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Attentional development can help us understand the inattentional blindness effect in visual search

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Introduction: Inattentional Blindness (IB) is the failure to notice an unexpected, usually salient stimulus while immersed in a different, often demanding attentional task. More than just a laboratory curiosity, IB is an important phenomenon to understand because it may be related to real-world errors such as missed "incidental findings" in medical image or security searches. Interest in individual differences in susceptibility to IB has produced a number of studies showing inconclusive results.

Methods: Here, we tested IB in a sample of 277 participants, 4-25 years old performing a visual search task. On two critical trials, an unexpected letter and an unexpected word were presented among photorealistic objects.

Results: There was a clear age effect with younger individuals showing higher IB levels. IB correlated with attentional control in visual search and with Continuous Performance Test-CPT for d-prime, response times and attentional shifting measures. These effects disappeared if age was controlled. There were no general effects of intelligence (IQ; RIST) or gender. Younger observers showed a negative correlation of IB for the word with the verbal components of the RIST IQ-proxy (no effect for the letter).

Discussion: These results support a relationship between IB and cognitive-developmental changes, showing that maturation of attention and executive processes can help us understand the intriguing phenomenon of (sometimes) missing what is in front of our eyes.

KEYWORDS

inattentional blindness, visual search, development, attention, individual differences, Intelligence Quotient, gender

Introduction

In spite of our introspective impression that we see a world filled with recognizable objects, psychologists have long known that there are severe capacity limits on human perception and attention (Noë et al., 2000). The phenomenon of Inattentional Blindness (IB) is a striking example in which observers fail to detect a salient, but unexpected stimulus while engaged in a primary, attention-demanding task (Mack and Rock, 1998). The Simons and Chabris (1999) gorilla experiment is probably the most famous example. Observers were monitoring a ball game in which they had to count the number of times that a given group passed the ball to each other. About half of these observers failed to notice a person in a gorilla costume walking into the midst of the game. Subsequent studies have found that even when our eyes fixate the unexpected event/stimulus, our cognitive system can still fail to bring it into awareness (e.g. Drew et al., 2013). Indeed, IB has been studied using a variety of experimental paradigms. These include dynamic tasks with more conspicuous, moving IB stimuli (like the "gorilla-task" from Simons and Chabris, 1999), static tasks with less prominent IB-stimuli (e.g., Buetti et al., 2014, which used a version of the flanker task or Cartwright-Finch and Lavie, 2006, using a visual search task), and eye-movement recording (e.g., Drew et al., 2013). The IB magnitude in these paradigms ranges from 30–40 to 80% of people failing to notice the IB-stimulus, even when eyes fixate on the IB stimulus. IB may represent a failure of normal attentional capture when observers perform an orthogonal, demanding attentional task, even though the IB stimulus can be quite salient (see Simons, 2000, for a review). Alternatively, the IB stimulus might capture attention in the moment but might fail to leave a memory trace that can be retrieved when the IB stimulus is to be reported (*inattentional amnesia* as named by Wolfe, 1999, but see Most et al., 2005). The present work aims to shed more light on the sources of variation in the IB effect by examining the effects of age, attentional performance, intellectual capacity, and gender in a large sample ranging from 4 to 25 years old.

Several studies have used individual differences to better understand the IB phenomenon. Factors including effects of age, cognitive, and intellectual capacity have been tested (e.g., Cartwright-Finch and Lavie, 2006; Drew et al., 2013; Memmert, 2014). However, the results of these studies have been inconclusive to date, so some studies have pointed toward a purely stochastic explanation of an IB phenomenon common to everybody, arguing that, with just one or two critical trials per observer, any individual differences in IB may be nothing more than random variations, rather than reflecting any underlying stable individual differences in cognitive abilities (Kreitz et al., 2015). Surprisingly, although attentional processes seem to be critical to understand the inattentional blindness phenomenon (e.g. Simons, 2000), there are not many studies looking to determine whether differences in attentional skills/performance are correlated with differences in the IB effect.

In prior work on the effects of age, several studies have shown larger IB effects in older adults both in static and dynamic IB-tasks (O'Shea and Fieo, 2015; Horwood and Beanland, 2016), and in more applied tasks, like driving simulations (Saryazdi et al., 2019). At the other end of the lifespan continuum, using the gorilla paradigm, Memmert (2014) found that younger children were more likely to show IB effects in a large sample of 480 participants from 8 to 15 years-old. However, Zhang et al. (2018) failed to find that effect in their sample of 210 observers from 7 to 14 years-old, using a T among L's dynamic IB-task based on Most et al. (2001). Zhang et al. (2019) also tested 3 to 5 years-old observers in Mack and Rock's (1998) original "cross judging" IB paradigm. They found that IB decreased with age.

Why is there such a range of variation in the developmental studies? As with the effects of other variables, purely stochastic noise must play a role in paradigms that typically get one or very few trials per observer. In addition, there is considerable variation in the nature of the IB tasks, so there might be other factors explaining IB variability. The "gorilla-task", the "T among L's" task, and the "cross judgement" IB tasks may make different demands on attentional/executive processes. These processes, in turn, develop at different speeds in development (Anderson, 2002; Gil-Gómez de Liaño et al., 2020), potentially producing a variety of age differences in the IB effect. In the present study, we will use a visual search task as the primary attentional task, as it has shown to be useful in the study of different attentional processes during development (Gil-Gómez de Liaño et al., 2020) to test IB in a large sample from 4 to 25 years old.

As development of attentional processes could explain IB variability in age, another question raises: How might differences in "attentional performance" or "attentional demands" account for IB effects? Lavie's work suggested that perceptual load (as defined in Lavie's Perceptual Load Theory; Lavie and Tsal, 1994) might modulate IB, with higher perceptual loads producing higher levels of IB (see Lavie et al., 2014, for a review). One way to operationalize perceptual load in Lavie's theory is by changing the complexity and/or number of the distractor stimuli surrounding the target in a given display: The higher that complexity and/or number of distractors, the higher the perceptual load; and in the present case, the higher the hypothesized IB effect. Cartwright-Finch and Lavie (2006) showed data supporting this hypothesis. However, Wright et al. (2018) failed to find any modulation of attentional capture propensity with IB, although they did find that speed of processing was related to IB: Observers who showed more efficient encoding and recognition of the main task stimuli were less likely to show IB. Putting the results of Lavie et al. (2014) and Wright et al. (2018) together, we could hypothesize that those individuals with higher levels of attentional skills (with better performance in the attentional task) should show less IB. However, not all attentional tasks seem to produce data supporting this idea. Richards et al. (2010) tried and failed to modulate IB using a Stroop task and a global/local flicker task. Kreitz et al. (2015) failed to find effects of IB in spatial attention either and suggested that IB effects were driven more by stochastic processes, rather than by any stable individual differences in cognitive abilities.

