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Tracking the attentional blink profile: a cross-sectional study from childhood to adolescence

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Abstract

This cross-sectional study is the first to examine the developmental trajectory of temporal attention control from childhood to adolescence. We used a rapid serial visual presentation paradigm, calling for the identification of two targets (T1 and T2) embedded in a distractor stream. In adults, manipulating the lag time within the target doublet typically leads to pronounced impairment in report for T2, when it follows T1 after approximately 200 ms, with one intervening distractor (lag 2); this is referred to as the attentional blink (AB). Participants, however, tend to identify T2 more often when the targets have occurred in a row (“lag-1 sparing”), or are separated by larger lag times, resulting in a hook-shaped accuracy profile. Here, we investigated the extent to which this AB profile undergoes systematic developmental changes in 204 students aged between 6 and 16 years (grades 1–10). T1–T2 lags varied from zero up to seven intervening distractors. Behavioral accuracy in younger children (grades 1–2) was found to follow a linear path, having its minimum at the earliest lag. Lag-1 sparing, accompanied by a relative accuracy loss in the AB interval, first appeared in grade 3, and became more robust in grade 4. From grades 5 to 6, the hook-shaped profile remained stable, with steady increases in overall performance up through the highest grades. This suggests that younger children’s performance is limited by processing speed, while from preadolescence on, children are increasingly able to identify rapid target sequences at the cost of an interference sensitive, higher control system.

Keywords

attention capacity; attentional control; developmental trajectory; rapid serial visual processing

In a media-driven world, children are exposed to increasingly dense and rapid streams of information. In particular, electronic media platforms such as television, computer games, or the World Wide Web represent a formidable challenge for the processes regulating access to

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the limited capacity systems involved in many aspects of perception and cognition. In addition to selectively processing pertinent events of the sensory environment at the cost of others (i.e., selective attention), observers must also do so at a high temporal rate, engaging and disengaging selection mechanisms at a pace dictated by the external world. Accordingly, a child's ability to regulate attention processes over time has been suggested to play an increasingly important role in healthy development and well-being. Research in school-age students, for instance, indicated that interindividual differences in ignoring and attending of stimuli embedded in a rapid stream predict specific aspects of academic performance (Heim & Keil, 2012). Quantitative and objective data regarding children's ability to shield task-related information against a torrent of distractors also have implications for the construction of teaching media, the design of classroom activities, and policies regarding handheld media use, among others. Given their obvious relevance, the question arises regarding the developmental trajectory of the cognitive processes underlying temporal attention control. The current study takes a cross-sectional approach to address this topic, applying the well-established rapid serial visual presentation (RSVP) paradigm to students aged between 6 and 16 years, thus spanning grade levels 1 to 10.

The RSVP design represents a robust cognitive task, which allows researchers to examine the selection of predefined task-relevant items (the targets) from a stream of competing, extraneous events (the distractors). Stimuli (words, digits, symbols, etc.) are delivered sequentially at high rates, typically in ranges of 8–12 exemplars per second (see Raymond, Shapiro, & Arnell, 1992). Target items are often highlighted by a specific feature, such as a certain color. When two targets are embedded within the temporal stream, then attending to the first target (T1) tends to be associated with a transient impairment in detecting the second target item (T2). This performance decrement is referred to as the attentional blink (AB) and is particularly evident when T1 and T2 are separated by at least one distractor and about 200 ms of time.

The exact mechanism underlying the AB effect has been extensively debated and an exhaustive review and discussion of the literature is outside the scope of this manuscript. We refer to Dell'Acqua, Dux, Wyble, and Jolicoeur (2012), and Martens and Wyble (2010) for recent reviews. Numerous theoretical accounts of the AB emphasize limited capacity, with a potential locus of the "blink" in working memory (e.g., Chun & Potter, 1995; Jolicoeur, Sessa, Dell'Acqua, & Robitaille, 2006). In this view, over-allocation of attentional resources to T1 is associated with lack of resources available for T2 in a trade-off fashion. As a consequence, T2 cannot be transformed into a durable and thus reportable working memory representation. An alternative perspective has highlighted the role of interference created by the need to rapidly engage and disengage attention, as targets and distractors alternate quickly (e.g., Di Lollo, Kawahara, Shahab Ghorashi, & Enns, 2005). This notion has received solid empirical support, emphasizing the part of temporal attention selection in the AB (Vul, Nieuwenstein, & Kanwisher, 2008; Nieuwenstein, Potter, & Theeuwes, 2009). For instance, attenuated AB impairment is found when observers are prevented from over-attending to T1, e.g., by listening to music (Olivers & Nieuwenhuis, 2005) or viewing multiple targets in a row without intervening distractors (Di Lollo et al., 2005; Olivers, van der Stigchel, & Hulleman, 2007). Other findings, however, suggest that a pure resource-oriented account may have difficulty explaining the entirety of the data (Martens & Wyble,

