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Motion-Induced Blindness as a Tool to Measure Attentional Biases and the Link to Attention-Deficit/Hyperactivity Traits

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Typically, individuals have an attentional bias toward the left visual field. This is often absent in individuals with attention-deficit/hyperactivity (ADH) disorder (ADHD). We used a motion-induced blindness task with targets in 4 quadrants to assess left/right as well as upper/lower spatial biases in perceptual disappearances and also measured changes in the disappearances with time-on-task. Fifty-eight university students (41 female) completed the Conners Adult ADHD self-report short-form to assess the number of ADH traits, and 48 trials of a 1-min motion-induced blindness (MIB) task. Through a hybrid hypothesis-driven and data-driven analysis approach, we found that the MIB illusion increased with more ADH traits, decreased with time-on-task, and was stronger for left and lower quadrants. The time-on-task likely contributed to the strength of the illusion through changes in arousal, as pupil size decreased with time-on-trial in a subset of participants ($n = 11$) for whom we measure eye movements. In addition, although participants were biased toward the lower left visual field, this was, unexpectedly, most prominent with those with higher ADH traits. This novel result suggests an additive effect of left/right and upper/lower spatial biases. Taken together, this study supports an association between spatial attention, arousal and ADH traits in MIB.

Keywords: motion-induced blindness, spatial attention, individual differences, arousal, attention-deficit/hyperactivity disorder

Attention-deficit/hyperactivity disorder (ADHD) is a developmental attention disorder, characterized by a persistent pattern of inattention and/or hyperactivity-impulsivity (American Psychiatric Association, 2013). ADHD was initially believed to be a childhood disorder, but growing evidence has supported its persistence throughout the life span (Boomsma et al., 2010; Kan et al., 2013; Larsson, Chang, D'Onofrio, & Lichtenstein, 2014; Wilens & Dodson, 2004). ADHD diagnosis relies on subjectively assessing behavioral criteria, and therefore diagnoses do not capture the underlying mechanisms and causes of the disorder (Insel et al., 2010). This is of particular relevance for the assessment and diagnosis of ADHD in adults, as it has been found that as age increases, the overt behavioral (predominantly hyperactive-impulsive) symptoms tend to decline, while inattentive and/or cognitive symptoms are more likely to persist (Millstein, Wilens, Biederman, & Spencer, 1997).

There are limitations associated with the current categorical approach to an ADHD diagnosis, and some researchers argue that ADHD can be more accurately considered as an extreme on a continuum, indexed on attention-deficit and hyperactivity (ADH) traits in the general population (Biederman, 1998; Cornish et al., 2005; Levy, Hay, McStephen, Wood, & Waldman, 1997; Lubke, Hudziak, Derks, van Bijsterveldt, & Boomsma, 2009; Marcus & Barry, 2011; Polderman et al., 2007). Measuring deficits and behavioral performance on a continuum, with ADHD at the extreme, adds value to understanding attention problems throughout the general population (Polderman et al., 2007).

In this study, we propose the utility of perceptual disappearance phenomena to assess modulations in spatial attention, arousal, and perceptual inhibition associated with ADH traits. We will start by briefly reviewing spatial attention, arousal, and inhibition deficits

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in ADHD and then explain why perceptual disappearance of motion-induced blindness (MIB; Bonneh, Cooperman, & Sagi, 2001), considered as a form of perceptual rivalry (Carter & Pettigrew, 2003), is a useful tool to investigate these constructs.

Right Hemisphere and Spatial Attention in ADHD

Right hemisphere dysfunctioning is associated with ADHD (for review, see Stefanatos & Wasserstein, 2001). The right hemisphere plays a dominant role in spatial attention (Loftus & Nicholls, 2012; Siman-Tov et al., 2007), regulating arousal (Harrison, 2015) and inhibition (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002). Indeed, these functions have been heavily investigated in relation to ADHD (see below), and behavioral measures of them may be important for ADHD research in adults, who manifest less overt behavioral symptoms.

Healthy individuals tend to preferentially attend more to the left visual field, with leftward biases in spatial attention reported across a range of visuospatial tasks (Benwell, Thut, Learmonth, & Harvey, 2013; Jewell & McCourt, 2000; Newman, O'Connell, & Bellgrove, 2013; Voyer, Voyer, & Tramonte, 2012), without strong gender differences (but see Hausmann, Ergun, Yazgan, & Güntürkün, 2002; Jewell & McCourt, 2000). This bias is thought to occur due to the asymmetrical neural processing of spatial attention (Loftus & Nicholls, 2012; Siman-Tov et al., 2007), which is usually associated with the dominant activation in the right posterior parietal cortex (e.g., Fink, Marshall, Weiss, Toni, & Zilles, 2002; Foxe, McCourt, & Javitt, 2003). The leftward biases in various behaviors with healthy individuals are termed *pseudoneglect* (Bowers & Heilman, 1980). (Note that [original] neglect in the clinical context refers to the rightward biases with unilateral neglect patients resulting from neurological damage to their right hemisphere [Karnath & Rorden, 2012].) However, individuals with ADHD frequently demonstrate a smaller left-sided bias compared to controls (Bellgrove, Hawi, Kirley, Gill, & Robertson, 2005; Jones, Craver-Lemley, & Barrett, 2008). A right-sided bias has even been found in both children (Carter, Krener, Chaderjian, Northcutt, & Wolfe, 1995; McDonald, Bennett, Chambers, & Castiello, 1999; Nigg, Swanson, & Hinshaw, 1997; Sheppard, Bradshaw, Mattingley, & Lee, 1999; Voeller & Heilman, 1988; Waldie & Hausmann, 2010) and adults (Epstein, Conners, Erhardt, March, & Swanson, 1997; ter Huurne et al., 2013) with ADHD, although some reports suggest that left- or right-sides biases may depend on the ADHD subtype in children (Rolfe, Hausmann, & Waldie, 2006). Taken together, this evidence from visuospatial tasks support right hemisphere abnormalities in ADHD.

The right hemisphere abnormalities in ADHD may not extend to healthy population with ADH traits. Although some research reports such a tendency in nonclinical samples of adults (Bellgrove, Dockree, Aimola, & Robertson, 2004; Poynter, Ingram, & Minor, 2010), other studies report no differences in spatial biases between children with ADHD compared to controls (Ben-Artsy, Glicksohn, Soroker, Margalit, & Myslobodsky, 1996; Klimkeit, Mattingley, Sheppard, Lee, & Bradshaw, 2003).

Less frequently, vertical asymmetries in attention have also been reported. Upper or lower spatial biases may arise from the two neural pathways involved in visual processing, as one is dominant over the other based on the visual task's requirements. The dorsal stream (or "where" pathway) is dominant for processing motion and location, and the ventral stream (or "what" pathway) for object identification (Previc, 1990). Previc (1990) proposed that when the ventral pathway is dominant, spatial attention would preferentially focus on the upper visual field, whereas the dorsal stream would favor the lower visual field. However, to our knowledge, no study has used a visual task involving motion, which would dominantly involve the dorsal stream and would thus be expected to bias processing toward the lower visual fields (Previc, 1990). Some research has reported enhanced left spatial biases in either the upper or lower visual field (Barrett, Crosson, Crucian, & Heilman, 2000; McCourt & Garlinghouse, 2000; Thomas, Castine, Loetscher, & Nicholls, 2015; Thomas & Elias, 2010), suggesting an interaction between horizontal and vertical hemifields. Whether these effects occur on a motion-based task has yet to be investigated. Furthermore, the impact of the dorsal and ventral streams on asymmetric visual processing has not been investigated in ADHD populations, limiting our understanding of spatial attention in this population.