Other variables have been studied in combination with IB and we will also consider some of these in the present study. We test for an effect of gender. Prior work did not find such an effect (e.g. Hannon and Richards, 2010) and we replicate that lack of an impact of gender on IB. We also look for a relationship between cognitive capacity (Intelligence Quotient -IQ- and working memory capacity) and IB. Prior work has produced somewhat unsettled results on IQ-IB relationships. Although several results show a small-to-moderate correlation, with people having higher capacity showing lower levels of IB, this result is in need of more empirical support. O'Shea and Fieo (2015) found lower levels of IQ for individuals not noticing the IB stimulus, but the sample size in this study was probably underpowered, especially for lower-IQ individuals (9 individuals noticing the IB stimulus compared to 25 that did not notice the IB stimulus), making it difficult to establish the strength of these conclusions. Zhang et al. (2016) reported a similar relationship between IQ and IB effects studying gifted children. Intellectually gifted children showed significantly lower levels of IB (18%) compared to a group of IQ-average children (46%). Though different from IQ, working memory capacity is clearly related to IQ (e.g. Colom et al., 2007).

Thus, Hannon and Richards (2010) found similar correlations when measuring working memory capacity, as measured by the *Operation Span* (OSPAN), though not when using a simple visual working memory task. In contrast, Kreitz et al. (2016) failed to find a relationship between working memory capacity and susceptibility to cross-modal IB and *inattentional deafness* in a sample of almost 100 adult participants. Taken together, the results on IQ and/or working memory capacity show that there may be a small-to-modest relationship between IB susceptibility and lower levels of capacity. As noted, the data are not strong, and our results, reported below, do not support a relationship of IQ to IB.

To summarize, we study how individual differences in age, attention, intellectual capacity and gender modulate the IB effect. Our sample of 277 participants from 4 to 25 years old is well-suited to the examination of effects of age on IB, in part because we have data on other measures of attentional and executive functions, developmental indexes that may vary with age (e.g. slopes of search functions, intercepts, misses, etc.; see Gil-Gómez de Liaño et al., 2020). To anticipate our results, effects on IB of variation in visual search in standardized measures like the Continuous Performance Test (CPT) essentially vanish if age is controlled.

Methods

Participants

An initial sample of 293 observers participated in the study. Previous studies of age effects in visual search showed that with alpha set to 0.05 and 1-beta (power) over 0.9, we can detect significant effects (partial eta-square $\eta^2 = 0.01$), if we run between 21–33 participants per age group. We maintained those numbers in each age group. Participants were excluded from the sample if they had an estimated IQ below 70 (based on the Reynolds Intellectual Screening Test—RIST—score, see materials below), sensory or neurological pathology, motor impairments, learning disabilities, a diagnosis of schizophrenia, or a generalized developmental disorder (based on family interviews and standardized questionnaires). In addition, there were two sessions for the experimental procedure (see procedure for details) and the second session is critical to this study. Thus, observers who did not show up for the second session could not be included in the final sample. Sixteen participants were excluded on those bases, leaving the final sample of 277 observers from 4 to 25 years old. We attempted to divide those 277 observers into age groups consisting of at least 21 participants. As noted above, this should yield power over 0.9. The exceptions are the 11–12 year-old group with a final sample of 18 participants after losing several to the aforementioned exclusion criteria, and the 13–14 year-old group with a final sample of 20, for the same reasons. Fortunately, the main developmental changes in visual search occur at younger ages (Gil-Gómez de Liaño et al., 2020) so the modest loss of power in the 11–14 range should have little effect on the conclusions of the study.

All participants performed the Continuous Performance Test (CPT or K-CPT- Kids Continuous Performance Test depending on the age) and the RIST test as a proxy for IQ (see materials below). For minors (observers below 18 years-old), the BASC (Behavior Assessment System for Children) and BRIEF (Behavior Rating Inventory of Executive Functions) family versions tests were administered to the caregivers/relatives as a way to control and dismiss all children with clinical or generalized development disorders, as previously mentioned. The present sample is a subset of the one reported in Gil-Gómez de Liaño et al. (2020). In this final sample, there were 138 identified as females and 139 as males, and the mean IQ as measured by the RIST was 106 ($sd = 13.6$).

All participants were drawn from public schools and universities in Madrid, Spain. All had normal or corrected-to-normal vision. The Institutional Review Board (IRB) at the Universidad Autónoma de Madrid (UAM-Ethical Committee) approved the study before any testing (Code: CEI67-1193). A parent or guardian gave written informed consent for every minor, and each child gave oral/written assent. Regular informed consent forms were given to adult participants as well.

Materials

The experiments were run using E-prime 3.0 (Psychology Software Tools, Pittsburgh, PA). All images in the visual search were taken from a heterogeneous set of 3,000 unique photorealistic objects provided by Brady et al. (2008) following the same procedure as in Gil-Gómez de Liaño et al. (2020). For the targets, we selected a pool of 190 child-friendly images (toys, animals, arts-craft images; see Figure 1). Target and distractors came from a separate pool of images, so target images would never appear as distractor. Monitor resolution was 800 x 600 pixels. Each image fit inside an invisible box that subtended a visual angle of 2.3° x 2.3° at an approximate 57 cm viewing distance. The IB targets (discussed below) were the letter "N" and the word "COLOR". These alphanumeric stimuli are perceptually and categorically different from all other images shown in the task (see Figure 1). Similar stimuli have been used likewise in other IB studies (e.g. Buetti et al., 2014). These subtended 1.3° x 1.5° and 2.3° x 0.5°, respectively. Children responded via touch-screen (Microsoft Surface pro i5).

As previously mentioned, we applied several standardized tests: The Conners Kiddie Continuous Performance Test 2nd Edition™ (K-CPT) assessed attention capacity and deficits in children up to 7 years old, and the Conners Continuous Performance-3 (CPT-3) was used for observers 8+ years old. Both the K-CPT and the CPT are useful tests to measure performance in areas of inattentiveness, impulsivity, sustained attention and vigilance, being usually used in clinical contexts in the process of diagnosing Attention Deficit/Hyperactivity Disorder (ADHD), as well as other psychological and/or neurological deficits in attention. Both are based on a go/no go task in which observers must respond only to one target, avoiding responses to any other distractor. In the K-CPT the target is a soccer ball in a stream of other images. In the CPT-3, it is the letter X among other letters. To assess IQ, we used the Reynolds Intellectual Screening Test (RIST; Reynolds and Kamphaus, 2003). This short test takes around 20–30 min to be administered and shows high reliability with other measures of intelligence (Reynolds and Kamphaus, 2003). Finally, for minors, we asked parents to fill out the parent report form of the Behavioral Assessment Scale for Children

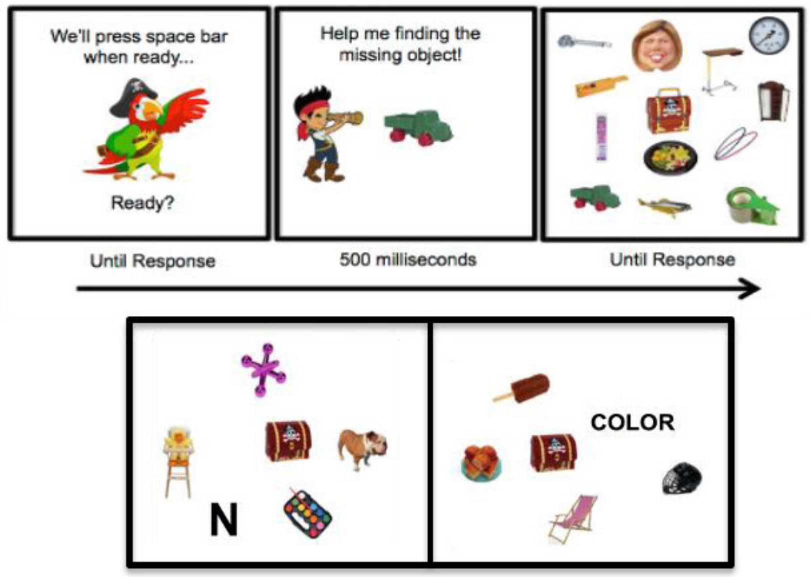

FIGURE 1
Upper row shows an example of the procedure, with presentation times written below each frame. **Lower row** images are examples of IB trials for Letter and Word conditions.

