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Developmental changes in feature detection across time: evidence from the attentional blink

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Abstract

The ability to select targets from an ongoing stream of visual information is critical to the successful management of visual attention. The Attentional Blink (AB), a phenomenon elicited using Rapid Serial Visual Presentation paradigms, allows for the assessment of the limits of the temporal visual system, and is reflected in a decrease in accuracy in the detection of the second of two targets when it occurs within 200–500ms of a first target. Evidence regarding the development of the AB is mixed and appears dependent on the task demands. Here we present data examining the AB across middle childhood, early adolescence, and adulthood using a color binding task in which participants had to detect, and report, the identity of two purple letters presented in a stream of black letters at a rate of 135ms/item. Results suggest that on these feature binding tasks, the depth of the AB is invariant across development, but that AB recovery gets faster with age. Further, the error data suggests important developments in temporal binding that are reflected both in a decrease in the number of swaps (where participants reverse the order of the targets but identify them correctly) and in the spread of temporal binding errors with age. These findings suggest that the characteristics of the AB and its development are task dependent, and also suggest that the development of binding abilities in visual search tasks mirror the time course of multisensory binding effects, perhaps suggesting a common mechanism.

Keywords

attentional blink; temporal processing; development

The development, and fine tuning, of the visual system during maturation presumably allows for increases in our ability to parse, encode, and process incoming information across both the spatial and temporal domains to make sense of our constantly changing visual world. These developmental changes provide an important means to answer questions about visual

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cognition that are not otherwise easy to address. For example, if a phenomenon observed in adults is thought to reflect a limitation of the system, then that phenomenon should be more pronounced in a less-developed visual system. On the other hand, if that phenomenon is thought to reflect a useful mechanism, or is the result of learning, it should be less pronounced in a less-developed visual system. This paper builds on previous efforts (Russo, 2016) to better understand developmental changes in how the visual system processes information across time by studying phenomena related to sequential processing that includes the attentional blink, and different types of errors made under temporal pressures.

Rapid Serial Visual Presentation (RSVP) is an experimental technique that measures the ability of the visual system to rapidly attend to and consolidate information distributed in the temporal domain. In RSVP, stimuli are presented rapidly, around 10 per second, and targets must be selected from among distractors (Forster, 1970; Potter, 1984) that can consist of characters, words, or even natural images. These targets can be specified in multiple ways, such as by feature (e.g. color), category (e.g. letters) or by some combination (Potter, 1976). RSVP tasks are designed to explore the temporal limitations of attentional selection, a central aspect of the successful management of visual attention in daily functioning.

One well-studied phenomenon that arose from RSVP studies is the attentional blink (AB). The AB occurs in RSVP tasks in which participants must detect two targets, and is reflected in a dip in accuracy when the second target occurs between 200–500ms of the first (Broadbent & Broadbent, 1987; Raymond, Shapiro, & Arnell, 1992). This AB, which is not a physical, but rather a metaphorical blink, is thought to reflect a mechanism that limits the amount of information that is being attended to, and can thus be used as an index of the time course of processing a given target (Dux & Marois, 2009; Martens & Wyble, 2010). That is, when participants are asked to attend to a stream of visual information and look for targets, when they detect a target, their attention becomes focused on that target so that they can process it, identify it and store it in memory. During this time, attention is diverted away from the main stream of information, to allow for deeper processing of the target, which takes around 200–500ms. If a second target appears during that time frame, it is often missed, and is reflected in a drop in accuracy for the second target. In the first computational AB models, the depth of the AB, measured in decreased accuracy for the second target (conditionalized on accurate report of the first target) reflected the ‘amount’ of resources required for target processing. It would thus logically follow that the deeper the blink, the greater the amount of attentional processing required. Given that children are generally less efficient at processing information, it was expected that the AB would get shallower with age, which has been substantiated in some, but not all papers on the topic.