2010). In this perspective, the AB effect has been interpreted to reflect implementation of an individual visual or cognitive processing strategy (Shapiro, Schmitz, Martens, Hommel, & Schnitzler, 2006; Wyble, Bowman, & Nieuwenstein, 2009). Thus, a variety of factors affecting attention control can be explored using AB-RSVP paradigms. In addition, since the blink phenomenon has been reliably demonstrated even with very simple stimulus materials, it provides a promising research design for developmental studies of attention.

Research drawing on various experimental paradigms has shown that the ability to select stimulus input and exert attention control continues to develop from childhood into early adulthood (e.g., Ridderinkhof & van der Stelt, 2000). Recently, Heim, Wirth, and Keil (2011) compared two groups of school children in terms of their AB performance. Lag time or stimulus-onset asynchrony (SOA) within a target doublet varied between no intervening distractor (116-ms SOA) up to seven intervening distractors (928-ms SOA). Fifth and sixth graders (aged 10 to 11 years) already exhibited the hook-shaped performance profile often found in adults: Second target identification was highest at the longest T1–T2 lag, decreased toward the critical blink interval (232-ms SOA, lag 2), and showed a relative gain when targets occurred in a row (so-called lag-1 sparing; Potter, Chun, Banks, & Muckenhoupt, 1998; Visser, Bischof & Di Lollo, 1999). In first graders (aged 6 to 7 years), on the contrary, behavioral accuracy continued along a linear slope having its minimum at the earliest T1–T2 lag. These findings were taken to indicate strong cost effects of processing speed in younger children, as compared to optimized attentional capacity (sparing when T2 followed T1 immediately) and impediments related to attention control (impairment when targets and distractors alternated rapidly) in older students (Heim et al., 2011; Heim & Keil, 2012). Such data are relevant for our understanding of how and when individuals are capable of applying strategies to support deployment of cognitive resources over time, during competition. The question arises as to the exact locus of this transition along a more fine-grained cross-sectional developmental trajectory. Here, we aimed to identify when between the ages of 6 and 11 years, and at what rate, changes occur to a more mature attention control system. Furthermore, we explored whether there are notable changes beyond early adolescence. The present study was therefore designed to include a sizable study sample spanning a large age range distributed on an ontogenetic scale of high resolution.

Here, we extend previous research by examining the AB profile across multiple grade levels in elementary and secondary education programs. Parameters of attentional selection have been shown to be strongly related to academic experience, as well as language skills, and cognitive strategies (Martens & Wyble, 2010; Heim & Keil, 2012; Stevens & Bavelier, 2012). Thus we used grade level rather than chronological age as a grouping variable. In Germany, compulsory education starts with the first grade of elementary school (alternative schools exist for children with different educational needs), when children are usually 6 or 7 years of age. The majority of federal states provide four grades of elementary schooling until children enter lower secondary education curricula around ages 10 or 11. These include grades 5 to 9/10 and prepare students for courses of education at the upper secondary level, which is necessary for vocational or university entrance qualification (Secretariat of the Standing Conference of the Ministers of Education and Cultural Affairs of the Länder in the Federal Republic of Germany, 2010). The most salient changes in attentive and cognitive processing occur during the early years of schooling, with less fine-grained differences

across adolescence (Ridderinkhof & van der Stelt, 2000; Heim & Keil, 2012; Stevens & Bavelier, 2012). We therefore grouped the younger students based on the four grades of elementary education, while the secondary school students were assigned to a total of three groups with each group combining fifth and sixth, seventh and eighth, and ninth and tenth graders. Based on our previous study (Heim et al., 2011), we hypothesized that first graders would exhibit a linear performance profile in the AB task, with an overall lower accuracy level. This would indicate that temporal attention in the younger children is driven primarily by capacity limitations, meaning that higher temporal density of the two targets predicts inferior performance. Hence, the lag-1 condition, in which targets follow each other directly, is associated with poorer accuracy than the lag-2 condition, in which a distractor appears between T1 and T2. As children progress through the elementary grades, we expect to see a developmental trend towards an interference sensitive, higher-order control system characterized by increased top-down regulation of attentive and perceptual processing. The development of such a system, allowing rapid selection of specific target features, is expected to result in the typical hook-shaped accuracy pattern of the AB. This pattern can be taken to indicate a relative benefit of two targets succeeding each other without intermediate distraction. Once established, the AB profile is expected to remain developmentally stable, with steady quantitative increases in overall performance into the final secondary school grades.