(BASC; Reynolds and Kamphaus, 2004), and the Behavior Rating Inventory of Executive Function (BRIEF) (Gioia et al., 2000). The BASC measures potential behavioral problems, assessing adaptive and problem behaviors in the community and home setting. The BRIEF measures potential problems with executive functions. The parents also provided information about the development of their children and their medical history using a short questionnaire developed by the researchers. These questionnaires were used to assess potential developmental disorders to dismiss those individuals under such circumstances to focus our study on typically developing persons.

Design and procedure

In a first phase, observers performed a visual search (VS) task (see Gil-Gómez de Liaño et al., 2020). Since different executive functions involved in VS have shown different rates of development using this task (Gil-Gómez de Liaño et al., 2020), we embed our IB stimuli into the ongoing VS task. That way, we will be able to study how those cognitive processes tested in VS can (or cannot) be related to the potential IB effect at different ages. For instance, approximately adult levels of attentional control seem to be achieved by 8–9 years old, as measured by speed-accuracy measures in the VS task, while intercepts and slopes reach adult levels later in development, potentially related to development of information processing capabilities and/or cognitive flexibility (see Gil-Gómez de Liaño et al., 2020). Thus, by relating IB to the VS indexes, we can propose potential relationships between IB and other aspects of cognitive development.

In the VS task, observers searched for a different target on each trial among a variable number of distractors. Trials were divided evenly among three set sizes (4, 12 and 32) as in classical VS tasks, allowing us to measure the standard effects of set size on search performance. A new target was identified in isolation at the beginning of each trial (see Figure 1). Set size and target presence/absence were randomized across a block of trials. Thus, each set size appeared on 33% of trials and targets were present on 50% of trials. Observers were asked to look for target items that "had been stolen" from the pirate chest (see Figure 1). They were encouraged to tap on the given target, that is, on the "stolen" items, as quickly and accurately as possible. If the target did not appear in the search display, they were told to tap on the pirate chest in the center of the screen as fast as possible in order to proceed to the next "treasure" (the next target). Nine practice trials were followed by 180 test trials (30 trials in each cell of the 3 set size by 2 target presence/absence design). The time needed to do the task varied for each participant, from about 15 min to 25 min, with younger more likely to require more time to finish, and stopping for resting times as needed by every observer. The results from this first phase are reported in Gil-Gómez de Liaño et al. (2020).

In a second phase (the IB phase), carried out on a different day from this first phase, observers performed the same VS task. This time there were only 24 trials that took between 5–8 min to be performed. Two trials were IB trials. For 50% of observers, on the 7th trial the letter, N, was shown among the distractors and on the 21st trial the word, COLOR was shown. For the other 50% of observers, the order was reversed; word trial first, letter second. Both of these IB trials were set size 4 displays and were target-present trials. According to Load Theory (Lavie and Tsal, 1994) there should be less IB in low load conditions (Cartwright-Finch and Lavie, 2006). Our aim was to create a typical IB situation in which the IB stimuli were visible and salient enough to be easily detected. We chose to use target-present trials in order to be able to determine whether finding the VS target is related to reporting the IB stimulus. Note also that the word and letter IB stimuli were visible throughout the critical trial. That is, they did not disappear until the observer ended the trial with a target present or target absent response to the search task. Unlike the classic gorilla-stimulus, the IB letter stimuli did not move. Thus, this is a static IB task. However, the instructions to the participants stressed that the observers should respond quickly because "*there was a pirate following them to steal the treasure items again*".

At the end of the 24 search trials, IB was assessed by asking observers to respond to the following questions:

A) Free-Recall:

1) *Was there something unexpected/different in this Treasure game? If so, please tell us what,*
2) *Did you notice there were letters or words among the images shown in the game? If so, please tell us what letter/s and/or word/s you saw,*

B) Recognition:

3) *Did you see any of these letters or words among all the images seen during the game? S, L, N, O, P, E and SILLA, AMOR, CUENTO, AMIGO, COLOR, PUERTA.*

Statistical analyses

To assess the IB task, we calculated the proportion of individuals giving responses consistent with IB separately for the letter and word IB conditions. For some analyses, we also differentiated those individuals who showed IB in both the letter and the word conditions. Since the pattern of results is very similar across the two free recall questions and the recognition question, we report the results for the free recall. Free recall data have the advantage of not requiring a correction for guessing. All analyses reported below only included individuals who correctly selected the target in the VS trial that included the IB. These observers can be assumed to have been paying attention to the primary task, especially since they had to tap on the target to perform the task. Under these conditions, for the letter-IB condition, there were 257 participants included in the analysis, for the word-IB they were 256, while for the joint IB condition, both letter and word, there were 241 observers[1].

Both for the RIST and the CPT we used the T scores calculated in the standardized tests. The RIST screening test is composed of two scales: "*Guess What*", a verbal scale measuring crystallized intelligence; and "*Odd-Item Out*", a nonverbal scale focused on fluid intelligence. Thus, we included in the analyses the three potential scores: the verbal T-score in the first sub-scale, the nonverbal T-score in the second sub-scale, and the general IQ score, as the quotient between both. On the other hand, the K-CPT and CPT tests produce an assessment report for each participant using the T-scores for the different variables measured in the test: *Response Style* (related to the trade-off between response time and accuracy, with more *liberal* or faster over accurate, and *conservative* being more accurate over faster), *Detectability (d')* of target-distractor discriminability, errors (*misses, commissions, and perseverations*), and *response times* (for each trial and for changes between blocks, as well as for its variability between trials). In the CPT, those measures are considered to be related to different aspects of attention. For the following analyses, we will use all these T-scores both for the RIST and CPT tests measuring IQ and different attentional aspects, respectively. Finally, for the VS task, we analyzed those measures related to those executive functions reported in Gil-Gómez de Liaño et al. (2020), that is, performance (proportion of hits, response times, misses, and false alarms), the slopes of the search functions and intercepts.

