = .01$, $M_{\text{older}} = .055$, $S.E. = .01$, $M_{\text{adult}} = .041$, $S.E. = .007$, but only the differences between younger and older children ($p = .034$) and younger children and adults ($p = .0001$) were significant. A typical pattern emerged for the swap data, with the proportion of swaps decreasing rapidly over lags 1, 2, and 3 (see Figure 5). Significant lag differences were noted between lag 1, which had the highest proportion of swaps, and all other lags (all p 's $< .0001$). Swaps at lag 2 were significantly lower than at lag 1 and significantly higher than all subsequent lags (all p 's $< .001$), and swaps at lag 3 were lower than lags 1 and 2, no different from lags 4–7 but higher

than lag 8. Finally, swaps at lag 4–8 did not differ from one another. Together these findings suggest that although younger children made more swap errors in general, the pattern of these errors and their distribution over lags appears to be adult-like by the age of 7.

Discussion

This study analyzed the temporal properties of visual attention across groups of children, adolescents and adults. Our findings indicate that the recovery from the AB, and the occurrence of swap errors follow a similar time course across the lifespan. This is intriguing because it suggests that the temporal characteristics of visual processing are fixed at a relatively young age. However, there are also clear differences in the magnitude of these effects across age groups with the AB becoming deeper into adulthood, lag 1 sparing being absent in the youngest children and the proportion of swaps decreasing with increasing age.

Conditional accuracy in reporting the second target was lower at lags 2 and 3 compared with performance at later lags for all 3 groups. These lags correspond to a range of approximately 270–400ms, suggesting that the time frame of the AB is generally similar for both younger and older children, though deeper for the older children and adults, and is consistent with findings from the adult literature (Raymond, Shapiro, & Arnell, 1992; Chun & Potter, 1995; Kelly & Dux, 2011). There was also a reliable recovery of performance, with the conditional accuracy of the T2/T1 being highest at later lags for participants in all three age groups, but again, this was most pronounced for the older children and adults. Additionally, the pattern of swaps measured in the two child groups were similar to those noted in adults, with a similar falloff of swap errors as lag increased, despite a higher baseline level of swaps relative to adults. The depth of the AB, however, as measured by a difference between performance at lags 7 and 8 and lags and 2 and 3, differed systematically across age groups with the deepest AB being observed in the adults and the shallowest in the younger children. The overall percentage of swaps decreased systematically across age groups while having the same overall time course.

These findings contribute to the developmental literature on the temporal characteristics of visual processing in several ways. First, our findings that the AB duration is relatively preserved in children when using a simple task differs from the findings of previous explorations of the AB in children, which found a protracted duration of the AB, which presumably results from the difference in the tasks used to elicit the AB. All of the AB tasks reported in the literature (Dye & Bavelier et al., 2011; Garrad-Cole et al., 2010; Heim, Benasich, Wirth & Keil, 2013; Heim, Wirth & Keil experiment1, 2011), with the exception of one, used complex tasks that either required participants to shift their attentional set, or had complex stimuli in which targets and distractors shared multiple features. For example, in the two studies by Heim et al, participants had to detect a first target, which consisted of a drawing of a mode of transportation (e.g. a boat, a car or a bicycle), and a second target that was a shape (e.g. a circle, triangle, or square), among distractors that consisted of symbols. Garrad-Cole et al., 2010, and Dye and Bavelier, (2010) had participants detect first a red isosceles triangle pointing left or right, and then a blue isosceles triangle pointing up or down and report the direction in which they pointed. Thus, across experiments participants had to maintain two distinct mental sets and in some cases might have tried to switch their

task set after spotting the T1 to focus on the features that would allow them to detect the T2. In contrast, Heim, Wirth & Keil, (2011) found that on the featural AB task (experiment 2), in which participants had to detect two colored letters (or words for their older participants) in a stream of letters (or words), the younger children appeared to show a more traditional AB and also recovered from the AB more quickly than in the experiment with a switch in the T1–T2 task (as can be seen in figure 3 of their paper). Taken together, these findings suggest that although the basic mechanisms underlying the AB are present in fairly young children, tasks selection requirements may mask these effects.

We suggest that our method of recording the AB by asking subjects to report letters in a stream of digits (Chun & Potter 1995) is even simpler than the featural task of Heim, et al., (2011) and should be preferred as the purest measure of the AB. In this categorical discrimination task, there are fewer cognitive operations that have to be performed, since the visual attribute that defines the target (being a letter) is the same information that should be reported. In contrast, featural tasks, such as reporting colored letters, involve an extra cognitive operation because after the target color has been detected, the visual system must determine which letter was associated with that color and store that letter into memory. The necessity of binding a color to a letter identity may highlight developmental differences in cognitive processes that are additive with the AB. The results of Heim et al. 2011 in conjunction with our own suggest an opportunity to explore in greater detail the developmental differences in feature binding and category detection tasks since adults demonstrate a nearly identical AB time course of the AB between featural and categorical AB tasks (Dale, Dux & Arnell 2013).

Another important contribution of the present results is that with the categorical AB task we found a dramatic change in the pattern of the lag-1 sparing across a relatively small age range. Older children (mean age 12) had a precisely adult-like pattern of lag-1 sparing, while younger children (mean age 8.5) exhibited a complete absence of lag-1 sparing. The lack of lag-1 sparing in the youngest group of participants might be related to a difficulty in clearly separating the two target letters when they occurred immediately one after the other. Young participants, who have had less experience with the categories of letters and numbers, might have had more trouble judging the duration of the briefly flashed letters, which might have caused them to infer that only a single target had been presented.

This experiment also provides the first measurement of temporal order errors across developmental stages, and revealed that while there was an overall increase in the baseline level of swaps in children, the time course of recovery from swap errors was very similar across groups. This finding was unexpected because there were dramatic differences in overall accuracy between the age groups, which might have led to a slowed recovery of the swap curve for younger children.