Method

Study Participants

A total of 204 students aged 6 to 16 years volunteered in the present study. Participants attended regular classes of elementary or secondary schools in the catchment area of the University of Konstanz and were divided into seven grade groups: elementary school grade (ESG) 1 ($n=24$; 10 females; mean age $\pm$ standard deviation [SD]: 6.83 years $\pm$ 0.38), ESG 2 ($n=24$; 14 females; 7.83 years $\pm$ 0.56), ESG 3 ($n=37$; 22 females; 8.41 years $\pm$ 0.50), and ESG 4 ($n=27$; 15 females; 9.33 years $\pm$ 0.62), as well as secondary school grade (SSG) 5–6 ($n=39$; 17 females; 11.18 years $\pm$ 0.68), SSG 7–8 ($n=33$; 19 females; 12.73 years $\pm$ 0.63), and SSG 9–10 ($n=20$; 8 females; 14.90 years $\pm$ 0.72). None of the students failed to reach class level in school or performed below average in nonverbal intelligence measures, including Raven's Colored (for ESGs 1 and 2; Bulheller & Häcker, 2002) and Standard Progressive Matrices (for ESG 3 to SSGs 9–10; Heller, Kratzmeier, & Lengfelder, 1998). The average IQ was 106.30 ($SD = 13.88$) in a range between 86 and 145 across groups. A posteriori analyses revealed no significant relation between nonverbal intelligence and overall performance data in the AB design, with Spearman's r values centered around zero. Moreover, neither intelligence nor AB achievement scores were significantly modulated by gender (p values varied between $< .104$ and $.995$). This converged with earlier research in children, where effects of gender and general intellectual capacity were also absent in the AB task (McLean, Castles, Coltheart, & Stuart, 2010; Heim et al., 2011; Heim & Keil, 2012).

All participants were native speakers of German and reported to have normal or corrected-to-normal vision, no developmental disorder, psychiatric and/or neurological disease, and

none were taking medication that might affect central nervous system functioning. Because stimuli in the AB paradigm (see “Attentional Blink Task”) were presented very rapidly, only seizure-free students with a negative first-degree family history of epilepsy were examined.

The study was conducted at the University of Konstanz and approved by the local Ethics Committee. Prior to the experimental session, parents of students provided written informed consent; students gave their verbal assent. Including breaks, a typical laboratory visit lasted 1.5 hours. Participants received a shopping voucher or cinema ticket for volunteering their time at the end of the session.

Attentional Blink Task

In the AB task, stimuli appeared centrally on a computer screen with a retrace rate of 60 Hz, at a distance of 50 cm from the observer. A script written using Presentation software (Neurobehavioral Systems, Inc., Albany, CA, USA) controlled stimulus delivery and response registration. T1 items were three sketches of means of transport (car, airplane, and boat) and T2 items consisted of three geometric shapes (circle, triangle, and square), selected from the SPSS Marker Set (True Type). Twenty different geometric figures and shapes of the same typeface served as distractor stimuli. Targets and distractors were pictured in bright green and white color, respectively, using 40-point Arial font, against a black background. Each stimulus on the screen subtended a vertical visual angle of 0.82° . Target symbols had a luminance of approximately 24.9 cd/m^2 . Each stimulus in a trial was displayed for 50 ms, followed by a blank screen for 66 ms, which resulted in a rapid presentation rate of 8.7 items per second. A trial started with a randomized number of 5 to 25 distractors to avoid anticipation of T1 occurrence. The T1 symbol was followed by zero, one, two, four, or seven distractors until the T2 symbol appeared. These T1–T2 intervals represent SOAs (and lags) of 116 ms (lag 1), 232 ms (lag 2), 348 ms (lag 3), 580 ms (lag 5), and 928 ms (lag 8), respectively. T2 was always succeeded by 10 distractors. Presentation mode was pseudo-randomized to control for immediate repetitions of the same target as well as the same lag condition. There were a total of 100 trials (20 trials per lag), which were equally divided into two blocks, allowing the student to take a short break. A schematic of an example trial is shown in Fig. 1.

