CHAPTER 1

Development of Visual Attention

LISA OAKES AND DIMA AMSO

INTRODUCTION

Consider a child searching a crowded room for her parent. Perhaps there are several people in the room as well as furniture, toys, and other objects. In addition, there may be decorations on the wall, light fixtures hanging from the ceiling, windows, curtains, and so on. *Visual attention* is the set of processes that allows the child to filter the overly cluttered visual world, selecting some available information to process—in this case the people—and inhibiting other available information—in this case the furniture, light fixtures, and curtains. These attentional processes are governed by a complex set of interacting neural systems that develop over infancy and childhood.

In what follows, we provide formal definitions of those visual attention processes that are most relevant to infants and children. Next, we describe influential models and tasks of visual attention. Then we discuss what is known about the development of attentional processes during infancy, early childhood, and later childhood and beyond. We describe historical work examining looking behavior as a measure of visual attention, which provides a foundation for our understanding of the development of visual attention across childhood. We also discuss more contemporary work using more standard visual attention tasks, often adapted from work with adults. Throughout, we discuss the paradigms that have been used to assess visual attention in infancy and childhood, including a discussion of what specific computations or processes of visual attention each assesses. Finally, we examine how visual attention processes (and their development) interact with other cognitive and perceptual systems such as memory and learning, how novel neuroimaging tools add insight into neural systems development underlying visual attention, and future directions in visual attention research.

BACKGROUND ISSUES

Defining Visual Attention

Defining attention is not trivial. In part, this is because many meanings of the term “attention” are intuitive—we know that children who are paying attention are quiet, looking at the thing they are paying attention to, and not doing something else. We know that children who have problems with attention have difficulty staying on task and are easily distracted by thoughts, tasks, or stimuli in their environment. We command others to “pay attention,” and we talk informally about the inability to maintain attention (e.g., “spacing out”).

However, the scientific study of the development of attention requires a more formal and precise definition. As the example just described illustrates, attention is necessary in contexts of information overload. Without attention, it would be impossible to bind features of visual objects (such as color and shape) (Treisman, 1998), overcome limited visual working memory capacity (Awh, Vogel, & Oh, 2006), or process a signal effectively in a noisy context (Carrasco, 2014). Luck and Vecera (2002) offer a process-oriented definition of attention that states that (1) attention is the selection of information among alternatives, and (2) this selection improves the effectiveness of mental processes. Visual attention, therefore, allows us to *select* information from the visual environment for further processing while simultaneously ignoring or inhibiting competing information that is not selected. The point is that when defining the term "attention," we can focus on the function of attention. By engaging in selection and inhibition, visual attention turns up the gain on some items and locations for subsequent goal-relevant action, perception, and memory (Carrasco, 2011, 2014; Markant, Worden, & Amso, 2015; Zhang et al., 2011).

Note, however, that this definition of attention does not restrict attention to a single modality or level of processing. Our task here, however, is to describe the development of *visual* attention. It is important to recognize that even behavior that we would clearly consider visual attention—for example, directing fixation or processing resources to an aspect of the visual environment—is a function of many processes, only some of which are solely visual. General level of arousal, for example, may influence the depth of one's attentional engagement. Voluntary control over head and eye movements will contribute to overt direction of visual attention. And high-level processes, such as establishing goals, prioritizing events and stimuli in terms of their relevance, and applying existing knowledge to a current situation, will influence visual attention. As such, visual attention does not operate in isolation. Recognizing these connections and evaluating the literature with an understanding of the possible roles of multiple factors and processes on visual attention can enable us to attain deep understanding of visual attention and its development.

It is also important to recognize that visual attention is a set of computations or processes rather than a skill or content domain. A formal and precise definition of attention requires consideration of the structures and mechanisms that support these processes and functions. An important framework for understanding visual attention is Posner and Petersen's (Petersen & Posner, 2012; Posner & Petersen, 1990) classic model. This model describes three aspects of attention—alerting, orienting, and executive attention—that are supported by different neural networks (Fan, McCandliss, Fossella, Flombaum, & Posner, 2005; Fan, McCandliss, Sommer, Raz, & Posner, 2002; Posner & Petersen, 1990). Each of these aspects of attention applies to specific aspects of visual attention. The alerting response, supported by thalamic involvement, is a phasic attentional readiness and is a prepared response to a warning (a tone prepares runners for the official start of a race) stimulus. A related sustained attention mechanism involves a more continuous focus on a particular task or stimulus. The orienting mechanism involves shifting attention to an item or a location either with an overt eye movement or covertly, without a physical eye movement. Visual attention orienting recruits a parietal network. The executive attention mechanism is involved in switching, inhibiting, and general top-down control of visual attention, and it involves frontoparietal cortices and the anterior cingulate cortex. Clearly, each of these attention functions also is influenced by and relies on other processes.