We run binary logistic regressions to determine the contribution of all factors to understand how they might modulate IB effects within a unified model. Inattentional blindness results for letter and word were included as the dependent variables in the analyses, and age (in months), CPT performance (with all the T-scores previously mentioned), RIST (including general IQ and both sub-scales described), gender, and VS performance—slopes, intercepts, misses, and inefficiency scores (Townsend and Ashby, 1983), as the covariables. We did not include false alarm measures in the analyses since their levels were at or near zero for most of the observers. We ran several versions of hierarchical logistic regressions, including all factors, or only those that seemed to better contribute to explaining IB effects, both for Letter and Word conditions. However, the regressions included too many factors with very high multicollinearity among them (even after reducing them in the VS task, by calculating the inefficiency scores), making it difficult to produce an understandable, comprehensive, unified model. The results of those regressions are shown in Annex A of Supplementary material 1, for the interested reader. Those results essentially show that Age, VS and CPT factors (not gender nor IQ in any RIST factor) might contribute to explain IB variability. Thus, we decided to analyze data separated for Age, VS and CPT, to better understand their contributions to IB.

For Age, we run again binary logistic regressions, but also ANOVAs to deeply study age effects on IB using the following age-bins: 4 yr old (36 observers), 5 (25), 6 (28), 7 (25), 8 (21), 9 (27), 10 (21), 11–12 (18), 13–14 (20), 15–17 (24), and 18–25 (32). We use finer age groupings at the younger ages because studies of attentional and executive functions in visual search (Gil-Gómez de Liaño et al., 2020) and clinical neuropsychological development (Anderson, 2002) show that the changes at younger ages from 4 to 10 can be more rapid than the changes in adolescents, who we consider in 2 year-bins. All observers from 18 to 25 are grouped

1 As we had two IB measures per observer, we could also compute a dependent variable to test IB propensity by coding observers not showing IB as "0", those showing IB for one of the IB stimuli (letter or word) as "1", and those showing IB in both IB trials as "2". Since the results are essentially the same as those shown in the manuscript for the classic binary analyses with IB dependent variables as "IB/no-IB", the outcomes of this analysis are shown in Annex B of Supplementary material 1 for the interested reader. We have maintained the classic analysis in the manuscript, though, for two reasons: first, because it allows splitting results into IB for letter and IB for word. It is interesting to test IB in development for literacy reasons that we will explain in detail in the final discussion. Second, because it allows comparisons with other IB studies.

into a single, "adult" bin. Given the nature of the variables analyzed here, a binary logistic regression could be considered to be a better option than the ANOVA. However, the regression does not allow us to look for differences among different age bins. Since we wanted to compare age bins between each other, especially at those initial ages from 4–5 years to 11–12 years, the ANOVA is a good option to do so. Moreover, the binary logistic regressions show very high levels of collinearity (as just mentioned), so looking at the ANOVA results could help us better understand those relationships among all variables. Indeed, the results using the ANOVAs and the regressions show similar patterns for the main effects, strengthening our conclusions, and the ANOVA allowed us to study finer differences among age-bin groups.

Following the same rationale, we also performed ANOVAs and logistic regressions for the VS and CPT measures after splitting the sample as follows. For some analyses, we split the sample into 4–8 years old observers and those equal to or above 9 years. As we will see in the results, the biggest changes in IB occur at the first stages of development, so looking carefully at those ages can help in understanding IB. For other analyses, we split every age bin into those with higher or lower skills in the VS and CPT tasks, to more deeply understand the relationship between IB and attentional performance. Although splitting the sample for each age bin group will result in some loss of power, it can still give us some hints as to how the attentional variables are related to IB levels. Finally, we compared IB effects between the two IB conditions (letter and word), using the McNemar test.

Results

Inattentional blindness by condition and age

Figure 2 shows the rates of IB for letters and words as a function of age group. The impression is of a clear age effect with, perhaps, a modest interaction of Age and Letter/Word Condition. The McNemar test showed no significant differences between Letter and Word IB conditions [$\chi^2_{\text{McNemar}}(1, N = 241) = 2.58$; $p = 0.11$; $\varphi = 0.004$]. When looking at those differences by age using an ANOVA with Letter/Word Condition as the within-subjects factor and Age-Group as the between-subjects factor, the Letter/Word condition effect does reach significance [F(1,230) = 3.71; $p = 0.05$; $\eta_p^2 = 0.02$], although the effect size is very small[2]. In general, if anything, it seems a little easier to see the word (41% reporting the word) than the letter (33% reporting the letter). The main effect of age was significant and large [F(10,230) = 5.92; $p < 0.001$; $\eta_p^2 = 0.20$]. As we can see in Figure 2, as age increases, IB decreases both for Letter and Word conditions. Logistic regression for age confirmed these effects: An age predictor showed a significant effect both for Letter [$\chi^2(1, N = 257) = 5.12$; $p = 0.02$; $OR = 0.99$] and Word [$\chi^2(1, N = 256) = 26.5$; $p < 0.001$; $OR = 0.98$] conditions. The predicted change odds ratio was equal to 0.99 for Letter, and 0.98 for Word, showing that increases in age correspond to decreases in IB (see again Figure 2). Finally, returning to the ANOVA, the interaction between Age-Group and Letter/Word condition did not reach significance [F(10,230) = 1.11; $p = 0.35$; $\eta_p^2 = 0.05$]. As can be seen in Figure 2, age effects are not linear. Changes in IB are obvious at early developmental stages, and by ages 8–9, those IB effects have roughly stabilized (c.f. Anderson, 2002; Gil-Gómez de Liaño et al., 2020). Indeed, if the analysis is split into observers less than or greater/equal to 9 years, the results change. For older observers (9+ years) there is no effect of Age-Group, (F < 1), while the Letter/Word Condition effect is clearer now [F(1,125) = 8.09; $p = 0.005$; $\eta_p^2 = 0.06$], although still small. On the contrary, the effect of age is clear for younger observers (4–8 years) [F(4,105) = 6.83; $p < 0.001$; $\eta_p^2 = 0.21$], with no effects of Letter/Word Condition (F<1). Interaction is not significant for any split sample (F < 1 for both ANOVAs).

To have a more robust measure (two, instead of just one data point per observer), we also calculated the proportion of observers showing IB in both Letter and Word trials compared to those showing IB just once or not at all. As we can see in Figure 2 (triangle line), there is again an evident age effect, both in the logistic regression [$\chi^2(1, N = 241) = 26.8$; $p < 0.001$; $OR = 0.98$], and in the ANOVA with Age-bin as the factor [F(10,230) = 6.14; $p < 0.001$; $\eta_p^2 = 0.21$]. Although the tendency to show IB in both conditions is a bit lower than the Word and Letter alone conditions (especially for participants 6 years old and older), the pattern is quite similar to that found for the Word condition: The main age changes occur from 4 to 8–9 years (steeper age function), after which performance stabilizes, showing similar IB levels from 8 to 9 and above ages ($p > 0.05$ for those older ages).