Reduced Arousal Hypothesis of ADHD

In addition to playing a dominant role in various spatial aspects of attention, the right hemisphere also critically controls nonspatial aspects of attention such as arousal (Bellgrove, Eramudugolla, Newman, Vance, & Mattingley, 2013; Malhotra, Coulthard, & Husain, 2009; Robertson, Mattingley, Rorden, & Driver, 1998; Shapiro, Hillstrom, & Husain, 2002). Corbetta and Shulman (2011) have argued that the neglect symptoms in patients with damage in the right hemisphere arise primarily from the impairment in nonspatial mechanisms such as arousal rather than spatial attention mechanisms. Consistent with this arousal-neglect hypothesis, neglect patients temporarily reduce their symptoms when they were aroused with loud warning tones (Robertson et al., 1998) and psychostimulants (Grujic et al., 1998; Malhotra, Parton, Greenwood, & Husain, 2006; Mukand et al., 2001). Psychostimulants also reduce the symptoms of pseudoneglect in nonclinical population (Dodds, Müller, & Manly, 2009). Conversely, the neglect symptoms in the right-hemisphere damaged patients were exaggerated by decreasing their arousal using sedatives (Lazar et al., 2002). Similarly, in nonclinical populations, left spatial biases (pseudoneglect) were reduced by decreasing arousal following sleep deprivation (Manly, Dobler, Dodds, & George, 2005) and by diminishing alertness over the course of the experiment, that is, with increased time-on-task (Dodds et al., 2008; Dufour, Touzalin, & Candas, 2007; Manly et al., 2005; Newman et al., 2013). Collectively, arousal is shown to interact with spatial attention, with increasing arousal associated with leftward attention bias and decreasing arousal associated with rightward bias.

Although the above studies provide evidence that modulation of arousal leads to attentional biases, the other direction of effect is also reported: Impaired attention reduces arousal. For example, chronically reduced alertness is frequently reported in ADHD (Lou, Henriksen, Bruhn, Børner, & Nielsen, 1989; Rubia et al., 1999) and has been proposed by Satterfield and Dawson's (1971) hypoarousal model as the underlying mechanism from which the core symptoms of ADHD arise. Silk, Newman, Eramudugolla, Vance, and Bellgrove (2014) argued that methylphenidate, a commonly prescribed psychostimulant for ADHD, increases arousal (through upregulation of noradrenaline), which in turn decreases their rightward attentional bias.

Impaired Inhibition Hypothesis of ADHD

Impaired inhibitory control, the inability to suppress an attentional or behavioral response to salient but irrelevant events (Casey et al., 1997), is another core trait of ADHD (for review, see Nigg, 2001), and some even consider that impaired response inhibition is actually the primary deficit of ADHD (Barkley, 1997). Problems with intentional response inhibition have been widely documented in children and adults with ADHD (Aron, Dowson, Sahakian, & Robbins, 2003; Barkley, 1997; Roberts, Fillmore, & Milich, 2011; Schachar, Tannock, Marriott, & Logan, 1995) and some automatic/reflexive inhibitory impairments have recently been reported (Fillmore, Milich, & Lorch, 2009; Roberts et al., 2011). The right hemisphere, specifically the right inferior frontal cortex (IFC), has been implicated with inhibition from neuroimaging evidence in nonclinical population (Bunge et al., 2002; Garavan, Ross, Murphy, Roche, & Stein, 2002; Garavan, Ross, & Stein, 1999; Konishi et al., 1999; Konishi, Nakajima, Uchida, Sekihara, & Miyashita, 1998; Rubia, Smith, Brammer, & Taylor, 2003) and deficits in the right IFC associated with impaired response inhibition in ADHD populations (Casey et al., 1997; Castellanos et al., 1996; Overtoom et al., 2002; Sowell et al., 2003; Vaidya et al., 1998). Thus inhibition, another key role of the right hemisphere, may be impaired in individuals with ADHD (Braet et al., 2011).

Perceptual Rivalry as a Measure for Attention, Arousal, and Inhibition

Perceptual rivalry is the occurrence of alternating perceptual experiences despite unchanging sensory input (Blake & Logothetis, 2002), which can occur with minimal cognitive involvement (Carter & Pettigrew, 2003). This includes multistable phenomena such as Troxler fading, binocular rivalry, and MIB, which invoke alternating perceptual experiences despite unchanging sensory input (Bonneh, Donner, Cooperman, Heeger, & Sagi, 2014). Because of the constant competition for visual awareness in perceptual rivalry, perceptual alternations can be considered to reflect the extent of perceptual inhibition. The neural competition is modulated by spatial attention, with attention selecting the perceptually dominant image and leading to the subsequent inhibition of the competing image (Alais & Blake, 2005). Furthermore, neuroimaging evidence has supported the role of inhibition in perceptual rivalry phenomena (Lumer, Friston, & Rees, 1998; Sterzer & Kleinschmidt, 2007). Specifically, it was found that event-related activity was greater in the right IFC during perceptual rivalry compared to stimulus-driven (physical) changes (Lumer et al., 1998; Sterzer & Kleinschmidt, 2007). Because, as mentioned, the right IFC has been implicated in inhibition, these findings suggest a role for inhibition in perceptual rivalry. Thus, perceptual rivalry tasks could be used to understand and measure impaired inhibition and associated right IFC deficits in ADHD.

There is limited literature on perceptual rivalry in ADHD. In binocular rivalry, children with ADHD compared to controls exhibited fewer perceptual alternations and slower times to the onset of the first exclusive dominance (or perception) of one image and longer times between exclusive dominances (Amador-Campos, Aznar-Casanova, Moreno-Sánchez, Medina-Peña, & Ortiz-Guerra, 2013; Amador-Campos, Aznar-Casanova, Ortiz-Guerra, Moreno-Sánchez, & Medina-Peña, 2015). Similarly, in Troxler fading, children (Jansiewicz, Newschaffer, Denckla, & Mostofsky, 2004) and adults with ADHD (Massa & O'Desky, 2012) were slower to report perceptual disappearances compared to controls. This perceptual rivalry literature supports the impaired inhibition hypothesis of ADHD. (For inconsistent findings, however, see Aznar-Casanova, Amador-Campos, Moreno-Sánchez, and Supér (2013) and Amador-Campos et al. (2015)).

Apart from the influences of spatial attention and inhibition, there is evidence for arousal to influence perceptual inhibition on perceptual rivalry tasks. In nonclinical populations, frequency of perceptual switches in binocular rivalry tends to reduce within trials and over the course of experiments (Carter et al., 2007; Klink, Brascamp, Blake, & van Wezel, 2010; Mamassian & Goutcher, 2005; Suzuki & Grabowecky, 2007; van Ee, 2005, 2009). Arousal is likely to decrease with time-on-task in a monotonous task, thus if rivalry tasks induces lower arousal, then perceptual inhibition should weaken as time-on-task. Indeed, mean duration of exclusive dominances varies with time-on-task in ADHD (yet remained relatively stable for controls; Amador-Campos et al., 2015). These results suggest an interaction between inhibition and arousal—two key roles of the right hemisphere—in perceptual rivalry tasks.

Therefore, although perceptual rivalry tasks such as binocular rivalry could assess right hemisphere abnormalities in ADHD, binocular rivalry requires interocular conflict induced by wearing goggles or using custom-made mirror setups (Blake & Logothetis, 2002). This restricts flexibility in the experimental set-up, making it difficult to present target stimuli across different visual quadrants to assess spatial bias and to measure pupil dilation as a measure of arousal. Thus, here we propose the use of an alternative perceptual rivalry task, MIB, that can much more easily provide insight into spatial attention, perceptual inhibition, and arousal than binocular rivalry.