Developmental studies of the AB

Developmental studies of the AB have been conducted, with varying results. Some studies have shown that the AB gets shallower with increasing age (Dye & Bavelier, 2010; Garrad-Cole, Shapiro, & Thierry, 2011; Heim, Benasich, Wirth, & Keil, 2015), while others have shown that the AB gets deeper with age (Russo, 2016). This juxtaposition can be explained, in part, by task demands. For example, both Dye & Bavelier (2010) and Garrad-Cole, Shapiro, & Thierry (2011) had their participants detect a red triangle (T1) oriented left or

right, and then, detect a blue triangle oriented up or down (T2), among distractors of different shapes and colors (e.g. green triangles, blue circles and yellow squares). Participants had to report the orientation of both the red and blue triangles at the end of each trial. Thus, participants had to shift their mental set between the detection of the first and second target. In addition, the targets and distractors shared both color and shape features, requiring additional discrimination. Both groups of authors found that the AB gets shallower with age, reaching adult like levels around age 15.

Using a simpler, categorical task with no set-shift, in which participants had to detect two letters in a stream of numbers, we reported that, perhaps somewhat counterintuitively, the AB gets deeper with increasing age from late childhood, through adolescence and adulthood (Russo, 2016). Modelling these data using the Episodic Simultaneous Type, Serial Token model (eSTST; (Wyble, Bowman, & Nieuwenstein, 2009), suggested that the development of inhibitory control mechanisms could account for both the findings of an increasing AB depth with age, and of a concomitant decrease in the number of swaps, a type of error where participants report both targets, but do so in the wrong order. These modelling findings suggest that inhibition plays a key role in the development of temporal visual attention, with an important transition occurring around age 10 (Garrad-Cole, Shapiro, & Thierry, 2011; Heim, Benasich, Wirth, & Keil, 2015; Russo et al., 2016). This task related distinction is particularly 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 among adults. Thus, charting the development of the AB requires consideration of the specific tasks used to elicit it.

In category tasks, such as the one reported above, participants seemingly must attend to every stimulus, and decide whether it is, for example, a letter or a number; that is, each stimulus must be processed separately, and sequentially to distinguish targets from distractors, and as such, the finding that inhibition plays a key role in task performance is not surprising. However, different types of tasks make different demands on attention and allow participants to use different strategies. For example, in featural tasks in which targets differ from non-targets with respect to a specific feature (e.g. color), the task encourages more passive monitoring of the stream until the colored letter ‘pops out’ and then that color is bound to the co-occurring letter. Assessing developmental changes with a task that makes different demands on visual attention, allows for the establishment of the concurrent validity, or for the task dependence of phenomena to be examined within a developmental context. This can help to inform both theory and our understanding of the manner in which temporal attention develops.

What can collateral error measures of the AB tell us about development?

Understanding the types, and magnitude, of errors under different processing demands is a hallmark of research in the study of perception, cognition and memory. Here we extend this notion to development by examining changes in both the rates and the nature of errors made by individuals across different developmental periods. Much like in the study of atypical development, we can learn a lot by examining what children do that adults do not do, in

addition to the more common perspective of examining the kinds of things that children cannot do that adults can. The later focus on a deficit approach in the study of typical development has certainly advanced our understanding of developmental processes but ‘how’ one processes information, informed by our understanding of errors, can provide a more nuance landscape for untangling how processes come together developmentally to lead to an ‘ultimate’ level of functioning (Burack, Russo, Kovshoff, Fernandes, Ringo, Landry & Iarocci, 2016). Thus, in addition to examining how the AB changes over the course of development in relation to its depth or duration, here we focus on two classes of errors, swaps and binding errors, in order to inform our understanding of the development of temporal processing and feature binding more generally.