Inattentional blindness and the visual search task

We performed binary logistic regression with IB as the dependent measure, using VS variables separately for Letter and Word conditions[3]. Although the omnibus test was significant for Letter [χ^2 (7) = 16.32; $p = 0.02$; $r^2_{\text{Nagelkerke}} = 0.08$], the effect was not as big as for Word [χ^2 (7) = 57.66; $p < 0.001$; $r^2_{\text{Nagelkerke}} = 0.27$]. When we split the sample at 9 years, we find no effects for Letter ($p > 0.14$ in both samples), while for Word, all the variability comes from the younger observers (below 9 years) [χ^2 (7) = 23.7; $p < 0.001$; $r^2_{\text{Nagelkerke}} = 0.28$], with no significant effects for the older observers of +9 years [χ^2 (7) = 9.12; $p = 0.25$; $r^2_{\text{Nagelkerke}} = 0.09$]. For the younger group, there are marginally significant effects of absent trials in inefficiency scores ($p = 0.06$). The more efficient the search, the less IB is shown. This may be related to development of attentional control since the factors from VS that are related to IB modulations (essentially, efficiency measures in the VS) are those overlapping attentional control processes (see Figure 5 in Gil-Gómez de Liaño et al., 2020, and reproduced also in Figure 5 in the discussion below).

2 All interpretations of effect sizes were based on Cohen (1988) and Lakens (2013).

3 We will not include further analyses for those observers presenting IB both for Letter and Word from now on, as we have shown for the Age analysis. The reason is that the results of those analyses replicate those found for the Word condition, both for the VS and the CPT analyses. So, we do not want to overload the manuscript with too many analyses.

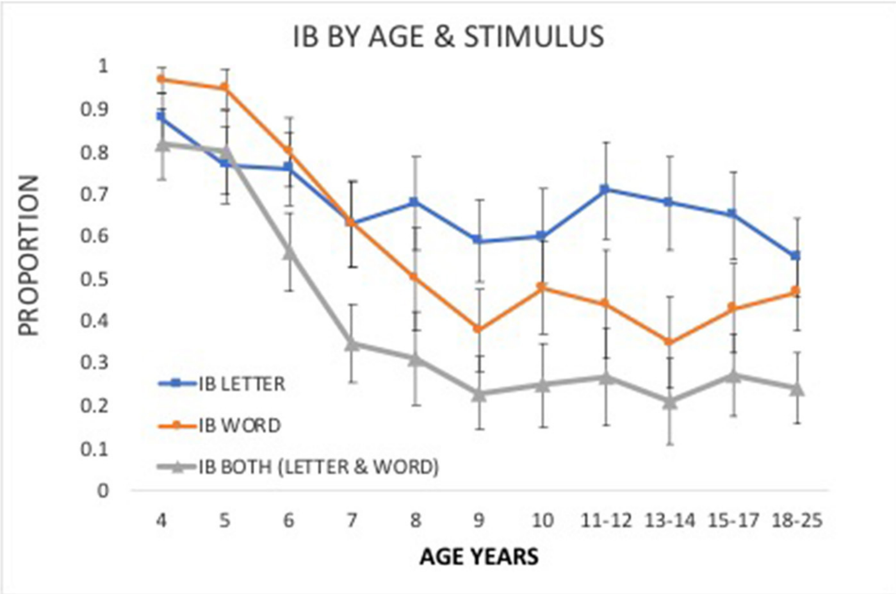

FIGURE 2
Proportion of inattentional blindness for letter, word, and both for letter and word by age.

As another way to examine the effects of Age together with those of the VS measures, we performed ANOVAs with the VS measures (inefficiency scores, slopes, intercepts, and misses) split by the median into two levels as shown in Figure 3 (High-Low), and used Age-Group levels as the factors and IB results as the dependent measure. Figure 3 shows the effects of those VS variables as a function of age for the Word condition. The Letter condition produced a similar pattern and the small effects were not informative. There are hints that *more* IB may be associated with *worse* VS performance but the effects are modest.

Indeed, the ANOVAs showed a pattern of results pointing to effects of Age in the Word IB condition[4] for the VS measures (age main effect for inefficiency scores [$F(10,234) = 6.05$; $p < 0.001$; $\eta^2_{partial} = 0.21$], for slopes [$F(10,234) = 6.20$; $p < 0.001$; $\eta^2_{partial} = 0.21$], for intercepts [$F(10,234) = 6.17$; $p < 0.001$; $\eta^2_{partial} = 0.21$], and for misses [$F(10,234) = 6.16$; $p < 0.001$; $\eta^2_{partial} = 0.21$]), but no modulation by VS-skills ($p > 0.20$, for all cases), nor for the interactions ($F<1$, for all cases). Therefore, although splitting age bin samples for every group of age could reduce statistical power, these results support the impression that there are no main effects of other variables besides age development in those attentional processes immersed in VS related to attentional control (as we have seen, misses and inefficiency scores). If effects were present, they appear to be not as big as those found for age changes. That is, the changes in IB are essentially produced by age, and/or changes in cognitive function (particularly, attentional control) that accompany age.

4 We also made the same analyses for Letter conditions, and, essentially, no significant effects show up in these ANOVAs, replicating previous results both for VS and Age modulation of IB effects.

Inattentional blindness and the CPT test

Using the same binary logistic regression with IB as the dependent measure and CPT variables as factors, the omnibus test showed that the model was not significant for Letter [$\chi^2(10) = 7.89$; $p = 0.64$; $r^2_{Nagelkerke} = 0.04$]. When the sample was split, no differences showed up either for younger or +9 observers.

For the Word condition, as before, the omnibus test is significant [χ^2 $(10) = 25.41$; $p < 0.001$; $r^2_{Nagelkerke} = 0.13$]. The significant factors from the CPT that contribute to the model are D-prime ($p = 0.04$), Mean RT ($p = 0.01$), and RT block change ($p = 0.04$). However, these effects do not survive if the data are split by age at 9 years. No significant effects are found in younger or older groups, assessed separately. If age is added as a factor in the main analysis, the model is significant [χ^2 $(11) = 39.05$; $p < 0.001$; $r^2_{Nagelkerke} = 0.19$], but, again, the CPT variables are no longer significant ($p > 0.05$ for all). Age is clearly significant ($p < 0.001$) though. Again, as age increases, IB decreases. Thus, the results of this analysis indicate that the CPT measures only modulate the IB effects for the Word condition when age is not controlled. This is illustrated in Figure 4, where the age functions are split into high- and low-performing groups, based on the median scores in each age group. As with the similar analysis for VS variables (Figure 3), it is clear that there are substantial effects of age before age 9 and no very systematic effects of the CPT variables. This is born out in ANOVAs on the Word condition with CPT (high/low) and Age Group as factors. Although again, the high/low split of age bins could result in some lack of power, the main effects of CPT variables are not significant: mean RT($F<1$), D-prime ($F<1$), and Block-change RT [$F(1,234) = 2.76$; $p = 0.10$; $\eta^2_{partial} = 0.01$]. On the contrary, the effect for Age Group is significant for the three ANOVAs: For mean RT [$F(10,234) = 6.29$; $p < 0.001$; $\eta^2_{partial} = 0.21$], D-prime [$F(10,234) = 6.53$; $p < 0.001$; $\eta^2_{partial}$