MIB

MIB is a perceptual rivalry phenomenon during which peripheral salient stimuli temporarily appear and disappear from perception when superimposed on a moving background (Bonneh et al., 2001). The movement of the mask is essential in MIB (Bonneh et al., 2001), which distinguishes it from the similar phenomenon of Troxler fading (Bonneh et al., 2014).

In their original paper, Bonneh et al. (2001) provided an attentional account of the MIB phenomenon. They hypothesized that in MIB the mask and targets compete with one another for conscious perception in a winner-takes-all manner, with attention modulating the degree of competition (Bonneh et al., 2001; Carter & Pettigrew, 2003; Tong, 2001).

Geng, Song, Li, Xu, and Zhu (2007) later designed MIB tasks to directly manipulate the participants' spatial attention. Participants were required to respond to the disappearances/reappearances of two targets simultaneously presented in both sides of the central fixation point (divided-attention condition) or to respond to only one of the targets as cued by an arrow at fixation (focused-attention). The percentage of target disappearances in the focused-attention condition was (paradoxically) greater than in the divided-attention condition. This demonstrates the modulatory effect of attention, with greater attention to the targets increasing the probability of disappearance (Geng et al., 2007; see also Scholvinck & Rees, 2009). To date, no investigation has been reported on the influence of cognitive development, in particular attention deficits, on MIB.

Consistent with pseudoneglect findings, and attentional biases, the MIB target in the upper left visual field disappears more compared to the other targets in the display (Bonneh et al., 2001; Grindley & Townsend, 1966; Rosenthal, Davies, Aimola Davies, & Humphreys, 2013). These studies, however, presented targets in a triangular formation (upper left, upper right, and lower center), rather than a square formation. This design prevents one from disentangling any left/right (LR) versus upper/lower (UL) visual field asymmetries. In fact, in these studies, the left field bias was only significant in comparison to the lower central target, but not the upper right (Bonneh et al., 2001; Nuruki, Oliver, Campana, Walsh, & Rothwell, 2013), which can be also explained by upper field bias. The only study that used all four spatial quadrants (the lower left, lower right, upper left, and upper right) in a single experimental paradigm is from our group (Thomas, Davidson, Zakavi, Tsuchiya, & van Boxtel, 2017). In that study, we found significantly more and longer disappearances for targets in the upper compared to the lower visual field, whereas no significant differences were found between the left and right visual fields in either the upper or lower fields. By expanding the MIB paradigm to include four targets in every trial, we here aimed to investigate the spatial biases in nonclinical and ADHD samples in all four visual quadrants.

Specifically, we will use the MIB task, with four targets arranged in a square formation to measure spatial biases in all four visual quadrants. In addition, we will have 48 one-min trials, allowing us to measure time-on-task effects, that is, the effects of diminishing arousal on perceptual inhibition and spatial attention (George, Dobler, Nicholls, & Manly, 2005; Newman et al., 2013). We investigate these effects in typically developing adults indexed on their ADH traits, to contribute toward addressing the ADHD research gap in visuospatial impairments with adults, while considering attention-deficits as a continuum with ADHD at the extreme end.

Perceptual biases in visuospatial tasks have been successfully used as tests for right hemisphere dysfunction associated with ADHD/ADH traits using tasks like the line bisection task (Boles, Adair, & Joubert, 2009)—in which poor performance has explicitly been linked to right hemisphere damage (Finney et al., 2015)—Greyscales Task (Bellgrove et al., 2004), visual search task (Poynter et al., 2010), and Landmark Task (Bellgrove et al., 2008). And although MIB itself has not been used to investigate spatial biases in ADHD, our MIB set-up with a visuospatial task would probably be able to measure spatial biases in attention. In addition, perceptual rivalry tasks, in particular binocular rivalry(Amador-Campos et al., 2013; Amador-Campos et al., 2015) and Troxler fading (Jansiewicz et al., 2004; Massa & O'Desky, 2012) have been investigated for their ability to measure right hemispheric mechanisms such as perceptual inhibition in ADHD samples, again suggesting that MIB (as a perceptual rivalry task) would potentially be a powerful behavioral test of right hemisphere mechanisms.

In this article, we examined (a) if healthy controls with more ADH traits would show fewer perceptual disappearances and of shorter duration, (b) if the effects are biased toward the left visual field, and (c) if the effects are modulated by the level of arousal (also gauged by pupil dilation) as a function of time-on-task. We also anticipated that these effects would interact significantly in a complex manner, thus planned a comprehensive linear mixed modeling approach. Specifically, based on the literature reviewed above, it was hypothesized that the horizontal and vertical spatial biases would interact. If MIB does indeed preferentially activate the dorsal stream, then an overall lower left spatial bias was predicted. However, it was hypothesized that spatial biases would differ between participants with higher or lower ADH traits. In addition, it was hypothesized that spatial biases would decrease with time-on-task, and that ADH traits would modulate the time-on-task effects on spatial biases. To obtain an objective, though still indirect, measure of arousal, we will measure pupil size in a subset of our participants. We predicted that pupil size, as a measure of arousal, would decrease with time-on-task.

It is currently unknown whether different measures to gauge perceptual disappearances (i.e., the number, percentage, and duration of disappearance) measure different mechanisms or are different measures of the same underlying mechanism (e.g., Bonneh et al., 2014). Therefore, the hypotheses were not separated for the specific dependent variables, and we analyzed all three measures.

Method

Participants

Ethics approval was obtained from the Monash University Human Research Ethics Committee, and the research was conducted in accordance with the Declaration of Helsinki. Informed consent was obtained from all participants in the form of written permission. Participants were recruited from Monash University and social media groups of local university psychology students. Inclusion criteria required participants to be over 18 years of age and have normal or corrected-to-normal vision. Participants were reimbursed AUD 15 for their time.

Our sample size estimate focused on revealing an interaction between location (hemisphere) and time-on-task. The work by Newman et al. (2013), showed differences in left and right hemisphere brain responses dependent on time-on-task, and reported an $\eta_p^2 = .13$. We used G*power (Faul, Erdfelder, Lang, & Buchner, 2007) to calculate the sample size needed for statistical power of at least 80% with an effect size of $\eta_p^2 = .13$ ($f = 0.3866$; numerator $df = 1$, groups = 2), and a sample size of 55 participants was required. This was exceeded with a final sample of 58 adults. We chose to use estimate required sample size with an independent samples approach, and not a repeated-measures approach, to be conservative, as our experimental approach differs substantially from Newman et al. Admittedly, this sample estimate is not ideal because our behavioral variable is equated to an EEG brain response and not a behavioral response. However, we feel that these differences mean that our power-analysis is probably conservative, as noise in EEG measurements is often large.

Seventy-five participants were recruited. However, seven participants were excluded from analyses for having scores greater or equal to eight on the Conners Adult ADHD Inconsistency Index (explained in detail in the Materials section). An additional seven participants were excluded because they missed more than one catch event on the MIB task in the first 24 trials and/or more than three in the second 24 trials (explained in detail in the Procedure section). Three participants were excluded having very few button presses and of very short duration throughout all trials, resulting in a large number of trials with no button presses. Thus, the final sample consisted of 58 participants (41 females and 17 males) having an average Conners Adult ADHD Rating Scale (CAARS). *T* score of 51.16 (SD = 8.08). Our sample included three participants who had scores 65 or above (65, 68, 73), two participants disclosed to the first author that they had ADHD diagnoses (they had scores of 65 and 73), and one participant had a "history of ADHD" and scored 55. Because we did not ask for this information from any of our participants, we do not know if other participants had previously received a diagnosis of ADHD.

They were largely right-handed (89.70%) on the Edinburgh Handedness Inventory (EHI; Oldfield, 1971)with only six participants being left-handed. Mean handedness score was 58.98 (SD = 48.78, range = −100 to 100). The participants' mean age was 21.93 years (SD = 4.50). The data of this study, including excluded participants, have been made publicly available at https://osf.io/m8zxc/.