Participants were invited to monitor the stimulus stream for the identity of two green target symbols. Prior to the experiment, each student was informed about the types of stimuli that could occur as T1 and T2. Responses were given at the end of a trial, by mouse clicking the appropriate T1 and T2, all of which consecutively appeared among three alternatives (see Fig. 1). Students were encouraged to guess when unsure about the stimulus; no feedback was provided. After response completion, they initiated the next trial using the mouse button. The 100-trial testing phase was preceded by five practice trials to demonstrate the procedure and make sure that all participants understood the task correctly. To keep the duration of the experimental session short, and because the focus of the present study was on the profile of T2 report during dual-task demands, we did not include a control condition in which participants reported only T1 while instructed to ignore T2 (see also MacLean & Arnell, 2012).

Data Analysis

Target identification performance was expressed as the percentage of correct responses for each of the five lags. T2 report was considered correct only on trials with accurate T1 identification (T2|T1 accuracy). This is generally assumed to emphasize specific effects of limited resources across the two targets (Raymond et al., 1992). Subsequently, separate F values for T1 and conditional T2 responses were calculated using mixed-factor analyses of variance (ANOVAs) crossing the between-participants factor Grade Group (7; ESG 1, ESG 2, ESG 3, ESG 4, SSG 5–6, SSG 7–8, SSG 9–10) and the within-participants factor Lag (5; 1 = 116-ms SOA, 2 = 232-ms SOA, 3 = 348-ms SOA, 5 = 580-ms SOA, 8 = 928-ms SOA). Greenhouse-Geisser adjustments to degrees of freedom and p values for deviations from sphericity were conducted. With respect to T2|T1 accuracy, a significant Grade Group $\times$ Lag interaction was expected. Interaction patterns resulting from repeated measures ANOVA are limited in their ability to quantify how the overall shape of the AB curve differs across grade groups. To further explore the developmental trajectory of the AB profile, we thus quantified T2 performance as the sum of lag differences in the direction expected under the assumption of a typical AB profile with lag-1 sparing. Thus lag difference (Σd) scores were calculated for each participant using the following formula: $\Sigma d_{(T2|T1)} = ((\text{Lag 1} - \text{Lag 2}) \times 1.2) + ((\text{Lag 3} - \text{Lag 2}) \times 1.2) + (\text{Lag 5} - \text{Lag 3}) + ((\text{Lag 8} - \text{Lag 5}) \times 0.8)$. Weights for the differences were chosen based on earlier work showing that T2 accuracy can be predicted by a linear combination of the response to T1 and time between the targets, i.e., lag (Keil & Heim, 2009). The weighting procedure was based on the notion that the two earliest lags and the latest lag carry most information about the nature of the AB profile, i.e., it being linear or hook-shaped. To formally determine the weights, we first formed sum scores of the grand mean accuracy scores (percentage of correct responses) for all next neighbor lag conditions (lags 1 and 2, 2 and 3, and so forth). These four values were then expressed as multiples of the overall mean accuracy, inverted (such that deviating from the mean yields stronger weight for a given lag) and rounded to the first decimal. Accordingly, the first two lag difference terms were weighted by a factor of 1.2, giving greater weight to the critical intervals encompassing lag-1 sparing and the “blink”. The last difference term was weighted by a factor of 0.8 (i.e., an attenuation of 20%). In simplified form, by lag, the weights read $1.2 \times \text{Lag 1} - 2.4 \times \text{Lag 2} + 0.2 \times \text{Lag 3} + 0.2 \times \text{Lag 5} + 0.8 \times \text{Lag 8}$. High or positive Σd values indicate considerable performance sparing at lag 1 with a minimum around lag 2 and progressively superior percentages at later intertarget intervals. In contrast, low or negative Σd reflects a monotonous AB curve with decreasing accuracy related to increasing temporal proximity of the target doublets. The summed difference scores were then entered into a one-way ANOVA with Grade Group as the independent variable. This allows delineating the emergence of a potential hook-shaped performance profile as grade level progresses. Significant results obtained in the ANOVA models ($p < .05$) were followed up by Fisher’s least significant difference (LSD) tests. To counteract the multiplicity effect across all LSD tests, we controlled for false discovery rate at the 5% level by adopting the Benjamini-Hochberg algorithm (Benjamini & Hochberg, 1995). This algorithm resulted in a corrected significance level of $p = .0341$.