Binding errors are errors in which participants erroneously report an adjacent distractor as the target. For example, the target in the following stream ACDHGIS is H, then temporal binding errors in the +1 and –1 direction would occur if participants reported that the target was a G or a D respectively. *Swaps*, are errors in which participants report both targets correctly but in the wrong order. Together, these errors provide additional information about the temporal precision of memory consolidation processes that is complementary to what we learn from the attentional blink. Though temporal order memory and feature binding each have a long history of their own, understanding their presence and nature within a temporal attention task provides a rich tapestry for placing their development into a broader context. Thus, assessing how errors change over the course of childhood, early adolescence and adulthood can provide critical information regarding the factors that support the healthy development of visual attention, which can inform both adult models of attention, as well as atypical development.

The goals of the present study are to assess the development of the AB on a feature detection task in older children, young adolescents and adults. Similar to our previous work, and work in the literature on the AB in adulthood, we assess specific characteristics of the AB: lag 1 sparing, in which accuracy at lag 1 is higher than lag 2, the AB, recovery of performance, and swaps, but do so in a feature binding task in which participants were asked to detect 2 purple letters in a stream of black letters. Swaps are becoming particularly relevant to the AB literature as recent work has focused on the interaction of the attentional blink and temporal order errors that have been found to be exaggerated in atypical populations (Hommel & Akyürek, 2005; Spalek, Lagroix, Yanko, & Di Lollo, 2012; Wyble et al., 2009). The study of swaps allows us to add a developmental lens to our understanding of the perception of temporally contiguous events. In addition to these standard metrics, we also assess a unique characteristic of feature binding task, referred to as temporal binding errors. Temporal binding errors occur when participants erroneously bind the color to a different letter presented in the stream. These errors generally occur for the distractors occurring just prior or just after the target, and their developmental patterns provide insight into whether quantitative or qualitative changes occur with development in the precision and spread of temporal attention.

Method

Participants

30 typically developing children between the ages of 6 years, 10 months, and 14 years, 11 months (16 females, 87% white, 6.5 % Asian, and 6.5% more than one race), as well as 32 adults between the ages of 18 years, 0 months, and 21 years, 11 months (22 females, 66% white, 12.5% African American, 12.5% Asian, 3% more than 1 race, 6% declined to respond) had a mean age of 19 years, 2 months (S.D. = 10 months) participated in this study. In accordance with findings from the literature that show developmental changes in the AB around 10 years, the children were divided into younger ($N = 15$, $M = 8.6$ years, $S.D. = 1.2$ years) and older groups ($N = 15$, $M = 12.1$, $S.D. = 1.6$ years). All participants had normal or corrected-to normal vision and no history of psychiatric or educational diagnoses. The study was approved by the IRB review board of a large northeast private college (protocol # 11–281). The title of the protocol was: the study of sensory processing and multisensory integration in autism spectrum disorders. All adult participants and the parents of children provided written consent, and all of the children provided written assent.

Experimental task

As reported elsewhere (Russo et al, 2016), the task consisted of 234 trials, preceded by a practice block to ensure comprehension of the task. The stimuli were presented Matlab on either a Macintosh Mini (resolution: 1680 by 1050 pixels; 60Hz refresh rate) or a DELL Trinitron (resolution: 1680 by 1000 pixels, 60 Hz refresh rate.) The visual angle of all the stimuli subtended 1.2 degrees vertically and 1.3 degrees horizontally from the center of the screen, despite changes in screen resolution. The experiments were programmed using Stream, a programming interface that uses Psychophysics toolbox (Brainard, 1997) designed by the last author of this paper (Wade & Wyble, 2016). 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. Only the letters A, B, C, D, F, H, J, K, L, N, P, R, T, V, X and Y were used. 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) occurred in positions 6 to 18 in the stream. T1 position and T1-T2 lag (which included a no-T2 condition) were counterbalanced. Any of the presented letters could be targets or non-targets and were randomly selected on each trial, with the limitation that letters could not be repeated within a range of 5 items in the RSVP. The inter-target interval, that is, the amount of time between the presentation of the T1 and the T2 (Lag) varied such that between 0 and 7 distractors could be presented between the T1 and the T2. Thus, the ITI's at each lag were: lag 1 (135ms), lag 2 (270ms), lag 3 (405ms), lag4 (540ms), lag 5 (675ms), lag 6 (810ms), lag 7 (945ms), and lag 8 (1080ms). On 11% of trials T2 was omitted (T1 only trials) to serve as baseline data. On these T1-only trials, the target appeared randomly between positions 6 and 26 in the stream.