Materials

CAARS-Short: Self-Report Form. The CAARS-Short: Self-Report Form (CAARS-S: S) was used to measure participants' ADHD symptomatology (Conners, Erhardt, & Sparrow, 1999). The CAARS-S: S gives an ADHD index, measuring the presence and severity of ADHD-related symptoms with higher scores indicating a greater number of symptoms. In this report, we used the normalized *t*-scores with a mean of 50, with a standard deviation of 10, with scores greater than 70 representing clinically significant symptoms (Conners et al., 1999). Raw scores have not been analyzed.

The CAARS-S: S also includes an inconsistency index, which identifies random or careless responding, by calculating the sum of the absolute difference in scores between eight pairs of similar questions, which should give a score of zero if participants respond with perfect consistency (Conners et al., 1999). A total score greater than eight indicates potential cases of inconsistent responding (Conners et al., 1999). Seven participants were excluded from analysis on this basis.

EHI. The EHI assessed participants' handedness on a quantitative scale for 10 everyday unimanual activities, such as drawing and throwing (Edlin et al., 2015; Oldfield, 1971). Laterality quotients could range from −100 to +100. Using the cut-off score of zero as set by (Oldfield, 1971), a positive laterality quotient indicated right-handedness and negative scores indicating left-handedness.

Apparatus

Of the included participants, 47 completed the MIB task on a 29.5 × 52.5 cm VIEWpixx/3D monitor with a refresh rate of 120 Hz and resolution of 1,920 × 1,080 pixels. The experimental display was viewed from an approximate distance of 114 cm.

A subset (n = 11; four males and seven females) of the final 58 participants completed the task on a 1,920 × 1,080 resolution, 29 × 51.5 cm Tobii TX300 display with a refresh rate of 60 Hz, powered by a MacBook Pro OS 10.9.5. The inbuilt Tobii TX300 Eye-Tracking unit was used to track eye movements at a sampling rate of 300 Hz. Participants' heads were stabilized using a chin-rest, with a viewing distance of approximately 57 cm.

The MIB stimulus was created using MATLAB (Mathworks, Natick, MA) and OpenGL, with the PsychToolbox extensions (Brainard, 1997; Pelli, 1997). Parameters were adjusted for the change between computers and viewing distance, ensuring the participants received equivalent visual information.

Stimulus

Figure 1 displays a snapshot of the MIB movie stimulus. It consisted of a moving 11 × 11 blue "+" square grid pattern (cross width/length of 0.8° and spacing of 0.81° between two neighboring crosses) on a black background. The mask rotated at a speed of 0.3 cycles/s. The direction of rotation was randomized over trials to reduce motion aftereffects. A static white cross (diameter 0.15°) served as a fixation point in the center of the screen. The foreground contained four yellow dots (targets), 0.2° in diameter. They were presented at an equal distance from center (3°) in a square formation. The yellow dots were surrounded by black circular "protection zones" (0.31°), to reduce local masking effects. Trials were 60-s long with a black screen with task instructions shown to participants between trials. The visual stimulation was identical throughout a trial, apart from the continuous rotation, and a single catch trial occurrence, therefore luminance was essentially identical within and between trials.

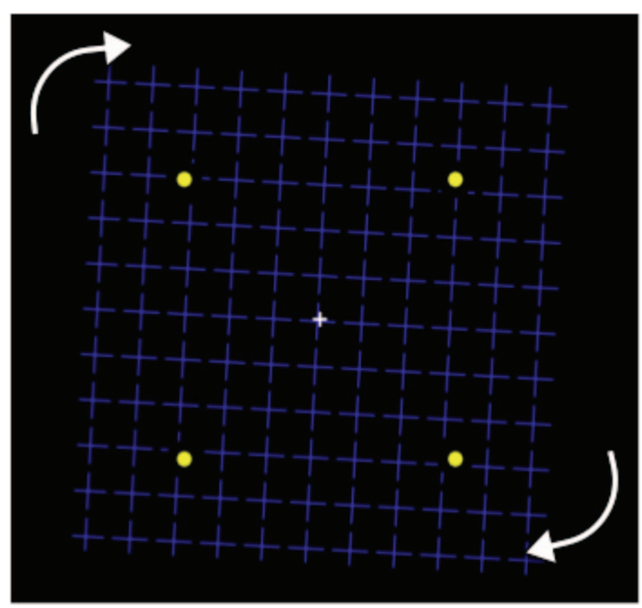

Figure 1. The motion-induced blindness display consisted of a white fixation cross and four yellow targets, which were static, and the background dynamic mask, a pattern of blue crosses ("+") that rotated around center, as indicated by the white arrows. See the online article for the color version of this figure.

Procedure

The experiment took place in a quiet computer laboratory. A static image of the MIB stimulus was used to explain the task, with participants instructed to focus their eyes on the white fixation cross for the duration of every trial. Participants pressed assigned keys (numbers one, three, seven and nine) on the number pad that corresponded to the target's location on the screen to report the targets' disappearances for the entire duration of each disappearance. When the target disappeared from the participant's perception, participants pressed the assigned key, held it down, and released the key when it reappeared. Participants were not instructed as to which hands/fingers to use for the key presses. Before each trial, participants were instructed as to which of the two among the four targets to report on. The targets to be reported varied across trials. Participants completed all six combinations of two targets eight times, resulting in a total of 48 trials. To start the trials, participants pressed the two keys required for that trial and released them to begin, ensuring that they were responding using the correct keys and for the correct targets for each trial. Participants completed two practice trials. Short, self-paced breaks were permitted between trials. After the MIB task, participants completed the CAARS-S: S on the computer.

Each MIB trial included a "catch event" in which one of the two targets and its accompanying protection zone were physically removed for a period between two and three seconds. The two yellow dots which were not reported on by participants, never disappeared physically. Catch events were included to check whether participants were continuing to pay attention to the task and/or were responding accurately to the disappearances. The catch disappearances were preceded and followed by a linear up and down ramp of the target's luminance over 1.5 s. The catch could occur anywhere between 0 and 58 s into the trial. Postexperimental debriefing indicated that participants could not differentiate between the catch events from perceptual disappearances. Participants were excluded from analysis if they failed to report on the physical disappearance of the target during the catch event more than once in the first 24 trials. To accommodate for the reduced arousal, we further excluded participants if they failed in more than three catch trials in the second half of the trials (this arbitrary decision was made before analyzing any of the data). This excluded seven participants. The decision to exclude these participants was a priori, not post hoc, mainly due to a consideration unrelated to ADH. For example, the participant perhaps did not understand the task instruction, or did not report the percept faithfully. This behavior could conceivably correlate with ADH traits, but the main problem is that it makes the behavioral report unreliable, which is why we did not include these data. Nevertheless, to check whether there is a correlation between ADH traits and the number of reported catches, we correlated ADH traits and number of reported catches for all participants (while still excluding participants with an inconsistency score of 8 or higher on the CAARS), and only for those that were included in the main analysis. Neither correlation was significant (Kendall $\tau = -0.004$, $p = .97$, Kendall tau $= -0.07$, $p = .52$, respectively), suggesting that, in our sample, individuals with higher ADH scores were not more likely to miss catches.

Data Analysis

Data was analyzed using MATLAB (Mathworks, Natick, MA). The catch events were excluded from the analysis of the number, percentage and duration of perceptual disappearances. Specifically, the *number* of perceptual disappearances was calculated as the number of key presses. The *duration* of disappearance was calculated as the length of time (in seconds) that participants held down one of the two assigned keys (i.e., the length of time of each separate key press). The *percentage* of disappearance (i.e., the percentage of MIB) was calculated as the total disappearance duration (i.e., how long the target had disappeared for) divided by the trial duration (adjusted for catch events, see below).