Results

Fig. 2a illustrates the mean percentage of T1 accuracy at each temporal lag for the seven grade groups. Mixed-factors ANOVA revealed that T1 performance was not lag-dependent, but generally improved from group ESG 1 to SSG 9–10, $F(6, 197) = 11.77, p < .001$. Overall identification scores (standard error of mean, SEM) listed in ascending grade order amounted to 83.96% (1.37), 86.58% (1.37), 88.70% (1.10), 90.59% (1.29), 92.92% (1.07), 95.09% (1.17), and 96.60% (1.50). Fisher's LSD testing indicated a "two-stairs-at-the-time" performance increase from ESG 1 to SSG 5–6, reflecting similar T1 accuracy in two consecutive grade groups, but significant differences between the next-but-one groups (false discovery rate corrected ps between = .0066 and .0341 for the next-but-one groups comparisons). Although no systematic changes were evident among the secondary-school groups, students of SSGs 7–8 and 9–10 identified significantly more T1s than ESG-4 students (false discovery rate corrected ps = .0104 and .0027, respectively). As just previously described, this was not the case for the SSG 5–6 group.

Mixed-factors ANOVA run on conditional T2 report resulted in significant main effects of Grade Group, $F(6, 197) = 38.57, p < .001$, and Lag, $F(3.69, 726.74) = 122.14, p < .001$, Greenhouse-Geisser $\epsilon = 0.922$, which were affected by a significant Grade Group $\times$ Lag interaction, $F(22.13, 726.74) = 2.86, p < .001$, Greenhouse-Geisser $\epsilon = 0.922$. Fig. 2b presents the mean percentage of accurate T2 report contingent on the correctly identified T1 at each lag for the seven groups. Following the Group main effect, it can be seen that there is a general performance increase from ESG 1 to SSG 9–10. As demonstrated by Fisher's LSD statistics, no significant differences emerged between the two youngest ESG and between the two oldest SSG groups. All other comparisons reached statistical significance having p -values less than the false discovery rate corrected $p = .0341$. When observing the overall shape of the AB profiles, it becomes evident that students in the first and second ESGs tend to improve T2 identification with lengthened lag time. In ESG 3, however, a slight enhancement in accuracy report is visible when T1 and T2 occurred in a row (i.e., lag 1, 116-ms SOA). This spared lag-1 performance accompanied by a relative accuracy loss at the critical blink interval (lag 2, 232-ms SOA) happens to be more pronounced in ESG 4, yielding a prominent hook-shaped AB curve. By the time of entry into secondary education programs (SSG 5–6), the T2/T1 pattern remains stable, with slight but constant increases in accuracy across temporal lags into late adolescence.

Quantifying the AB curve based on the Σd scores of conditional T2 report (see "Data Analysis"), one-way ANOVA revealed a significant main effect of Grade Group, $F(6, 197) = 5.92, p < .001$. Fig. 3 depicts the mean Σd scores for the seven groups. False discovery rate corrected Fisher's LSD comparisons confirmed the characteristics of the AB patterns presented descriptively above: Groups of ESG 1 and 2 students exhibited similarly low mean Σd values. A dramatic value increase occurred in ESG 3 (as compared to ESGs 1 and 2, ps = .0080 and = .0140, respectively) and continued with an escalation rate of about 75% until ESG 4 (difference from ESG 3, $p = .0198$). Henceforward, mean Σds decreased slightly across the higher grade groups (SSGs 5–6 to 9–10). These changes, however, were not significant and reflect the overall higher performance levels of secondary school students in the task.

Discussion

This study set out to identify cross-sectional changes in the AB profile across age cohorts, spanning school grade levels 1 through 10. We expected that the grade groups would display pronounced differences in their AB profile, reflective of the developing ability to exert top-down control of target selection during rapid serial presentation. The present results demonstrate that the dual-target accuracy pattern shows robust changes when students are compared cross-sectionally. We found that younger children consistently displayed a monotonous AB curve, indicative of limitations in processing targets occurring in rapid succession. By contrast, older children were characterized by a hook-shaped pattern often observed in adults: T2 stimuli appearing after T1 without intervening distractors were identified more accurately than T2s separated by one distractor. This lag-1 sparing effect (e.g., Visser et al., 1999) is thought to reflect a heightened ability to engage attention to the target features and successfully process targets matching this feature set, as long as intervening distractors do not disrupt this process. The complexity of attending to multiple targets in rapid succession is apparent in the lag-2 condition, where the presence of a distractor between T1 and T2 is associated with a sharp decline in report accuracy. In the current study, a qualitative change was observed from a predominantly linear pattern to a hook-shaped pattern. When quantifying the AB profile with a simple linear index, grade level 4 stood out as the age group showing marked relative lag-1 sparing, a pronounced lag-2 deficit, and prominent accuracy increments with increased lag intervals. Importantly, no lag dependency was observed for the T1 performance, which was found to linearly rise with grade level.

