adults. In addition to presenting novel insights into the development of attention and action, these results highlight the benefits of incorporating hand-tracking techniques into developmental research.

Introduction

Adaptive behavior requires the ability to filter out distractions and focus one's attention on the task at hand. The term *attentional capture* refers to instances in which salient but task-irrelevant information disrupts our ability to respond to task-relevant information (e.g., Theeuwes, 1992). Although this interference is often innocuous, lapses of attention can have real-world impacts ranging from impaired classroom learning (Fisher, Godwin, & Seltman, 2014) to fatal auto accidents (National Center for Statistics and Analysis, 2019). A central topic in the attentional capture literature therefore concerns the extent to which individuals can use top-down control to avoid or recover from capture.

Although attentional capture has been investigated in detail in adults, comparatively few studies have explored how the ability to avoid or recover from attentional capture changes across development (see, e.g., Gaspelin, Margett-Jordan, & Ruthruff, 2015). Similarly, hand-tracking techniques are commonly used in adult research to study how the processes underlying attentional capture and recovery from capture unfold over the course of a trial (*within-trial dynamics*) and are modulated by qualities of the previous trials (*cross-trial dynamics*) (e.g., Kerzel & Schönhammer, 2013; Moher, Anderson, & Song, 2015; Moher & Song, 2013; Welsh, 2011). Yet, few studies have used hand-tracking techniques to explore how these processes change as a function of age and experience (*developmental dynamics*). Therefore, the current study aimed to investigate the within-trial, cross-trial, and developmental dynamics of attentional capture by measuring the reaching behavior of children, adolescents, and young adults as they perform a visually guided reaching task designed to elicit attentional capture on select trials. In addition to providing a detailed window into the dynamics of attentional capture across development, this approach offers a unique perspective on current debates regarding (a) the extent to which developmental differences in attentional capture reflect the ability to avoid or recover from capture and (b) the extent to which attentional capture results in the automatic activation of a task-irrelevant response.

Attentional capture, top-down control, and development

Developmental and individual differences in attentional capture are generally interpreted in terms of two theoretical accounts. According to the *susceptibility account,* top-down control enables us to *avoid* attentional capture under certain conditions, particularly when the attention-capturing stimulus is known to be irrelevant to the task at hand (e.g., Folk, Leber, & Egeth, 2002; Folk, Remington, & Johnston, 1992; Fukuda & Vogel, 2009; Gaspelin, Ruthruff, Lien, & Jung, 2012; Lien, Ruthruff, & Johnston, 2010). Early evidence in favor of the susceptibility account was offered by Folk et al. (1992), who observed that capture costs in adults were modulated by the relation between an attention-capturing cue and a target stimulus. For instance, the researchers found that when participants were instructed to search for a target that appeared abruptly in one of four possible locations, cues that appeared abruptly 100 ms before the target would capture the participant's attention, resulting in slower response times on trials in which the cue appeared at a different location than the target (*invalid-cue trials*) relative to trials in which no cue appeared before the target (*no-cue trials*). However, when the identity of the target was signaled by color (rather than abrupt onset), abrupt onset cues did not appear to capture attention given that no response time difference was observed between the invalid-cue and no-cue trials. This finding suggests that adults were able to use top-down control to avoid attentional capture when the dimension used to identify the target (color) differed from the dimension used to capture attention with the cue (abrupt onset).

In contrast to the susceptibility account, the *recovery account* proposes that top-down control may help individuals to efficiently *overcome* attentional capture (e.g., Fukuda & Vogel, 2011; Theeuwes, Atchley, & Kramer, 2000).[1] Evidence in favor of the recovery account was offered by Fukuda and Vogel (2011), who investigated how individual differences in adult working memory capacity (WMC) relate to one's ability to avoid and recover from attentional capture. The researchers found that adults showed equivalent capture costs on trials in which the attention-capturing stimulus appeared 50 ms before the target array regardless of their WMC level (low or high), suggesting that normal variations in WMC are not strongly related to an individual's capacity to avoid attentional capture. However, when the attention-capturing stimulus appeared 150 ms before the target array, individuals with higher WMC exhibited significantly smaller capture costs than individuals with lower WMC. Taken together, the results of Fukuda and Vogel (2011) indicate that low- and high-capacity individuals were equally susceptible to capture, but individuals with higher WMC were able to recover more rapidly from attentional capture than those with lower WMC.