These calculations were adjusted for the catch events, whereby any key presses that occurred during a catch event (or during the ramp-on and off) were excluded. The presses were also excluded if participants were holding the key down and this began to overlap with a catch event (or the ramp-on and off to a maximum of 5 s). In addition, the trial length was adjusted to exclude the catch and ramp-on and off period. For the calculation of the duration of disappearance, key presses that had any overlap with the end of the trial (i.e., the true length of that key press was cut short by the trial ending) were excluded. The number, percentage, and duration of perceptual disappearances were computed separately for each of two target responses.

Statistical Analysis

We used a hybrid hypothesis-driven and data-driven approach. The hypothesis-driven aspect refers to the fact that we only included in the linear mixed effects (LME) analyses the terms for which we had prior hypotheses based on the literature. The data-driven aspect refers to the fact that we tested all LME models with all combinations of the hypothesis-driven terms and interactions and used model comparison to select the best ones.

LME models (Matlab R2015b) were used to analyze the effect of (a) ADH traits, (b) target location (LR and UL position), and (c) the trial number on the strength of the MIB illusion. As a measure of the strength of the illusion, we used the total number, percentage, as well as the duration of the target disappearances. Mixed-effects models extend the standard linear framework by adding a random intercept for each participant. Visual inspection of residual plots revealed normality violations and heteroscedasticity for the percentage and mean duration of disappearance, thus we transformed these values in log scale.

We hypothesized, based on the literature, that the following terms could influence our data: the main effects of horizontal (LR) or vertical (UL) position of the target on the screen, ADH score, the trial number (i.e., time-on-task), as well as two-way interactions between LR and UL position, LR (or UL) position with ADH traits (i.e., larger or smaller biases with more ADH traits), and each of position (LR, UL) and ADH traits with trial number (i.e., spatial biases decrease with time-on-task). Finally, we included three-way interactions among ADH traits, the trial number, and LR (or UR) position (i.e., ADH traits modulate the time-on-task effects on spatial biases). In total, we had four main effects, six two-way interactions, and two three-way interactions. All possible permutations of these terms resulted in $2^{12} = 4{,}096$ LME models.

To compare the different LME models, we used a data-driven approach using the Akaike information criterion (AIC). Of the

4,096 models considered, the best model was that with the smallest AIC (Burnham & Anderson, 2003). We will discuss extensively the model that fits the data best and provide information on the additional models that scored within two AIC units from the best model. The cut-off of two units was chosen because differences less than two are considered not to provide "substantial" empirical support for the better model (Burnham & Anderson, 2003). We opted to use the AIC and not the Bayesian information criterion (BIC) to be more inclusive about the number of terms that would be included in the best fitting model. Having said that, using the BIC led to very similar conclusions.

Pupil analysis. Eye movements of 11 participants were recorded during the task, binocularly using a Tobii TX-300 Eyetracker (Tobii Technology, Danderyd, Sweden) at a sampling rate of 300Hz, controlled through the software package T2T (https://sites.google.com/site/t2tpkg/Documentation). We analyzed the data from the left eye, following previously published procedures for the data preprocessing, for example, detection and interpolation of blinks (Kloosterman et al., 2015; Thomas et al., 2017). We computed the mean pupil diameter over the entire 60 s per trial to index arousal (missed samples due to blinks and saccades were linearly interpolated).

Relationship between pupil size and behavioral measures. We performed LME analyses to investigate the relationship between pupil diameter and the strength of MIB illusion (i.e., the total number, log-transformed percentage and log-transformed duration of the target disappearances), especially as they relate to time-on-task, and, by extension, arousal levels. We used a random intercept of subject. Durations of disappearances were averaged over a trial. In case there were no reported disappearances in a trial, the duration for that trial was treated a missing data.

Results

We included reports of target disappearances in MIB from 58 participants, each completing 48 trials of 1 min, leading to a total of 2,784 min (46.4 hr) of MIB data. We analyzed the importance of various hypotheses about spatial biases, ADH traits, and time-on-task (see the Methods section), by comparing 4,096 LME models independently for the number of disappearances, the percentage of target disappearance, and durations of target disappearance.

Number of Disappearances

For the number of disappearances, the best model had the smallest AIC of 31,579.52, and included the terms ADH, trial number, the interactions ADH:LR position, ADH:UL position, and ADH:trial number:LR position (see Table 1 for details).

The influence of these terms is displayed in Figure 2. For illustrative purposes we performed a median split on ADH traits to display the dependence on trial number (Figure 2A–C), and spatial location (Figure 2D–F); in all statistical analyses ADH traits was a continuous variable. Figure 2A shows the number of disappearances decreases as the experiment advances, and this effect is the largest effect (see Table 1).[1]

Targets on the left had a higher number of disappearances in comparison to targets on the right, and targets in the upper visual field had more disappearances than targets on the bottom (Table 1 and Figure 2D). ADH traits influenced these effects as well, showing increased numbers with increases in ADH traits.

Twenty models scored AIC within two units of the best model's AIC. As displayed in Figure 2G, trial number, ADH traits, the interaction between ADH and LR position were present in all 20 models. This is similarly reflected in the associated effect size (t-values averaged across the 20 models) displayed in Figure 2D, with trial number associated overwhelmingly with the largest effect size (mean $t = 21.42$), followed by ADH and LR position interaction (mean $t = 4.52$), and the main effect of ADH (mean $t = 2.77$).

Percentage of Disappearance

For the (logarithmic) percentage of disappearance, the best model had an AIC of 8,537.41, and included trial number, ADH, the interactions ADH:trial number, ADH:LR position, ADH:UL position, LR position:UL position, and ADH:trial number:LR position (see Table 2 for details).

Figure 2B and 2E show the influence of trial number, ADH traits, and target position for the percentage of target disappearance. Similar to the number of disappearances, the percentage of disappearance decreased over the experiment. The lower left target was reported to have the highest percentage of disappearance and the group difference due to the median split according to ADH score was more pronounced for the duration than for the number of disappearances.

Twenty-eight models scored AIC within two units of the best model's AIC. The parameters in these models were compared and displayed in Figure 2H, with their effect sizes. Trial number (mean $t = 11.22$), the interactions between ADH traits and LR position (mean $t = 4.94$) and interaction between ADH traits and trial number (mean $t = 7.40$) were present in all 28 models.

Duration of Disappearance

For the (logarithmic) duration of disappearances, the best model had an AIC of $-2{,}753.70$, and included trial number and the interactions ADH:trial number, ADH:LR position, and ADH:UL position (see Table 3 for details).

For the duration of disappearance, Figure 2C displays the influence of trial number. Unlike the other two models, the episode durations increased over the experiment, though participants with high ADH scores mostly drove this trend, which is captured by the significant interaction ADH:trial number (see Table 3). Similar to the number of disappearances and the % disappearances, the lower left target had the highest duration of disappearance as well as the largest effect of ADH traits (Figure 2F), consistent with the significant interaction ADH:LR position (see Table 3).

Twenty-three models scored AIC within two units of the best model's AIC. Comparison of the parameters present in these

[1] One could argue that this could be due to our more lenient inclusion criteria for the second half of the experiment (in which participants could miss three catch trials before they were excluded). However, there was no difference between the trends observed in the complete data set and a subgroup of participants who caught all catch events ($n = 34$). Furthermore, of the 33 participants (including some that were excluded) that missed at least one catch event, there were significantly more catches missed in the 2nd half compared to the first half of trials, $t(32) = -3.20$, $p = 0.003$, 95% confidence intervals $[-1.39 – 0.31]$, thus meeting researcher's expectations.