The choice of lags may be regarded as a potential limitation of the current study. Conceivably, the longest T1–T2 interval (i.e., lag 8) did not provide enough temporal distance for some of the younger students to allow full recovery from the AB effect. To the extent, however, that these children tended to show a linear trend in the AB profile, the present analyses are expected to capture age-related differences in dual-target performance, based on the lags available. In sum, our results indicate that the capacity for processing rapid visual events undergoes dramatic changes around the beginning of preadolescence: Younger students are primarily limited in their performance by the required rate of processing, i.e., their behavioral accuracy declines with increasing temporal proximity of the target doublets. Older students, on the contrary, are increasingly effective in engaging an attentional set that allows them to report rapid target sequences. This emerging capacity is accompanied by superior ability to ignore distractors and focus on a target, resulting in cost effects when an initial target stimulus is followed by non-matching distractors and a subsequent second target (Wyble et al., 2009). The present findings replicate our prior work (Heim et al., 2011) suggesting that the AB undergoes major changes between first grade and early secondary education. Most importantly, they extend our previous observations in that the current data pinpoint the position in the developmental trajectory at which the transition towards a more mature attention control system occurs (viz., signs of a hook-shaped pattern begin to show in grade 3 and get most pronounced one school year later). The data also indicate that while quantitative changes happen in the subsequent grade levels, there are no further qualitative differences in the overall AB profile. In addition, these results are consistent with other

research reports demonstrating lag-1 sparing effects in typically developing adolescents when using RSVP streams with shapes and random-dot patches (Visser, Boden, & Giaschi, 2004), numerals and letters (Lum, Conti-Ramsden, & Lindell, 2007), or numerals and symbolic characters (Ray Li, Chen, Lin, & Yang, 2005).

Besides age, RSVP studies have shown links between the AB and measures of academic competency. In one study, 8- to 10-year-old children belonging to the upper half of readers in their grade were found to exhibit an overall superior accuracy in T2 identification (McLean, Stuart, Visser, & Castles, 2009). Moreover, interindividual differences in the shape of the AB profile have been reported to predict specific aspects of academic performance in younger versus older school students (Heim, Keil, & Ihssen, 2006; Heim & Keil, 2012): In the hook-shaped profile of 10- to 13-year-olds, greater lag-1 sparing (indicative of greater temporal capacity at short intervals) was primarily linked to automatized language processing, including reading/spelling of familiar words and sentences, whereas a pronounced AB effect at lag 2 (indicative of superior T1 shielding at the cost of T2) specifically accompanied better performance in controlled language-production tasks, such as rule-based decoding of pseudowords. A different pattern of correlations emerged in the rather monotonous AB profile of 8- to 9-year-olds, implying that less proficient literates seem to always benefit from efficient shielding of T1 irrespective of whether the verbal material is new or more familiar (e.g., pseudowords versus age-appropriate words, respectively). Paralleling the current study, these findings suggest that the cost effects observed at lag 2 may be regarded as a consequence of the maturing ability to maintain an attentional set for a period of time, and thus may index a potentially beneficial process of attention control. Younger school-children, who are still in the process of learning to read and spell and are primarily characterized by limited capacity (absence of lag-1 sparing) show a stronger positive relation between the AB deficit and literacy outcome, suggesting that temporal attention control (reflected in the AB) interacts with academic achievement. With age and print exposure, cognitive control styles appear to emerge that more strongly rely on effortful target shielding. In older children, both facets of attention control (lag-1 sparing and the AB deficit) may therefore be predictive of academic skills. In the same vein, Stevens and Bavelier (2012) propose that selective attention skills may play an important role in the development of neural networks underlying language development and efficient reading. This opens potential avenues for attention training procedures in education and rehabilitation. For instance, Rueda, Checa, and Cómbita (2012) reported that 10 sessions of computerized attention training with preschoolers resulted in more adult-like electrical brain responses during a task involving distraction by spatial cues as well as enhanced abstract reasoning abilities. Conversely, kindergarten children at risk for reading failure benefited from an intensive reading intervention not only in terms of their early literacy skills, but also on measures of brain activity underlying selective auditory attention (Stevens et al., 2013).