Given that top-down control and related constructs such as WMC are known to undergo significant development between childhood and adulthood (e.g., Bedard et al., 2002; Davidson, Amso, Anderson, & Diamond, 2006; Fry & Hale, 1996; Luciana, Conklin, Hooper, & Yarger, 2005; Luna, Padmanabhan, & O'Hearn, 2010; Velanova, Wheeler, & Luna, 2008), how might the ability to avoid or recover from attentional capture change across development? A number of studies have explored this question, including research with typically developing children (Gaspelin, Margett-Jordan, et al., 2015; Iarocci, Enns, Randolph, & Burack, 2009; Leclercq & Siéroff, 2013; Oh-uchi, Kawahara, & Sugano, 2010; Wainwright & Bryson, 2002) as well as children diagnosed with attention-deficit/hyperactivity disorder (Mason, Humphreys, & Kent, 2004), autism spectrum disorder (Greenaway & Plaisted, 2005), and epilepsy (Deltour et al., 2007). Although these studies vary across a number of dimensions (e.g., tasks used to assess attentional capture, number and range of age groups, analytic strategies employed), the existing data generally indicate that attentional capture costs decrease between the preschool years and early adulthood (see Gaspelin, Margett-Jordan, et al., 2015). This improvement is widely interpreted to reflect age-related gains in top-down control and is frequently linked to the development of the frontal cortex (Gaspelin, Margett-Jordan, et al., 2015; Leclercq & Siéroff, 2013; Mason et al., 2004). However, it is currently unclear whether the decrease in attentional capture costs observed between childhood and adulthood reflects age-related reductions in the *susceptibility* of attention to capture, age-related improvements in the ability to *recover* from capture, or a combination of the two.

The majority of previous studies investigating developmental differences in attentional capture have featured pre-cueing tasks in which the target was presented after a distractor or cue (Gaspelin, Margett-Jordan, et al., 2015; Iarocci et al., 2009; Leclercq & Siéroff, 2013; Wainwright & Bryson, 2002). For example, Gaspelin, Margett-Jordan, et al. (2015) found that children aged 4 and 5 years exhibited larger attentional capture costs in a pre-cueing task than adults and interpreted this difference in terms of the susceptibility account. Given that the target is presented after the distractor in pre-cueing tasks, it is possible that the age-related differences observed in pre-cueing tasks partly reflect an improved ability to recover from capture before the target was presented rather than an improved ability to block capture altogether. Interestingly, Oh-uchi et al. (2010) used a search task in which the target and distractor appeared simultaneously and concluded that the costs of capture were equivalent in 5- and 6-year-olds and adults, suggesting that the developmental differences observed in pre-cueing tasks may have partly reflected age-related differences in recovery. One of the central questions to be addressed in the current study therefore concerns the extent to which developmental differences in attentional capture are observed across childhood, adolescence, and early adulthood when the target and distractor are presented simultaneously.

[1] Note that these accounts are not mutually exclusive; top-down control may both reduce one's susceptibility to attention capture and enhance one's recovery from attentional capture under certain conditions

Targeting the dynamics of attentional capture with reach tracking

Attentional capture has traditionally been assessed with button-press measures of accuracy and response time (the time elapsed between target presentation and response completion). Although button-press measures have provided foundational insights into attentional capture and its development, accuracy and response time offer relatively limited insight into how the tension between attentional capture and top-down control unfolds over the course of a trial (Song & Nakayama, 2009). To shed light on these within-trial dynamics, researchers studying attentional capture and related topics have turned to motion-tracking techniques to record the temporal and spatial dynamics of participants' hand movements as participants perform tasks by (a) reaching to touch targets on a digital display (e.g., Chapman, Gallivan, Wong, Wispinski, & Enns, 2015; Erb, Touron, & Marcovitch, 2020; Erb et al., 2021; Gallivan, Barton, Chapman, Wolpert, & Flanagan, 2015; Gallivan & Chapman, 2014; Kerzel & Schönhammer, 2013; Moher, Sit, & Song, 2015; Welsh, 2011) or (b) navigating a cursor to targets on a screen using a computer mouse (e.g., Freeman, 2018; Freeman, Dale, & Farmer, 2011; Scherbaum, Dshemuchadse, Fischer, & Goschke, 2010).