Table 1
Best Linear Mixed-Effects Model for Predicting Number of Disappearances

Fixed effects	Estimate	Standard error	*df*	*t*	95% CI
ADH	0.15	0.057	5,562	2.65**	[0.04, 0.27]
Trial number	−0.13	0.006	5,562	−23.58***	[−0.14, −0.12]
ADH:LR position	−0.02	0.004	5,562	−4.74***	[−0.028, −0.012]
ADH:UL position	0.007	0.002	5,562	3.42***	[0.003, 0.01]
ADH:trial number:LR position	0.0004	0.0001	5,562	2.95**	[0.0001, 0.0007]

Note. *df* = degrees of freedom; *t* = t-statistic; CI = confidence intervals; ADH = attention-deficit/hyperactivity; LR = left/right; UL = upper/lower.
** $p < .01$. *** $p < .001$.

models and their effect sizes are displayed in Figure 2I. Trial number (mean $t = 7.55$) and the interaction between trial number and ADH traits (mean $t = 5.66$) were included in all 23 models.

Including Handedness

One of the reviewers suggested that handedness could be a factor that influenced our data. The literature shows that there is a relationship between hand preference and spatial bias (e.g., Bareham, Bekinschtein, Scott, & Manly, 2015), we included the interaction between EHI and LR position in our analysis. Further, given that handedness shows interactions with ADHD (Shaw & Brown, 1991; Yamamoto & Hatta, 1982), we also included the triple interaction between EHI, LR position, and ADH traits.

Including these two terms in the analysis increased the number of model fourfold to 16,380 models. Nevertheless, including EHI in the analysis had limited effect on the data for the number and percentage of disappearance. Specifically, either of the above two interactions (EHI × LR position and EHI × LR position × ADH) appeared only in the 10th best model and were present in only five out of 25 models within two AIC units from the best model. The best model remains the same as discussed above. For percentage of disappearance, interactions with EHI appeared in only the 22nd best model and are only present in two out of 30 models within two AIC units from the best model. Here, also the best model remains the same.

The analysis for the episode durations however did show evidence of an influence of EHI. EHI was present in the best model and in 22 of the 33 models that were within two AIC units of the best model. The best model included the following terms: **trialnum** + LRposition + **adh:trialnum** + **adh:LRposition** + *ehi:LRposition* + **adh:ULposition** + *adh:ehi:LRposition* + (1 | subjid), where the bolded terms are those of the best model in the article and the terms in italics are the ones that we added here. The influence of ehi:LRposition is that the left bias is larger in left-handers. The three-way interaction shows that there is a rightward bias for low-ADH left-handers, and a leftward bias for high-ADH left-handers, although there is a much smaller leftward bias for right-handers (independent of ADH). (These results are based on extrapolations from the LME model, at "extreme" values of EHI [−100 and 100] and ADH [10 and 70]).

The interpretation of this model remains essentially the same as the model we presented above, because none of the major terms changed. However, it has additional explanatory power provided by the two interactions with EHI.

Pupil Size

In 11 participants whose eye movements were recorded during the experiment, we analyzed their pupil diameter and considered the mean pupil diameter over the 1-min trial as the proxy of their autonomic arousal. We expected that the arousal, and thus pupil size, would decrease with time-on-task. To test this, we constructed a linear mixed model to determine whether trial number can predict pupil size, including a random intercept for participants (i.e., PupilSize ~ TrialNumber + [1|Subject]). And indeed, there was a negative correlation between the pupil diameter and time-on-task, $t(526) = -2.05$, $p = .041$; $\chi^2(1 = 4.19$ when compared to a model with intercept only). This suggests our time-on-task is a valid measure of autonomic arousal.

This correlation between pupil diameter and time-on-task suggests similar correlations between pupil diameter and our three measures of the MIB strengths (e.g., the number, percentage, and duration of disappearances) may be obtained, because the MIB strengths were correlated with time-on-task (Tables 1–3 and Figure 2). Indeed, pupil size was significantly correlated with the MIB strength in terms of the number, LME: $t(526) = 3.06$, $p = .0024$, and the percentage, LME: $t(526) = 3.46$, $p = .00058$, but not with duration, LME: $t(514) = 1.63$, $p = .104$, of target disappearances.

Fixation Stability

As a measure of fixation stability, we analyzed the standard deviation of the x and y position of the gaze (of the left eye) per trial. This measure reflects both gaze shifts due to saccades and gaze drifts. We then analyzed how well fixation stability (i.e., standard deviation of the eye movements) can be explained by our different experimental manipulations (including time-on-task), using the same model comparisons as above.

This analysis revealed that the best model for the standard deviations of both the x and y position, included the terms trial number (increasing with time-on-task), and the interaction ADH:trialnumber. This latter effect was observed as the increase of the standard deviation in the *x* direction for individuals with a lower ADH, although it increased more for those with a higher ADH. The standard deviation in the y direction decreased for low ADH and increased for high ADH.

Discussion

This study investigated the influence of ADH traits on MIB in a nonclinical adult sample. Our novel hybrid hypothesis-driven