Theoretical implications

In addition to informing us about developmental differences in temporal processing, the present findings also have implications for our understanding of the underlying nature of the AB since the results are not entirely compatible with any of the prevailing theories. First, the fact that the AB is deeper in adults than in children contradicts resource-based theories of

the AB since it would typically be assumed that healthy, young adults should be at the peak of their cognitive abilities and thus have an enhanced ability to detect and identify targets in an RSVP stream. Thus, adults should have had the smallest AB as measured by both duration and depth, in contrast to the results. Instead the results are more consistent with a competing theory in which the AB has an adaptively useful role in normal cognitive function and thus increases in depth with the maturation of the attentional system. An example of such a theory is embodied in the episodic distinctiveness model (Wyble et al. 2009), which proposes that the AB helps to segment visual input into short episodes for easy encoding into memory. This mechanism of episodic segmentation is presumably useful throughout the lifespan and thus should not diminish with age.

In this model, called the episodic Simultaneous Type Serial Token model (or eSTST hereafter), the AB results from an inhibitory control circuit that suppresses attention during encoding of a previously detected target into memory. Changing the strength of this inhibition allows the model to simulate the variability in the depth of the AB observed in the present comparison between age groups without affecting the duration of the AB (Figure 6a). Thus according to the eSTST model, the pattern of data observed here suggests that one of the developmental differences in visual cognition is that the magnitude of inhibition in this control circuit actually increases with age. The implications of this developmental change would allow an increasingly mature visual system to more effectively parcellate visual input into discrete memories. The fact that the reduction in the AB depth is accompanied by a decrease in swap errors provides some convergent support for this idea, since the eSTST model also simulates reduced swap errors at later lags as the magnitude of suppression increases.

However, the present results also provide data that the eSTST model has difficulty simulating. First, while the model does simulate an increased proportion of swaps at lag-2 when the strength of inhibition is reduced (Figure 6b), it does not predict that this change in swap errors would occur at lag-1 for parameter levels that are appropriate to simulate the typical depth of the AB. Thus while the model can simulate some developmental characteristics of the AB, there are a few aspects that it has difficulty addressing. This discrepancy highlights the fact that temporal order errors may not be as tightly tied to the AB as has been proposed in this model.

Another point at which the model has difficulty addressing these data regards the lack of lag-1 sparing for younger children. As can be seen in Figure 6a, manipulating the depth of the AB does not reduce the magnitude of lag-1 sparing. There is in fact no simple manipulation of parameters in eSTST that can accommodate the fact that there is no lag-1 sparing for categorical stimuli of this sort. One possible explanation for the present pattern of data is that it is difficult for younger children to understand how to separate the confusing situation when two items are encoded together at lag-1. The phenomenal experience of seeing two stimuli at lag-1 is that two items are perceived as occurring together. It may be easier for a more mature visual memory system to disambiguate this confusing percept so as to report the two letters separately, although the temporal order errors continue to occur at a fairly high rate even in the adults.

Conclusion

Together, these findings suggest that the AB becomes deeper with age, but that the timing of the AB, and its recovery, are consistent across development, after approximately 8 years of age. Future work will explore what changes to the parameters of the model are able to simulate differences in age groups such that overall accuracy can change without affecting the duration of the AB, as well as how task selection requirements affect the timing, duration and development of the AB.

Acknowledgments

We would like to thank all of the families who participated in this work. Our thanks also go out to Frances Batarse, Connor Black, Brandon Carlos, Samantha Debes, Leah Mattiaccio, Emily Payne, Alyssa Prawl, Alicia Rego, Amit Shapira, Magenta Silberman, Ashley Snider, Molly Waterman, and other members of the CARE lab for helping with data collection.

Grant sponsor: NIH; Grant number: 1R01MH101536-01 to N.R. and 5R01MH064824-13 to W.K.

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Highlights

- Developmental work provides evidence for and against models of the attentional blink that were developed based on adult data.
- Contrary to current models, the depth of the AB increases rather than decreases with age.
- Temporal order errors, or swaps, show a developmental change in terms of number of errors but not in terms of patterns of errors.
- The eTST model, which suggests that the AB is an adaptive function of the visual system can model some but not all of the developmental data, suggesting theory refinements are enriched by studying the phenomenon's developmental course.

Figure 1. Schematic of the categorical (right) task. T1 = first target, T2 = second target, Lag represents units of time between targets (lag1 = 135ms).

Figure 2.
Mean T1 accuracy as a function of lag and age group. Capped bars represent the standard error of the mean.

Figure 3.

Top half: Mean T2|T1 accuracy as a function of lag and age group. Bottom half: proportion of swaps as a function of group. Capped bars represent the standard error of the mean

Figure 4.

Depth of the AB measured as T2/T1 accuracy averaged over lags 2 and 3 relative to T2/T1 accuracy averaged over lags 7 and 8. Capped bars represent the standard error of the mean.

Figure 5.

Top panel: Simulated proportion of T2/T1 accuracy in the eSTST model at 130ms SOA for greater, and lesser amounts of inhibition

Bottom Panel: Simulated proportion of Swap errors for the same manipulation

Table 1

Participant Characteristics

Group	Younger	Older	Adults	F	p.
N	15	15	33	–	–
Age	8.48 (1.02)*	12.1 (1.51)	19.13 (.83)	58.64	.001
VIQ	115.7 (12.42)	114.9 (9.97)	N/A	.038	.85
PIQ	105.3 (17.24)	107.47 (12.5)	N/A	.16	.69
FSIQ	111.9 (14.56)	112.9 (8.81)	N/A	.052	.82

Mean values are presented with standard deviation values in brackets