After the stimulus presentation, two response screens were presented, one at a time. Each screen 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'. The possible targets always included the non-targets in the 5 previous and subsequent serial positions, as

well as the 2 targets. Participants first reported the first target they saw verbally, and the experimenter typed in their response. After the first response was typed in, the second response screen was presented, prompting them for their second target response, and the experimenter, once again typed in their response. Recognition rather than recall was selected as the best choice of response strategy to elicit responses for the younger participants, as there are notable developmental changes in free recall abilities and strategies with age (e.g. Ceci, 1980; Lehmann & Hasselhorn, 2007). In contrast, recognition memory abilities appear to be developmentally stable by age 7 (e.g. Mandler, & Robinson, 1978; Naus, & Kreshtool, 1977). As such, recognition was selected and kept consistent groups. Adult participants typed their answers on their own.

Analysis strategy and results

Detection accuracy was calculated individually at each lag for both the T1 and conditional T2 (T2|T1). Conditional T2 accuracy reflects those trials in which participants accurately detected both the T2 and the T1, regardless of the order in which they were reported. This method was selected for two reasons: first, it is one of the most frequent measures of the AB in the adult literature (Chun & Potter, 1995; Dell'Acqua, Doro, Dux, Losier, & Jolicœur, 2016), and second, it minimizes the effect of potential developmental differences in temporal order memory on assessing the AB. Swaps, which reflect the proportion of T2|T1 trials where the order of responses was reversed, as well as temporal binding errors, in which participants erroneously tagged the color to the letter in the previous 5, or subsequent 5 target positions was also examined.

All interactions were probed with tests of simple effects using Bonferroni corrections. As is common in studies of the AB, specific lag based comparisons that allow for descriptions of the typical AB characteristics were conducted on T2|T1 accuracy. Consistent with previous studies, (Russo, 2016), lag1 sparing was assessed with a series of paired t-tests between lag 1 and lag 2, and lag 1 and lag 8, for each age group separately. If lag 1 sparing was present, it would be evident in significantly higher accuracy at lag 1 relative to lag 2, as well as no differences between lag 1 and lag 8 accuracy. Two metrics of recovery of performance were assessed: first, to assess for the presence of performance recovery, comparisons are made between accuracy at lags 2 and 8, with the expectation that accuracy at lag 2 would be significantly lower than at lag 8. To assess for any developmental changes in the recovery of performance, we adopted the method outlined by Dye & Bavelier (2010), in which we examined the lag at which performance accuracy returned to 80% of lag 8 accuracy. This was tested using a one-way ANOVA, follow up by posthoc tests. Further, to assess for the presence, and depth of the 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 and children (Colzato, Spapé, Pannebakker, & Hommel, 2007; Kelly & Dux, 2011; Martens & Johnson, 2009; Russo, 2016) and was determined prior to examining the data.

Omnibus, RM ANOVAs with the between factor of age group and the within factor of lag on T1 accuracy, as well as T2|T1 accuracy were conducted. For the T1, there was a main effect of lag $F(7, 143) = 13.02, p < .01, \eta^2 = .181$, a main effect of age $F(2, 59) = 59.88, p = .000$,

$\eta^2 = .67$, as well as interaction between age and lag ($F(14, 413) = 2.73, p < .01, \eta^2 = .085$). The adults ($M = .921, S.E. = .021$) had higher T1 accuracy than older ($M = .786, S.E. = .030, p < .01$) and younger children ($M = .521, S.E. = .03, p < .01$), who also differed from one another ($p < .01$) suggesting developmental improvements in the ability to detect targets with age.