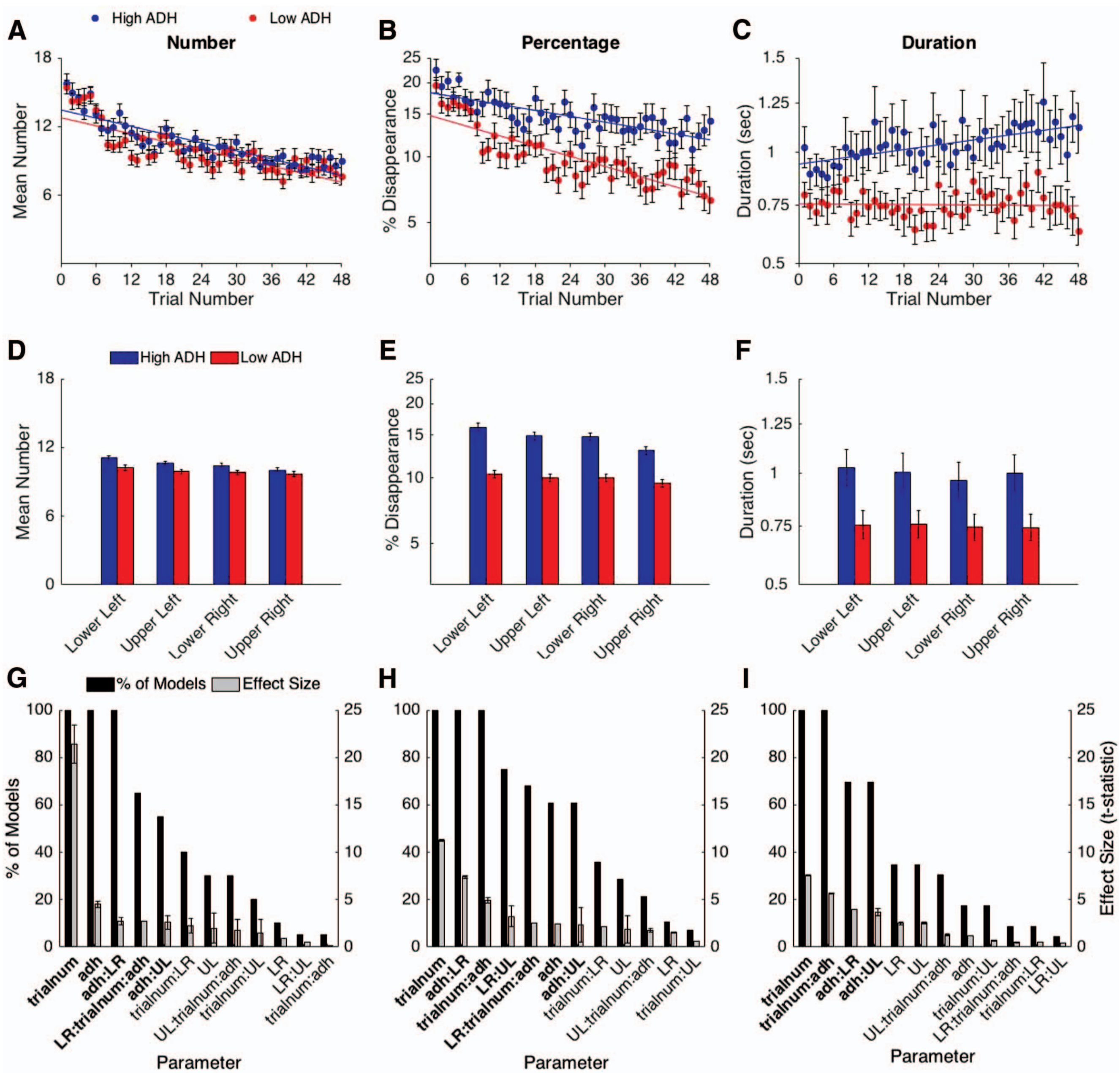

Figure 2. Influence of time-on-task and attention-deficit hyperactivity (ADH) traits on number (A), % disappearance (B), and duration of disappearance (C). The interaction between the target location and ADH traits for number (D), % disappearance (E), and duration of disappearance (F). The percentage of models (black bars, *y*-axis on the left side) in which the terms were included and the averaged effect size (*t*-statistic; gray bars, *y*-axis on the right side) of these terms across the models for the number (G),% disappearance (H), and disappearance duration (I). In G–I, percentages and averages are calculated over 20, 28, and 23, models respectively, that scored within two Akaike information criterion (AIC) units of the model with the lowest AIC for the respective analysis. The terms that were included in the model with the lowest AIC are bolded. Note that the median split (at an ADH *T* score of 52) on ADH traits was only conducted for illustrative purposes in this figure and that all statistical analyses were conducted on continuous data. See the online article for the color version of this figure.

and data-driven approach with LME models revealed that the strength of MIB (in terms of the number, the percentage, and the duration of target disappearances) can be predicted from the target's location, the participant's ADH traits, and time-on-task (i.e., trial number). Overall, the results demonstrate that autonomic arousal (measured as time-on-task and validated with our pupil analysis) and interactions between ADH traits and target location significantly explained the strength of the MIB illusion, largely

Table 2
Best Linear Mixed-Effects Model for Predicting Percentage of Disappearance

Fixed effects	Estimate	Standard error	*df*	*t*	95% CI
Trial number	−0.035	0.003	5,560	-11.01^{***}	[−0.041, −0.029]
ADH	0.015	0.01	5,560	1.52	[−0.01, 0.04]
ADH:trial number	0.0004	<.000062	5,560	7.18^{***}	[0.0003, 0.0006]
ADH:LR position	−0.003	0.0006	5,560	-5.06^{***}	[−0.0041, −0.002]
ADH:UL position	0.0009	0.0004	5,560	2.53^{*}	[0.0002, 0.002]
LR:UL position	0.044	0.027	5,560	1.65	[−0.008, 0.096]
ADH:trial number:LR position	0.000048	0.000019	5,560	2.52^{*}	[0.000011, 0.000085]

Note. *df* = degrees of freedom; *t* = t-statistic; CI = confidence intervals; ADH = attention-deficit/hyperactivity; LR = left/right; UL = upper/lower.
$^{*}p < .05$. $^{***}p < .001$.

confirming our hypotheses (see the last paragraph of Introduction) based on the prior research.

Time-on-Task (Arousal)

Because of the right hemisphere's key role in arousal and chronically reduced alertness as a characteristic of ADHD (Lou et al., 1989; Rubia et al., 1999), our study investigated the impact of diminishing arousal (associated with lengthy time-on-task) on the strength of MIB. Time-on-task had the largest effect size on all three measures of MIB. The influence of time-on-task appears to continue through the experiment but appears to be larger early in the experiment (approximately, the first 10 min). This finding is consistent with previous research that showed that perceptual rivalry alternation slows and then stabilizes over the course of experiments (Carter et al., 2007; Klink et al., 2010; Mamassian & Goutcher, 2005; Suzuki & Grabowecky, 2007; van Ee, 2005, 2009). Time-on-task is often assumed to modulate arousal (Lim et al., 2010), which we validated here with pupil diameter. This supports a strong association between arousal and the MIB.

ADH Traits

Our study is the first to consider the impact of individual differences in ADH traits on MIB. In MIB, targets disappear more often and longer as they are more strongly attended (Geng et al., 2007; Scholvinck & Rees, 2009). Thus, we predicted that increased ADH traits in nonclinical adult participants would be predictive of decreased MIB, assuming that higher ADH traits lead to weaker spatial attention to the target. Further, increased eye movements can counteract perceptual fading (Martinez-Conde, Macknik, Troncoso, & Dyar, 2006), and modulate MIB (Bonneh et al., 2010). Fried et al. (2014) showed that saccades and blink rates increase with time on task and do so more in ADHD. This would also predict that MIB would be smaller in individuals with more ADH traits.

However, even though our analysis of fixation stability is in line with the findings of Fried et al. (2014), we found that ADH traits increased the number and percentage of disappearance, while leaving duration of target disappearance largely unchanged. This suggests that differences in fixation stability do not explain our behavioral findings.

Our behavioral findings are inconsistent with previous findings that showed decreased binocular rivalry rate and increased episode durations, (Amador-Campos et al., 2013, 2015) and slower Troxler fading (Jansiewicz et al., 2004; Massa & O'Desky, 2012) in ADHD samples relative to controls. The fact that we found data contrary to predictions could be due to several causes. First, we used a nonclinical sample of adults, and second, we used MIB and not binocular rivalry or Troxler fading. In addition, this was a novel MIB paradigm with substantial methodological differences (particularly the number and arrangement of targets and reporting requirements), which may limit the comparability to other paradigms. Future studies will have to determine whether any or all of these differences matter.

Spatial Location

Apart from a direct influence of ADH traits, we also identified that ADH traits appear to interact with both the horizontal and vertical target location. Horizontal target location was a significant predictor for all measures (number, percentage and duration of disappearance) and appeared as an overall left spatial bias. This

Table 3
Best Linear Mixed-Effects Model for Predicting Duration of Disappearances

Fixed effects	Estimate	Standard error	*df*	*t*	95% CI
Trial number	−0.027	0.00047	55,925	-5.73^{***}	[−0.0036, −0.0018]
ADH:trial number	<.0001	<.0001	55,925	7.54^{***}	[.000049, 0.000085]
ADH:LR position	−0.0002	<.0001	55,925	-4.068^{***}	[−0.00023, −0.0000797]
ADH:UL position	0.0001	<.0001	55,925	2.65^{**}	[.000026, 0.00017]

Note. *df* = degrees of freedom; *t* = t-statistic; CI = confidence intervals; ADH = attention-deficit/hyperactivity; LR = left/right; UL = upper/lower.
$^{**}p < .01$. $^{***}p < .001$.