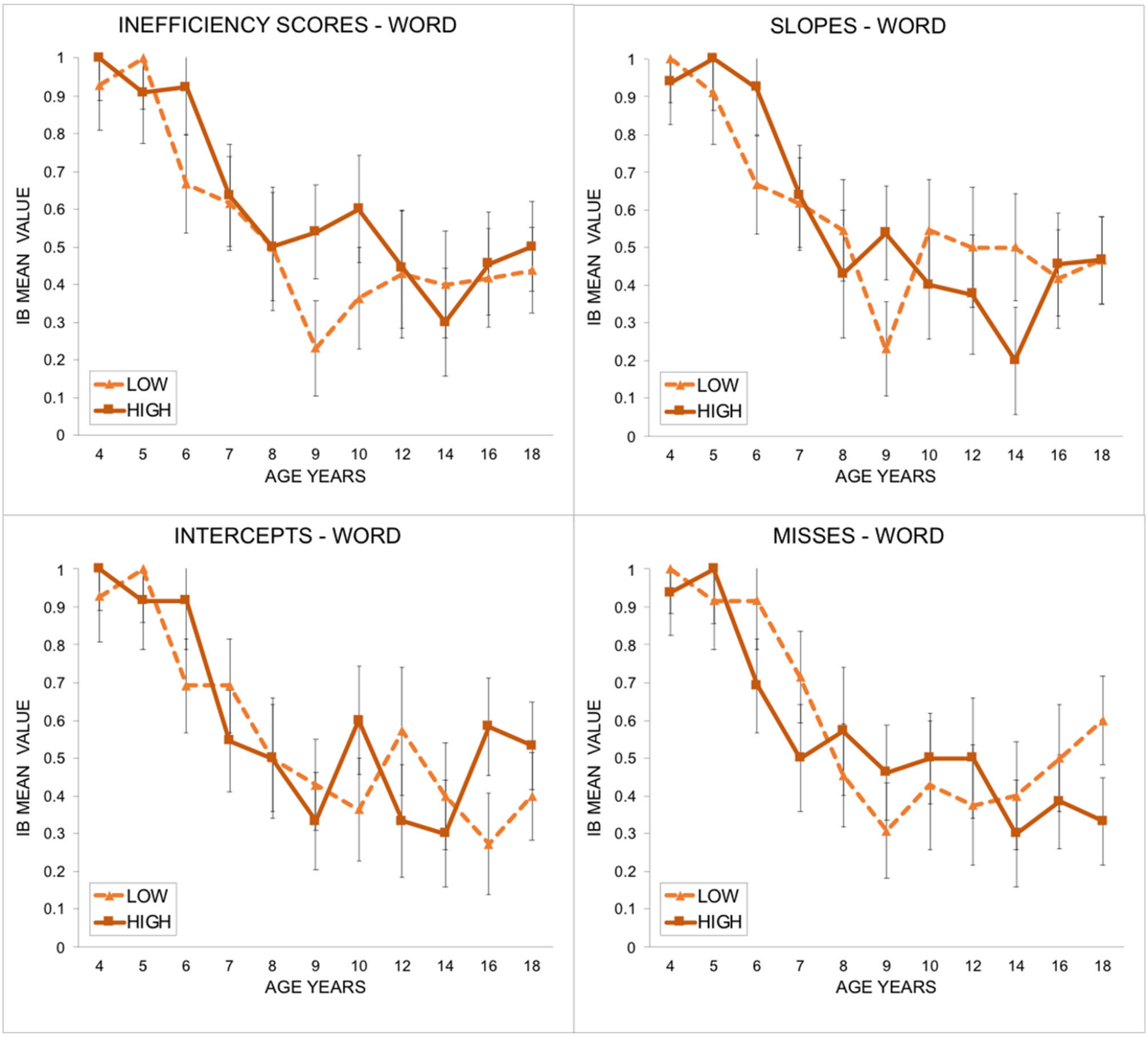

FIGURE 3
IB effects for different levels in the VS (high/low) for inefficiency scores, slopes, intercepts, and misses by age. They are examples to show the randomness of the distribution for IB, and the decrease by age-group.

= 0.22], and Block-change [$F(10,234) = 6.15$; $p < 0.001$; $\eta^2_{partial} = 0.21$].

Inattentional blindness and other individual differences: gender, IQ, and prior-IB

For gender, there are no significant differences for Letter [$\chi^2(1, N = 257) = 0.08$; $p = 0.78$; $\varphi = 0.017$] or for Word [$\chi^2(1, N = 256) = 0.11$; $p = 0.74$; $\varphi = 0.021$]. For Letter, there were 65% of women and 62% of men showing IB effects. For word, there were 50% of women and 48% for men.

For intelligence, we used the RIST and its subscales. We conducted logistic regressions with IQ as measured by the RIST (RIST T-scores) and its sub-scales as the factors and mean IB as the dependent measure. The results show no main effects of IQ on IB values both either letter and word conditions (see Table 1).

As in the previous analyses, we split the sample into two groups at age 9. In this case, although there seems to be no modulation of IQ in IB for our sample, the differences between letter and word conditions at different ages (particularly above or below 9 years) could be related to some sort of reading-like or language capacity that could be directly related to the verbal subscale of the RIST ("Guess What"). For letter, as expected there were no significant models for the regressions. But for word, we found a modulation for the non-verbal subscale of the RIST for the younger (<9 years) observers [$\chi^2(1) = 8.56$; $p = 0.003$; $r^2_{Nagelkerke} = 0.11$]. The effect showed that the higher the verbal capacity on the "Guess What" RIST sub-scale, the lower the propensity to show IB. Maybe, those