For T2/T1, there was a main effect of lag ($F(7, 413) = 16.2, p = .000, \eta^2 = .215$), a main effect of age ($F(2, 59) = 30.9, p < .01, \eta^2 = .511$) and a marginally significant interaction between age and lag ($F(14, 413) = 1.7, p = .057, \eta^2 = .054$). Overall, accuracy was higher for adults ($M = .88, S.E. = .021$) than both older ($M = .75, S.E. = .03, p < .01$), and younger ($M = .60, S.E. = .03, p < .01$) children who also differed from one another ($p < .01$). An examination of the pattern of means for the main effect of lag suggests that although there was overall no evidence for lag 1 sparing (lags 1, 2, and 3 did not differ from one another), accuracy at lags 2 and 3 was significantly lower than all later lags ($p < .05$), demonstrating the overall presence of an AB, which was followed by a recovery of performance. This main effect collapses across all ages and suggests that overall, the pattern of data was consistent with what would be expected for an AB task, but without evidence of lag 1 sparing. However, it is the age dependent pattern of scores that is of the most interest.

To assess for specific patterns of data related to the AB, a RM ANOVA was conducted with the within subject factor of lag (mean of lag 2 and 3 vs. mean of lag 7 and 8) for T2/T1 accuracy and the between factor of age group, which allowed for the examination of the depth of the blink. This analysis revealed a main effect of lag ($F(1, 59) = 59.6, p < .01, \eta^2 = .502$), with the mean of lag 7 and 8 being higher than the mean of lags 2 and 3, supporting the presence of an overall attentional blink. There was also a main effect of age ($F(2, 59) = 27.4, p < .01, \eta^2 = .482$) reflecting increased overall T2/T1 accuracy with increasing age. However, there was no interaction between age and lag, suggesting that the depth of the attentional blink did not differ as a function of age (see Figure 4), with a performance decrement of approximately 13% overall. In order to examine whether the characteristics of the AB were present in each age group, paired t-tests were conducted comparing T2/T1 accuracy between lag 1 and lag 2, and lag 1 and lag 8, which assess the presence of lag 1 sparing. The pattern of results was the same for all three groups, with no evidence of lag 1 sparing (lags 1 and 2 did not differ, and lag 1 accuracy was significantly lower than accuracy at lag 8 for each of the groups, see Table 1).

Time of AB recovery

To assess for the presence, and speed, of recovery of performance, two comparisons were made. First, a paired t-test was conducted between lag 2 and lag 8 to ensure that performance during the time period of the blink was lower than at the latest lag. This was true for all groups (see Table 3). Secondly, similarly to methods outlined by Dye & Bavelier (2010) we examined the lag at which accuracy (based on the max accuracy at lags 4–8) returned to 80% of maximum accuracy (between lags 3–8) and compared this across groups. Lags 1 and 2 were ignored, since the blink would not have occurred by lag 1 and would be occurring at lag 2. A one-way ANOVA with the factor of group, on the recovery lag yielded a main effect of lag ($F(2, 61) = 8.0, p < .01$). Post hoc comparisons suggested that the adults

($M = 3.2$, $S.E. = .09$) recovered earlier than the younger children ($M = 4.3$, $S.E. = .284$, $p < .01$) and that the older children recovered at intermediary lags ($M = 3.9$, $S.E. = .33$), which was no different than the younger children, but significantly slower than the adults ($p = .035$).