bias is consistent with previous findings of pseudoneglect on visuospatial tasks in healthy populations (Benwell et al., 2013; Jewell & McCourt, 2000; Newman et al., 2013; Voyer et al., 2012) consistent with the right hemisphere's dominance over the left for spatial attention (Siman-Tov et al., 2007). However, we observed a stronger left spatial biases for the high ADH group which would not be predicted based on previous findings of attenuated spatial biases in individuals with ADHD (Bellgrove et al., 2005; Carter et al., 1995; Epstein et al., 1997; Jones et al., 2008; McDonald et al., 1999; Nigg et al., 1997; Sheppard et al., 1999; ter Huurne et al., 2013; Voeller & Heilman, 1988; Waldie & Hausmann, 2010) and high ADH traits (Bellgrove et al., 2004; Poynter et al., 2010). Instead, our results are consistent with a handful of studies that found left (not right) biases in ADHD children (Ben-Artsy et al., 1996; Klimkeit et al., 2003) and young adults with ADHD (Boles et al., 2009) similar to typically developing controls. It is worth noting that one study reported that the spatial bias depended on the ADHD subtype, with that ADHD-I group showing a leftward bias, and the ADHD-C group showing a rightward bias in a line bisection task (Rolfe et al., 2006). Inasmuch as attenuated left spatial biases are indicative of right hemisphere abnormalities in ADHD (Stefanatos & Wasserstein, 2001), our findings of left spatial biases indicate that adults with high ADH traits did not have right hemisphere abnormalities or that the abnormalities were not severe enough to be reflected as spatial attention anomalies. Our finding of increased leftward biases in high ADH individuals is counterintuitive but it is consistent with reports of increased performance in divided attention tasks in ADHD (Koschack, Kunert, Derichs, Weniger, & Irle, 2003), and clinical observations that sometimes individuals with ADHD show superior performance in attention-demanding dual tasks. However, there is also a considerably larger literature that suggests that individuals with ADHD are worse at dual tasks (Siklos & Kerns, 2004). One limitation of our work is that we did not enforce or record the hand(s) used for reporting the perceptual changes. Because this factor interacts with both the age (Hausmann, Güntürkün, & Corballis, 2003) and sex (Hausmann et al., 2002) of the observer, and given that we had a sample strongly biased toward female participants, it is possible that the left-bias we observed is partly due these uncontrolled interactions.

Including handedness in our analysis had little influence, as the best models remained essentially the same and our conclusions therefore remain unaltered with consideration of handedness.

Interaction Between Vertical Position of MIB Target and ADH

Our novel paradigm with four targets also revealed vertical spatial biases in MIB. Based on the dominance of the dorsal visual stream on a motion-based visuospatial task (Previc, 1990), we anticipated a potential preferential processing of the lower visual field, and thus more disappearances. The interaction between ADH and vertical (specifically the lower) target location were significant predictors in all models, indicating that vertical spatial biases varied across ADH traits. This is a novel finding as previous literature considering spatial attention with ADHD populations has mostly neglected vertical spatial biases. These results suggest that stronger or potentially more preferential processing occurs by the dorsal visual stream in those with higher ADH traits. There is an emerging literature in typically developing populations on attentional biases across the vertical dimension (Loughnane, Shanley, Lalor, & O'Connell, 2015; Thomas et al., 2015). However, our results emphasize the importance of extending this research by measuring the entire visual field in those with high ADH traits or within clinical ADHD populations to gain a comprehensive understanding of spatial attention in those populations.

Lower Left MIB Target and ADH

Further analyses showed that participants, particularly those with higher ADH traits, were biased toward the lower left target on all dependent variables. As none of the best LME models included an interaction between the horizontal and vertical field, we propose that this finding is due to additive effect of the right hemisphere's and the dorsal visual stream's dominance. However, some earlier work in typically developing populations have shown interactions (Loughnane et al., 2015; Thomas et al., 2015). Therefore, future research should extend on these findings to determine whether there are significant interactions in the influence of attention between horizontal and vertical position. These different profiles of spatial allocation of attention in different populations, show that there is a clear advantage of dissociating the four spatial quadrants in MIB compared to the typical arrangement of three targets in a triangle formation with only one lower central target (Bonneh et al., 2001; Nuruki et al., 2013). Only two previous MIB experiments have used paradigms allowing for a comparison between targets in all four spatial quadrants. Similar to our results, Geng et al. (2007) reported stronger left biases in the lower compared to the upper visual field for the percentage and duration of disappearance in their focused-attention condition, but did so in two separate experiments with different observers. In contrast to the current study and Geng et al. (2007), our group (Thomas et al., 2017) found a bias toward the upper visual fields, with the left bias failing to reach significance. Intriguingly, Thomas et al. (2017) presented only one target on each trial in different locations on different trials, whereas Geng et al. and our current study presented multiple targets within a single trial. We note that this is also consistent with (Bonneh et al., 2001) who also reported an upper (left) field bias, when they tested with a single target. The presence of multiple targets may have altered the attentional demands suggesting an interesting direction of future investigation. Nonetheless, our current results provide evidence of additive spatial biases along horizontal and vertical axes in a MIB task.

Interaction of Spatial Biases and Time-On Task and Arousal

The three-way interactions between ADH, trial number and LR position were included as a significant factor influencing the number (Figure 2G) and the percentage of disappearance (Figure 2H). The decrease of the left spatial bias over the course of experiment is in line with previous pseudoneglect and ADHD literature (Dodds et al., 2008; Dufour et al., 2007; Manly et al., 2005; Newman et al., 2013). Thus, diminishing arousal with time-on-task impacted the spatial attention, supporting previous propositions that nonspatial mechanisms, such as arousal, can affect spatial attention (Corbetta & Shulman, 2011). However, surprisingly, individuals with high ADH scores had a smaller dependence on trial number, which is inconsistent with past research which has found that children (Dekkers et al., 2017) and adults with ADHD (Tucha et al., 2017) experience greater time-on-task effects compared with controls on sustained attention tasks. Our task may be different from those previous studies in that it is an attention-demanding double-response task, and as mentioned, sometimes individuals with ADHD are superior in those demanding tasks. Although the LME model for duration of disappearance did not include the three-way interaction as it did for the number and the percentage of disappearance, the interaction between ADH traits and trial number was a significant predictor for duration of disappearance. This suggests that time-on-task effects may differ between different MIB measures. It has been previously shown that both adaptation processes and antagonistic neural interactions (e.g., inhibition) may play key roles in MIB (Bonneh et al., 2014). These two processes may be affected differently by time-on-task, and ADH traits. Further research is required to unravel the underlying mechanisms and to establish whether any MIB measure, or a combination of MIB measures, can serve as a reliable marker of ADH symptomatology.

Concluding Remarks

This study investigated the influence of ADH traits on MIB in adults. We found and discussed links between developmental attentional deficits, perceptual inhibition, spatial attention and arousal, contributing to the growing body of literature supporting shared mechanisms governing these factors (Corbetta & Shulman, 2011). In general, our findings are consistent with several bodies of research on inhibition, perceptual inhibition, and attentional biases, but with the added benefit of tying these fields together within a single paradigm. We have shown the usefulness of MIB, which has various benefits over binocular rivalry, as a tool for tapping into the mechanism of right hemisphere function. We confirm our hypothesis that arousal (i.e., time-on-task) impacts on perceptual inhibition (i.e., perceptual disappearances), and this interaction is strengthened by spatial biases in attention (which themselves are stronger in individuals with higher numbers of ADH traits). However, our work also contradicts some theories of ADHD. We find that arousal (i.e., time-on-task) effects are smaller in individuals with more ADH traits, which is inconsistent with the arousal-neglect hypothesis.

Also, individuals with more ADH traits actually showed stronger left-ward biases, contradicting the hypothesis of a right hemispheric disadvantage. Further research is needed to clarify whether these discrepancies are due to the perceptual stimuli we used, or due to other design parameters, or perhaps are more characteristics of individuals with many ADH traits, or ADHD.

Our findings suggest that the assessment of right hemispheric functioning within those with developmental attention deficits must consider the interaction between arousal, perceptual inhibition and spatial attention and that MIB is a potentially potent tool to investigate these effects.

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