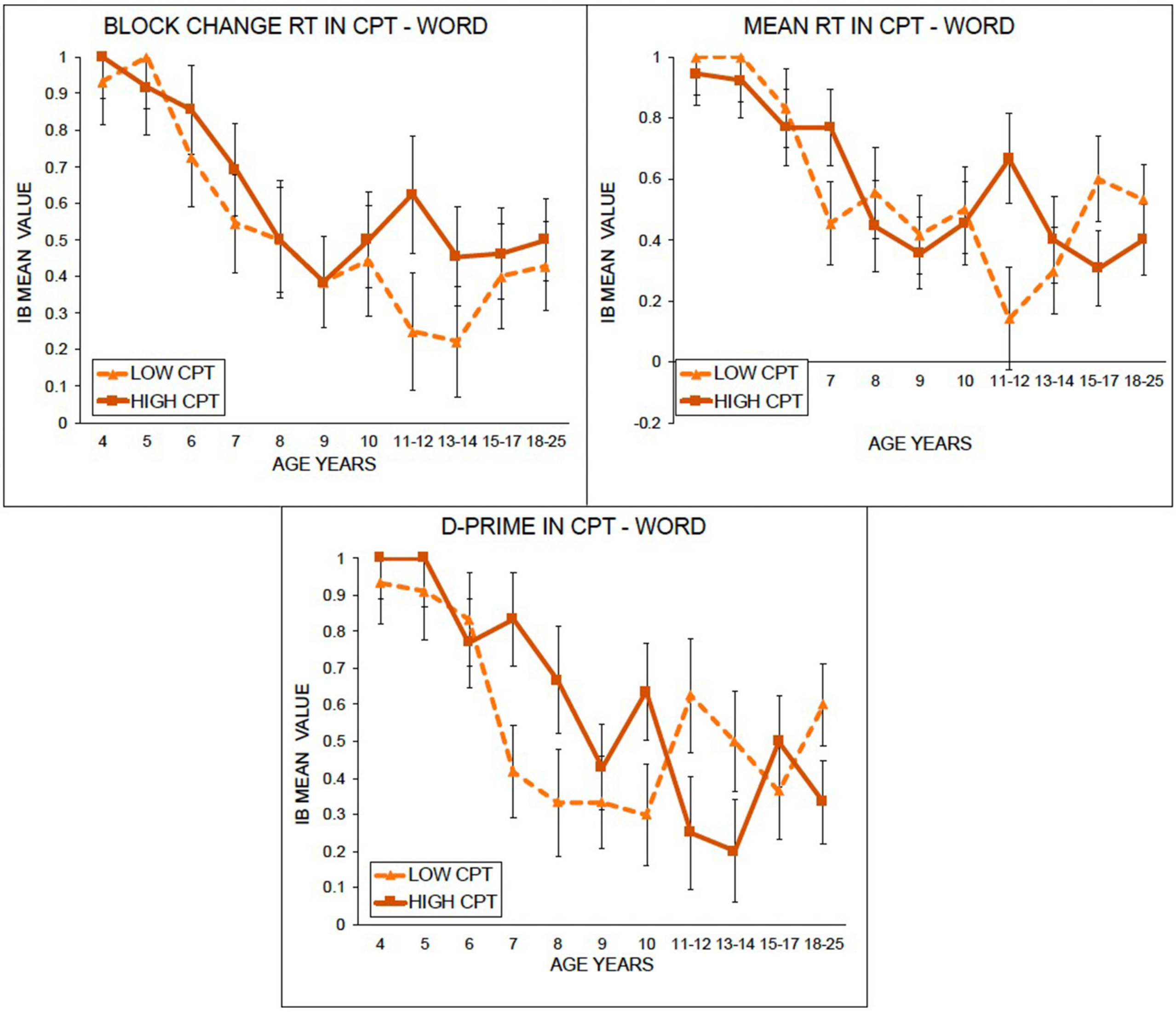

FIGURE 4
IB effects for different levels in the CPT (high/low) by age. We show here examples for D-prime, mean RT, and RT-block change, the factors that were significant for word IB conditions, when age was not controlled in the model.

TABLE 1 Statistics of the logistic regressions for the RIST screening test predicting IB values.

Predictor	*Wald's* χ^2	*df*	n	p	*OR*
RIST T Score	L(.12) W(.25)	1	L(257) W(256)	L(.74) W(.62)	L(.99) W(.99)
"Guess What" T Score	L(1.12) W(.001)	1	L(257) W(256)	L(.29) W(.98)	L(.98) W(1)
"Odd-Item Out" T Score	L(.48) W(.93)	1	L(257) W(256)	L(.49) W(.33)	L(1) W(.98)

L, for Letter condition; W, for Word condition.

younger observers who are acquiring reading skills (4–8 years) and thus have lower verbal-IQ results are less likely to identify and/or report out a word in the IB test. Similar results arise when testing the dependent measure of showing IB both for the letter and word conditions. For this measure, there is a significant effect for younger observers (<9 years) for the verbal sub-scale of the RIST, and also for the general IQ measure [χ^2 (1) $= 5.59$; $p = 0.018$; $r^2_{\text{Nagelkerke}} = 0.07$]; although as can be seen, the effects are small.

Finally, we also correlated IB between the two letter and word conditions. That is, is it more likely to show IB for the second IB stimulus, if you have previously shown IB for the first stimulus? The answer seems to be no, as the correlation between IB-letter and IB-word is very close to zero [r(n = 241) = 0.004; $p = 0.96$]. Similar results arise when splitting the sample (±9 years) or for any correlation at any Age-Group.

Discussion and conclusions

The results presented here are consistent with the failure to find conclusive evidence for individual differences that predict inattentional blindness effects (IB). With a sample of 277 observers, and using a visual search task as the primary attentional task, our results only show clear effects of age as a relevant variable to explain IB modulations. We find a strong age effect: Younger children from 4 to about 8–9 years old were less able to detect unexpected stimuli in our static-typical visual search task, with IB varying from 60% to over 90%. From about 9–10 years old to young adulthood, they significantly increased their capacity to detect these unexpected stimuli in visual search to adult levels (ranging from 40 to 50% of IB). One possibility is that general cognitive development is associated with an increasing capacity to detect unexpected stimuli during a modestly demanding visual search task. Individual differences in visual search performance, CPT attentional skills, IQ, or gender did not have significant effects on IB once age was controlled for. Actually, showing IB for the letter stimulus is not even correlated with showing IB for the word stimulus at any age group. An alternative possibility is that even the age effect might be less dramatic than it appears. Because we used letters and words as the IB stimuli, it is possible that at least some of the additional IB effect in younger children arises because they do not consider a word or a letter as particularly odd (or "unexpected") as an addition to a search array filled with other potential "treasure-images". Indeed, this idea might be associated with the correlation found between verbal-IQ skills and IB for younger children when detecting the word-IB stimulus. Those with lower verbal-IQ showed more propensity to present IB compared to those with higher verbal-IQ, somehow showing the IB may be associated with the nature of the IB stimulus itself, but not as a general propensity to show IB. If Simons and Chabris (1999) had a gorilla walking through a chimpanzee exhibit, it might be less surprising if that "unexpected" primate was not reported (because it seems not to be as unexpected as other type of stimulus). In a new study, we are looking for age effects in IB using non-linguistic stimuli, also manipulating the "un-expectancy" of the IB-stimuli. The effect on the youngest children might also be influenced by the use of letters/words. Although children of 4–5 years old are able to distinguish letters and words from images (Evans et al., 2009), it would be useful to replicate the IB results with non-linguistic stimuli. For the present, the development of reading skills at those ages may have complicated the detection of IB, particularly in the word IB task.

It seems unlikely that *all* of the age effects are due to the development of literacy though. There is a clear age effect up to about age 9, by which time children are very familiar with letters and words. How should we interpret the fact that IB performance seems to plateau around the age of 8–9 years old? This age seems to be a critical age when other important selective attention processes, particularly attentional control processes, approach their fully developed state. This is true for aspects of visual search performance (Gil-Gómez de Liaño et al., 2020), as well as for other attentional tasks like the Posner task (e.g. Rueda et al., 2005), and for applied neuropsychological assessments during childhood (Anderson, 2002). Indeed, our results support this idea, since those VS factors related to IB when age was not controlled were those shown in previous studies to correlate with attentional control. In Figure 5, reproduced with permission from Gil-Gómez de Liaño et al. (2020), we can see that those factors related to search efficiency were directly overlapping attentional control development described in previous neuropsychological child-development models (Anderson, 2002). It may be that IB declines because children become more competent at attentional control, which could be related to the propensity to show IB.