Swaps

To assess for developmental change in swaps, a RM ANOVA was conducted with the between factor of group and the within factor of lag on the proportion of correct (T2 & T1 both reported) trials in which participants reported the targets in the incorrect order. Main effects were noted for lag ($F(7, 413) = 47.4$, $p < .01$, $\eta^2 = .446$), and age ($F(2, 59) = 47.7$, $p < .01$, $\eta^2 = .618$), as was an interaction between age and lag ($F(14, 413) = 14.6$, $p < .01$, $\eta^2 = .332$). Younger children made significantly more swap errors ($M = .07$, $S.E. = .006$) than older children ($M = .02$, $S.E. = .006$, $p < .01$) and adults ($M = .009$, $S.E. = .004$, $p < .01$) but older children and adults did not differ significantly from one another overall. Lag effects were, as expected due to the presence of significantly more swaps at lags 1 ($M = .178$, $S.E. = .018$) and 2 ($M = .062$, $S.E. = .015$), than all lags (all p 's $< .003$). In addition, more swaps were noted at lags 4 ($M = .01$, $S.E. = .004$, $p = .029$) and lag 8 ($M = .01$, $S.E. = .004$, $p = .015$) than lag 6 ($M = .001$, $S.E. = .001$). The interaction between lag and age (see Figure 5) was driven by age related differences in the proportion of swaps at lags 1 ($F(2, 59) = 26.0$, $p < .01$, $\eta^2 = .469$) and 2 ($F(2, 59) = 12.6$, $p < .01$, $\eta^2 = .05$, $S.E. = .023$ for lag 1 = .299). Specifically, at both lags 1 and 2, the adults ($M_{adults} = .13$, $S.E. = .034$ for lag 1, and $M_{adults} = .00$, $S.E. = .02$ for lag 2) and older children ($M_{older} = .015$, $S.E. = .029$ for lag 2) did not differ from one another but had significantly fewer $M_{older} = .17$, $S.E. = .029$ swaps than the younger children ($M_{younger} = .35$, $S.E. = .034$ for lag 1 and $M_{younger}$ for lag 2, all p 's $< .01$).

Binding Errors

For binding errors, we examined the proportion of errors in which participants erroneously reported the target as the non-target in adjacent temporal position ($\pm 5, 4, 3, 2$ and 1) in a RM ANOVA with the factor of serial position ($-5, -4, -3, -2, -1, 1, 2, 3, 4$, and 5) and group for the average of T1 and T2 binding errors. The results revealed main effects of position ($F(9, 531) = 125.9$, $p < .01$, $\eta^2 = .681$), and age ($F(2, 59) = 61.3$, $p < .01$, $\eta^2 = .635$), as well as an interaction between position and age ($F(18, 531) = 21.1$, $p < .01$, $\eta^2 = .405$). Younger children made more temporal binding errors overall ($M = .035$, $S.E. = .002$) than older children ($M = .017$, $S.E. = .002$, $p < .01$) and adults ($M = .005$, $S.E. = .002$, $p < .01$), who also differed from one another ($p < .01$). The main effect of serial position was driven by proportions of binding errors being highest overall at position -1 , followed by positions $+1$, $+2$ and $+3$ (see Figure 6).

The pattern of binding errors for the adults found the proportion of binding errors to be numerically higher at position $+1$ ($M = .026$, $S.E. = .007$) than all other serial positions, but only significantly greater than at positions -3 ($M = .002$, $S.E. = .001$), $+2$, ($M = .004$, $S.E. = .003$), and $+3$ ($M = .002$, $S.E. = .002$). Overall binding error rates for adults were quite low. For the older children, the highest proportion of binding errors were also noted for position $+1$ ($M = .081$, $S.E. = .011$) which was higher than all other serial positions (all p 's $< .01$).

01), followed by serial positions -1 ($M = .019$, $S.E. = .003$) which was also higher than all positions with the exception of $+2$. Additionally, the proportion of binding errors in position $+2$ ($M = .018$, $S.E. = .004$), was significantly higher than position $+5$ ($M = .008$, $S.E. = .002$). For the youngest group, the highest proportion of binding errors also occurred for position $+1$ ($M = .12$, $S.E. = .011$), which was significantly more frequent than all other serial positions. Contrary to the older children and adults, serial position errors were both more frequent and more broadly distributed. The proportion of binding errors for the middle serial positions (-1 , 1 , 2 , 3) were significantly higher than serial positions more removed from the target, whereas for the older children and adults, these were close to zero. These findings suggest systematic developments in binding with increasing age.