For instance, Welsh (2011) used reach tracking to investigate the extent to which attention and action are linked in visually guided action during adulthood. The question of particular interest concerned whether attentional capture by an item would automatically generate response activations corresponding to the item. In other words, can attentional capture also result in action capture? Welsh found that participants' reach movements were curved toward the location of an attention-capturing cue on invalid-cue trials, indicating that attentional capture generated response activations corresponding to the cue's location. Notably, this effect was observed in reach trajectories only when the salient dimension of the cue (abrupt onset or color) matched the salient dimension of the target, mirroring the effects previously observed in response times (e.g., Folk et al., 1992). The observed impact of attention capture on reach movements is consistent with action-centered models of attention (e.g., Rizzolatti, Riggio, & Sheliga, 1994; Tipper, Lortie, & Baylis, 1992), which propose that action and attention are reciprocally linked such that to-be-performed actions influence the distribution of attention and, conversely, the distribution of attention influences the production of actions (Welsh & Zbinden, 2009).

The results of Welsh (2011) also presented early evidence that reach tracking can be used to shed light on how attention is captured and top-down control is implemented over the course of a trial. This interpretation is consistent with a growing body of hand-tracking research indicating that distractor items can generate early response activations for incorrect responses and that the activation of incorrect responses can be supplanted by activation of the correct response over the course of a hand movement (Erb, Moher, Sobel, & Song, 2016; Moher, Anderson, et al., 2015; Resulaj, Kiani, Wolpert, & Shadlen, 2009; Scherbaum et al., 2010; Schmidt, 2002).[2] However, little research has used hand-tracking techniques to investigate the interplay of attentional capture and top-down control in children and adolescents. Consequently, it is currently unclear whether the link between attention and action observed in adults is present to the same degree at earlier points during development.

In addition to providing insight into the within-trial dynamics of attention, distraction, and control, reach tracking presents new opportunities to explore how attentional capture is modulated by trial sequence effects in which qualities of a previous trial influence performance on the current trial. The cross-trial dynamics of top-down control have become a major focus of research during recent years as researchers have become increasingly aware of the impact that trial sequence effects can have on performance (Braem et al., 2019; Chapman, Gallivan, & Enns, 2015; Chapman et al., 2010; Egner, 2007, 2017), including within the domain of attentional capture (e.g., Kumada & Humphreys, 2002; Olivers & Humphreys, 2003). For example, previous work investigating pop-out effects in visual search tasks has demonstrated priming effects in which responses are facilitated if the target position on the current trial repeats that of the previous trial (Maljkovic & Nakayama, 1994, 1996). Similar effects of selection history have been observed in eye movements (e.g., McPeek, Maljkovic, & Nakayama, 1999;

[2] A similar idea has been explored in eye-tracking studies with double-step tasks (e.g., McPeek, Han, & Keller, 2003; McPeek, Skavenski, & Nakayama, 2000). This work indicates that saccadic eye movements may also reflect competition between targets and distractors.

Talcott & Gaspelin, 2020; Walthew & Gilchrist, 2006) and hand movements (Song & Nakayama, 2006) as well. Although researchers have begun to explore trial sequence effects in congruency tasks such as the Eriksen flanker task (Eriksen & Eriksen, 1974) and the Simon task (Simon, 1969) from a developmental perspective (e.g., Ambrosi, Servant, Blaye, & Burle, 2019; Cragg, 2016; Erb & Marcovitch, 2018, 2019; Erb, Moher, Song, & Sobel, 2017, 2018), comparatively little research has explored how target location repetitions affect attentional capture across development.

The current study

The preceding sections raised three open questions concerning the development of attentional capture and top-down control:

1. To what extent are age-related differences in attentional capture observed when the target and distractor are presented simultaneously?
2. Does attentional capture automatically bias response activations in children and adolescents as in adults?
3. How do the cross-trial dynamics of attentional capture change across development?

To address these questions, we presented children, adolescents, and young adults with a reach-tracking version of a visual search task adapted from Theeuwes (1992; see also, e.g., Moher, Anderson, et al., 2015). Participants were instructed to touch a circle that appeared simultaneously with three diamonds on a digital display. On half the trials, all the shapes appeared in the same color (*distractor-absent trials*). On the other half, one of the diamonds appeared in a different color than the other shapes (*distractor-present trials*).