Correlational work has also highlighted the many cognitive processes that may impact performance in the AB paradigm, as predicted by a plethora of conceptual models of the AB itself (see Martens & Wyble, 2010 for a review). For instance, recent electrophysiological research on the AB has consistently evinced trade-off effects between T1 and T2 processing: Greater brain-electric responses are typically observed for the T1 in trials with missed T2s,

whereas correct T2 trials are characterized by smaller response amplitudes to T1 (Kranczioch, Debener, Maye, & Engel, 2007; Keil & Heim, 2009). These findings are compatible with theoretical accounts of the AB, including overzealous attention deployment to T1 (Olivers et al., 2007), or general resource sharing accounts of visual processing (Shapiro et al., 2006). Although there is no direct evidence of trade-off between targets in the present data set, our study revealed that increased T1 performance and hook-shaped T2 profiles emerge with age. These latter findings may be more easily interpreted in the context of theories stating that the AB reflects fluctuations in attention control, subject to strategic modulation. Wyble et al. (2009), for example, propose that lag-1 sparing “appears to reflect a spatiotemporally constrained window of attentional enhancement that is deployed in response to detection of a potentially relevant stimulus” (p. 788). Although it is a matter of debate in the adult literature, whether or not the AB is related to other domains of cognition (e.g., Colzato, Spapé, Pannebakker, & Hommel, 2007; Martens & Johnson, 2009), it is conceivable that the development of temporal attention control as measured in the present study may be tightly related to other cognitive processes, including working memory, executive function, strategic skill, perceptual expertise, and similar constructs. In this regard, absence of lag-1 sparing and failure to recover from the blink would alternatively be consistent with a model in which younger children have a limited ability to maintain more than one target item in working memory.

Because the current research report is strictly cross-sectional in nature, it cannot examine the plausible hypothesis that different age cohorts, exposed to audio-visual media varying in complexity and speed, may differ in their ability to control temporal selection from a rapid stream. For instance, it is a relatively recent phenomenon to see kindergarten-age children equipped with handheld devices capable of presenting complex audio-visual material (Heim & Keil, 2012). Given the high density of cross-sectional sampling, and the sharp transition observed around the fourth grade level, it seems unlikely that cohort effects have strongly contributed to the present results. Future work may use longitudinal designs together with specific interventions such as attention training to study links between attention development and cognitive/academic changes.

In conclusion, this study shows that preadolescence is characterized by marked changes in the ability to engage and disengage attention to a set of task-relevant features in a rapid stream of distractors, ubiquitous in a media-driven world. The cognitive processes involved in this developmental step do not appear monolithically. Specifically, the emergence of the ability to process subsequent targets matching an attentional set comes at the cost of interference in response to non-matching distractors. Exploring the role of cognitive strategies in mediating costs and benefits of attention control provides an interesting object of future work.

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Fig. 1.

Schematic of the rapid serial visual presentation paradigm, implemented as an attentional blink task. Each trial included a baseline period of distractors, varying in number, before the first target (T1) was displayed. The second target (T2) was followed by another series of distractors. The number of intervening distractors between T1 and T2 was manipulated to yield different lag times. The present example illustrates a trial with one distractor amidst the target doublet, i.e., lag 2 with a stimulus-onset asynchrony of 232 ms. Students were asked to identify the two green targets at the end of the trial, by mouse clicking the

appropriate T1 sketch (car, plane, boat) and T2 shape (circle, triangle, square) on the computer screen

Fig. 2.

Behavioral accuracy at each interval between the first and second targets (T1–T2 lag) in the attentional blink task. Values represent means of the elementary and secondary school grade (ESG and SSG, respectively) groups. Vertical bars indicate standard errors of mean. Plot (a) illustrates the percentage of correctly identified T1 items. Plot (b) displays the percentage of accurate T2 report given T1 identification

Fig. 3. Weighted lag difference (Σd) scores extracted from conditional second target responses of the attentional blink task. Values show means of the elementary and secondary school grade (ESG and SSG, respectively) groups. Vertical bars reflect standard errors of mean