Discussion

The goals in the present study were to examine characteristic indicators of temporal visual processing within the context of an RSVP task in which participants had to detect two stimuli that differed from non-targets on the basis of their color. The results of this study indicate specific developmental differences in AB characteristics across early and late childhood and adulthood. Developmental changes were found with respect to both overall increases in performance accuracy with age, as well as with a faster rate of recovery from the AB. Age related differences in collateral measures that included errors related to temporal binding and the maintenance of temporal order suggest developmental fine-tuning in the ability to bind information.

The study of the AB generally focuses on three related phenomena: lag 1 sparing, the blink itself and performance recovery. None of the groups in the study showed any evidence of lag 1 sparing on this task, as there were no within group differences in accuracy between lags 1 and 2, and lag 1 accuracy was always significantly lower than accuracy at lag 8. Though this finding stands in contrast with findings from other feature binding AB tasks (Maki, Couture, Frigen, & Lien, 1997), this is likely to be a result of the fact that both the T1 and the T2 were the same color. As such, two items at lag 1 might appear as only a single instance of purple, but of double the duration as for a single target. Participants likely had trouble judging the duration of the purple feature, which would have caused them to infer that only a single target had been present, thereby abolishing lag 1 sparing. This notion is further corroborated by the finding that T1 accuracy at lag 1, and to a lesser extent, lag 2 were also lower than all other lags across all age groups. Previous studies using feature binding tasks have found lag 1 sparing for colored targets, but those studies used red for one target and green for the other, so that participants would know even at lag 1 that two targets had been presented (Maki et al., 1997).

In contrast to other developmental work, which has shown both increases (Dye & Bavelier, 2010; Garrad-Cole et al., 2011; Heim et al., 2015) and decreases (Russo, 2016) in the depth of the AB as a function of age until around age 15, the decrease in accuracy in the time frame of the AB in the present study was approximately 13%, and this was the case for all three age groups. These findings suggest that on a feature binding task, the AB is mature by the age of approximately 10 years, despite a systematic increase in overall target accuracy with age. Recovery of performance was examined by comparing accuracy at lag 2 with

accuracy at lag 8. For all three groups, performance was significantly higher at lag 8 than at lag 2, and the magnitude of this recovery did not vary as a function of age. However, the lag at which performance returned to baseline did, in fact, develop with age suggesting that the effects of the AB linger over longer time periods in young children.

It is, in some ways, the examination of error patterns that tell the most compelling developmental story and suggests an overall fine-tuning of supportive functions that include temporal order memory and temporal binding. Consistent with previous work, the overall proportion of swaps was found to be higher for lag 1 than all other lags (Potter, Chun, Banks, & Muckenhoupt, 1998), and decreased with increasing age (Russo, 2016). Older children and adults did not differ from one another at any of the lags, but younger children had significantly more swaps at lags 1 and 2 than both of these older groups of participants. These findings suggest that younger children are more likely to incorrectly store the order of closely spaced pieces of information, and do so over a broader temporal delay than younger children. The finding that the proportion of swaps at later lags was near zero argues that children did recognize the importance of reporting the targets in order.

In conjunction with the developmental fine-tuning of temporal order memory between younger and older children, there was also evidence for the development of temporal binding abilities across childhood, early adolescence and adulthood, as evidenced by developmental differences in the amount, and temporal distribution, of binding errors. Again, the overall pattern was the same across ages, in that participants, when they made errors, were most likely to report the non-target following the target as the target. For adults, there were very few temporal order errors, but when they occurred, they were mostly restricted to the +1 position, similar to other studies (Chun, 1977). For the older children, these errors were more broadly distributed occurring significantly more frequently for the -1, +1, and +2 positions than non-targets further away. Finally, for the youngest group, the range of binding errors was even larger, occurring significantly more often in the -1, +1, +2, and +3 positions.