This task was particularly well suited to address the questions outlined above for three reasons. First, the simultaneous presentation of the target and distractor increases the likelihood that the effects of attentional capture would be detected if capture were to occur, thereby allowing for a richer comparison of the susceptibility and recovery accounts. Strong evidence in favor of the susceptibility account would be provided if attentional capture effects were observed in the younger but not older age groups. If attentional capture effects were present in each age group but decreased with age, this would suggest that older participants (a) avoided capture more frequently than younger participants, (b) recovered from capture more rapidly than younger participants, or (c) both avoided capture more frequently and recovered from capture more rapidly than younger participants.

Second, in contrast to pre-cueing tasks, the task used in the current study did not feature cues that occasionally provided task-relevant information. Similarly, the task-relevant dimension (i.e., shape) and the task-irrelevant dimension (i.e., color) remained constant throughout the task. Consequently, if reach curvatures were to reveal a significant distractor effect in children, it would be unlikely that the effect resulted from confusion regarding the relevance of the distractor or switch costs associated with transitioning between different task-relevant dimensions. Third, the stimuli appeared at a small number of locations, resulting in a relatively high proportion of trials in which the location of the target matched that of the previous trial. Consequently, the task was well suited to identify how the cross-trial dynamics of attentional capture are influenced by repetitions of target location at different points during development.

Method

Participants

A total of 96 right-handed individuals with normal or corrected-to-normal vision participated in the study, with 24 participants in each of four age groups: 5-year-olds (M_{age} = 5.5 years, *SD* = 0.3; 37.5% female), 9-year-olds (M_{age} = 9.5 years, *SD* = 0.3; 58% female), 13- and 14-year-olds (M_{age} = 13.8-years, *SD* = 0.6; 58% female), and adults (M_{age} = 18.6 years, *SD* = 1.3; 71% female). An additional 4 participants were tested but excluded from the final sample due to difficulty in following the task

Table 1
Three-way analysis with factors of age, distractor presence, and target location.

Dependent Variable	Age Group	Target Location	Distractor		Main Effects		Interactions	
			Present	Absent	Distractor	Location	Distractor × age	Location × age
<u>Initiation Time</u>						***		***
	5	Repeat	508 ± 23 ms	531 ± 25 ms				
		Switch	563 ± 28 ms	556 ± 27 ms				
	9	Repeat	375 ± 16 ms	365 ± 15 ms				
		Switch	382 ± 17 ms	379 ± 16 ms				
	13/14	Repeat	282 ± 7 ms	287 ± 8 ms				
		Switch	286 ± 8 ms	285 ± 8 ms				
	Adult	Repeat	271 ± 6 ms	273 ± 6 ms				
		Switch	273 ± 6 ms	273 ± 5 ms				
<u>Movement Time</u>					***	***	***	***
	5	Repeat	631 ± 21 ms	598 ± 21 ms				
		Switch	689 ± 24 ms	642 ± 23 ms				
	9	Repeat	520 ± 15 ms	503 ± 16 ms				
		Switch	536 ± 16 ms	518 ± 17 ms				
	13/14	Repeat	504 ± 16 ms	501 ± 16 ms				
		Switch	507 ± 17 ms	499 ± 16 ms				
	Adult	Repeat	502 ± 15 ms	503 ± 14 ms				
		Switch	502 ± 13 ms	501 ± 13 ms				
<u>Movement Curvature</u>					***	***		***
	5	Repeat	0.128 ± 0.008	0.104 ± 0.005				
		Switch	0.173 ± 0.012	0.148 ± 0.009				
	9	Repeat	0.099 ± 0.005	0.082 ± 0.004				
		Switch	0.129 ± 0.006	0.099 ± 0.004				
	13/14	Repeat	0.082 ± 0.005	0.066 ± 0.003				
		Switch	0.087 ± 0.005	0.075 ± 0.003				
	Adult	Repeat	0.084 ± 0.007	0.069 ± 0.007				
		Switch	0.083 ± 0.007	0.076 ± 0.006				

Note: Error terms reflect standard error of the mean. * = $p < .05$, ** = $p < .01$, *** = $p < .001$. Columns omitted for interaction analyses where nothing was statistically significant.