In sum, it seems that, before selective attentional processes mature around 8–9 years old, IB rates are in general higher, at least in our visual search task. Once selective attention processes reach nearly full development (8–9 years old), IB plateaus. The adult rate of IB of between 40–60% does not seem to be correlated with attentional capacity/performance, IQ, gender, or previous IB propensity. As is almost always the case, more research would be helpful. Cognitive differences between 4 to 8 year-old children with those ranging 9–25 years old are probably larger than the differences between people with IQs of 90 or 110, or with different scores in visual search or CPT variables. As noted above, it would be useful to see if the same IB x Age functions are seen with a non-linguistic IB stimulus too, or explore those slight effects found for IQ, especially those associated with verbal components of intelligence. It could also be helpful to investigate different IB manipulations that have shown to be critical to understand IB modulations outside the individual differences field. For instance, target present conditions and low load (4 items) for IB trials could have caused some sort of trade-off effect on IB levels. As we have seen, we expect to see less IB in low load conditions (Cartwright-Finch and Lavie, 2006), but at the same time, target guidance on target present trials would presumably increase IB too. More research is needed to determine how load and guidance could interact in IB effects in visual search.

The inattentional blindness effect to study attentional processes

As we have seen in the introduction, the Inattentional Blindness effect (IB) has been widely studied from the first Mack and Rock (1998) experiment and the famous Simon and Chabris's gorilla study (1999). Here, we are using a similar, very standard IB paradigm in which only one (or two in our case) trials are studied as the critical trials to determine if observers can detect and/or report an unexpected/rare stimulus shown within an ongoing task that demands some attention. In our case, that is a visual search task. As we noted in the introduction, using a one-trial test causes obvious statistical power problems. Unfortunately, the problem is that once the observer is alerted to the phenomenon ("Did you see the gorilla?"), the effect goes away. The next time there is a gorilla or, in our case, a word or a letter, observers will report it. By using this paradigm, we can connect our work to the previous IB papers that have used this final one-trial measure of reporting seeing the IB

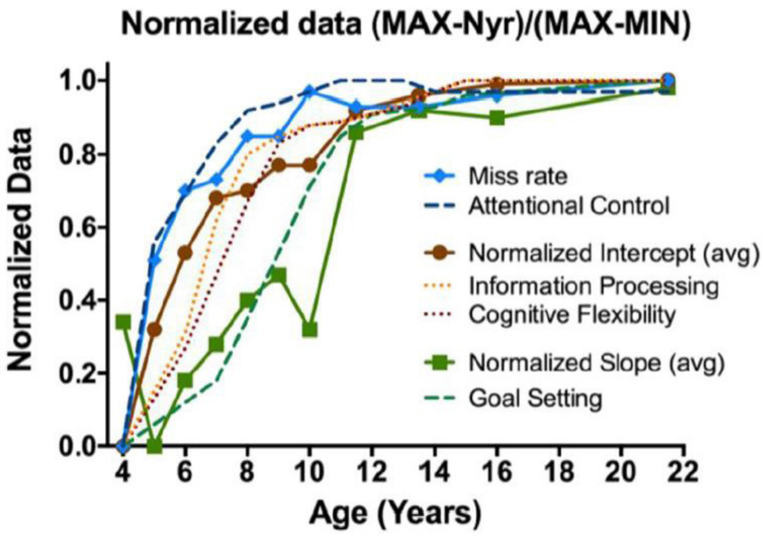

FIGURE 5
Normalized developmental curves for misses, slopes, and intercepts, reproduced with permission from Gil-Gómez de Liaño et al. (2020).

stimuli. However, this comes with the statistical problems inherent in a task that yields only one or two critical trials per participant. More research is needed to develop new IB paradigms that permit multiple trials, but within the classic IB paradigm, one trial is all you can get for analyses.

Other methodological factors can also have an impact on these types of IB paradigms. For instance, the dynamics of the task could be critical given that some tasks, like the "gorilla-task" of Simons and Chabris (1999), involve motion and very distinctive IB stimuli while other tasks are static and use less prominent IB-stimuli (e.g., Buetti et al., 2014). Indeed, some contradictory results have been found, using different dynamic/static tasks (Memmert, 2014; Zhang et al., 2018). Dynamic stimuli do not necessarily generate IB in the same manner as the static stimuli used here, especially in children (for instance, a word can attract more attention than a letter, as we have seen in the results for our older 9+ observers). Tasks with moving stimuli have shown interesting results in developmental studies, perhaps because they are easier and/or more attractive for younger observers. For instance, observers as young as 4-year-olds show a pop-out "attentional-capture" effect for chasing stimuli (Hofrichter and Rutherford, 2019). With these effects in mind, it might be that a dynamic attentional task, together with a moving IB stimulus could produce lower levels of IB in the younger children, at least compared to the high IB levels we have found using our static visual search paradigm with letter/word stimuli. A recent study has found results supporting this possibility, showing that young children (4–6 years-old) are more able to detect unexpected stimuli under dynamic conditions (Fang et al., 2021). We are also testing this motion-static difference in IB in our new study with non-linguistic stimuli. So far, these results may be telling us that IB is not a single phenomenon but something more like a term that covers a variety of situations that cause observers to miss seemingly obvious stimuli. Indeed, as we have seen, the IB effect can vary from 30–40% to 80% of people failing to notice the IB-stimulus upon some of these factors.

However, it is important to note that if attentional control development can help us understanding IB, thus supporting theories of attention failures are more likely to be in the base of the IB effect (Simons, 2000), and against the *inattentional amnesia* hypothesis (Wolfe, 1999). Forgetting is thought to be governed more by storage processes (and, potentially, by access to awareness), than by retrieval processes in childhood (see Howe and O'Sullivan, 1997, for a review). Looking at the time course of these processes, Drummey and Newcombe (2002) showed that older children do show more effective retrieval processes than do younger ones. Their 4-year-old children showed higher levels of amnesia in a source memory task. However, their 6–8 year-old children showed very few errors and, therefore, little amnesia in their task. Since in our study, those 6–8 year children still show elevated levels of IB compared to the older ones (8–9 years old and over), it appears that the time course of this aspect of memory development does not match the time course of IB development. Again, we need more developmental research using a wide-ranging battery of IB tasks across the lifespan, to rule out the *amnesia* hypothesis. Perhaps our search task (or other's) was too easy to reveal meaningful differences between observers over the age of 8–9 years old, and the use of linguistic stimuli might have affected the results.

Final conclusions

What seems relevant is that the present results constitute new evidence that the study of developmental changes in IB can be critical to understanding IB, and stress the fact that more research on IB across the lifespan will help to understand the phenomenon. More lifespan studies (not only developmental) are needed to test these hypotheses, as are new ways to improve IB paradigms to allow for more than one or two critical trials per observer. Those studies should also include older adults who have been found to show increasing IB levels at older ages quite consistently over several works (e.g., O'Shea and Fieo, 2015; Horwood and Beanland, 2016; Saryazdi et al., 2019). Lifespan studies could be a source of information to understand how these task-related variation and cognitive process maturation might interact to understand why we sometimes miss what is right in front of our eyes.

Data availability statement

The datasets presented in this article are not readily available because of the ethical restrictions as the study involved minors. Requests to access the datasets should be directed to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by UAM Ethical Committee Code: CEI67-1193. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

MQ-G programmed the experiments, and CC carried out the data collection and codification with help from MQ-G, BG-G, and EP-H. BG-G and JW performed the data analysis and wrote the paper. All authors conceived and planned the design and review the final version of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fcogn.2023.1134505/full#supplementary-material

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