This systematic fine tuning of temporal binding for targets provides a single-modality analog of findings that the temporal window of multisensory integration has a developmental trajectory. Hillock-Dunn & Wallace, (2012) found that children and adolescents were more likely to report that auditory and visual events were synchronous for longer stimulus onset asynchronies than adults, especially at SOA's that were greater than 250ms and up to 500ms (which was the latest SOA tested in their study). Interestingly, in our study the +2 position, for which temporal binding errors were more frequent in both children and adolescents corresponds to 270ms separation, whereas the +3 position, for which errors were more frequent for the younger children corresponds to a 405ms separation, suggesting perhaps that the fine-tuning of binding modalities. may be more generalized than previously assumed, since it occurs both within as well as between senses.

In visual RSVP studies, binding errors are commonly thought to occur when multiple stimulus 'types' (Bowman & Wyble, 2007; Mozer, 1987) are activated at the same time by each stimulus, and the visual system has to correctly link the target-defining type (in this case the color purple) to the to-be-reported type (in this case, the letter). RSVP pushes the

visual system to its limits such that the target-defining type is inappropriately bound to the type from a following stimulus (Chun, 1997). This causes, in effect, an illusory conjunction but across stimuli presented at different times, rather than in spatial locations (Treisman, 1996; Treisman & Schmidt, 1982). A computational model of target processing in color-marked RSVP streams accounts for these illusions using a set of mechanisms that allow multiple types to be bound to tokens, which are similar to the notion of working memory slots (Chennu, Bowman, & Wyble, 2011). In this model, when multiple stimuli are presented in rapid succession, each letter activates a type-neuron, and the binding system has to link the color type-neuron to the correct letter type-neuron while ignoring the temporally adjacent type neurons. A delicately tuned inhibitory control circuit is required for this system to function correctly. The present results place the tuning of these circuits into a developmental time course, in which the development of inhibition might underlie developmental changes in temporal processing. Interestingly, and in line with this notion, previous developmental modeling work of the AB using a different task, in which participants had to detect letters presented in a stream of numbers found that modulating the inhibition parameter accounted for both the deepening of the AB with development, as well as decreases in the number of swaps noted with increasing age (Russo, 2016).

Together these findings suggest that in feature binding tasks, the depth of the AB is invariant across development from childhood through early adolescence, and adulthood, but that the effects of the blink are longer lasting. Furthermore, there appears to be systematic development in temporal binding processes evidenced in both decreases in swaps as well as in binding errors.

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Highlights

- The depth of the attentional blink was invariant across middle childhood, early adolescence and adulthood in a feature binding task
- Recovery time from the attentional blink decreased with age
- Two types of errors, swaps and temporal binding errors, decreased systematically with increasing age

Figure 1.
Schematic of the feature binding AB task

Figure 2.
Developmental changes in T1 target detection as a function of lag. Errors bars represent the S.E.

Figure 3. Developmental changes in the conditional accuracy of T2 as a function of lag. Errors bars represent the S.E.M.

Figure 4. Depth of the AB, measured as the difference in accuracy between the average of lags 2 and 3 and the average of lags 7 and 8 across age groups. Error bars represent the S.E.M.

Figure 5. Proportion of swaps as a function of lag for each age group. Error bars represent the S.E.M.

Figure 6.

Proportion of temporal binding errors averaged over T1 and T2 trial types at each serial position for younger and older children and adults. Capped bars represent the standard error of the mean. The solid line in the center denotes a change from binding to previous distractors to binding to subsequent distractors.

Table 1
Results of the paired t-tests assessing for the characteristics of the AB as a function of group

Group	Lag 1 -Lag 2			Lag 1 -Lag 8			Lag 2 -Lag 8		
	t	SD	p	t	SD	p	t	SD	p
younger	-1.1	0.16	0.28	-6.65	0.17	<0.01	-6.58	0.15	<0.01
older	0.52	0.18	0.61	-3.50	0.13	<0.01	-3.42	0.16	<0.01
adults	-1.16	0.24	0.27	-2.53	0.27	0.024	-2.49	0.16	0.026