For example, motor development and oculomotor development are extremely relevant to the development of visual attention processes. Overt attention, which in some ways is the most straightforward and obvious example of visual attention, involves turning one's head and eyes to bring a stimulus, object, or feature of the environment into focus. Overt attention thus relies on the physical abilities involved in holding one's head upright, making effortful and voluntary head turns, and voluntarily controlling eye movements. Motor control over the head and eyes undergoes significant developmental change in infancy (Bertenthal & Von Hofsten, 1998; Canfield & Kirkham, 2001; von Hofsten, 2004), which opens up novel exploratory and attentional strategies for young infants (Gibson, 1988).

Moreover, there are many similarities between visual attention and related general attention processes as well as attention that operates over other sensory modalities, such as auditory attention. For example, regardless of the modality, attention involves selection of relevant stimuli and inhibition of distractors. In addition, attention as used in one modality may in fact influence attention in other modalities. Amso et al. (2014) argued that the development of visual attention may depend on the development of visual processing (see also Amso & Scerif, 2015). Smith and Trainor (2011) made a similar argument with respect to auditory selective attention: specifically that auditory selective attention in infants depends on infants' ability to perceptually process target and nontarget sounds. Direct data comparing the developmental trajectories of these processes is sparse. One recent study (Günther et al., 2014) compared visual and auditory selective attention processes in a group of participants 7 to 77 years on a focused-attention task. The authors found that participants were better in the visual than in the auditory conditions, but the modality effect diminished with age. These data suggest different developmental trajectories for visual and auditory attention. We highlight these similarities and differences to point out that although understanding visual attention is relevant to the study of auditory attention, the two processes have distinct and nontransferable developmental trajectories.

Influential Models and Common Tasks

Most views of attention derive from the influential model of Posner and Petersen (Petersen & Posner, 2012; Posner & Petersen, 1990). As described in the previous section, this model describes alerting, orienting, and executive attention, all subserved by different neural structures and all of which have different functions related to the selection and filtering of relevant information and the inhibition of irrelevant or distracting information. These attentional processes have been widely studied and have been examined over a wide age range. Thus, many other models of attention have focused on similar processes.

As an example, consider the four functions of attention Colombo (2001) described in infancy. These four functions are closely related to Posner and Petersen's attention networks (Petersen & Posner, 2012; Posner & Petersen, 1990). Specifically, Colombo describes alertness, spatial orienting, attention to object features, and endogenous control. Here, the term "alertness" refers to Posner and Petersen's alerting network. It reflects the ability to both attain as well as maintain an alert state. The terms "spatial orienting" and "attention to object features" correspond to Posner and Petersen's orienting mechanism. Colombo separated this network into two functions—one for selecting and shifting attention to particular locations (spatial orienting) and another for selecting and shifting attention to particular types of objects features (perhaps their shape or color). This differentiation roughly corresponds to the "what" and "where" visual systems (Ungerleider & Pessosa, 2008). Finally, Colombo (2001) described endogenous attention, which corresponds to Posner and Petersen's executive attention. For Colombo, this is the ability to voluntarily direct attention to particular features or aspects of the environment as well as the ability to inhibit attending to some features or aspects of the environment. These functions correspond to top-down control over the other visual attention functions. Therefore, Colombo's model is specifically directed at explaining attention in infancy, but the components and functions of attention are clearly closely tied to the classic Posner and Petersen conception of attention networks.

The tasks commonly used to assess visual attention are designed to index the visual attention processes and networks described in the Posner and Petersen model (Petersen & Posner, 2012; Posner & Petersen, 1990). A standard procedure used to study visual attention across populations is the spatial cuing procedure (Posner, 1980). In this general class of tasks, attention processes are invoked with a cue. The cue may indicate that a target is about to occur, or it may indicate a potential location of the impending target. For example, Posner and colleagues developed the Attention Network Test (ANT) (Fan et al., 2002), which includes several types of trials that use cuing to access alerting, orienting, and executive attention networks. Participants are instructed to respond to an identified target item. To assess alerting, a cue warns the participant to prepare for the coming target but gives no information about the location that the target will occur (e.g., in Figure 1.1a, there are asterisks—or cues—in both possible target locations). Thus, the presence of the cue invokes a phasic alerting response in preparation for the target stimulus but does not provide any useful information about how to selectively direct or control attention. To assess orienting, the cue also contains information about the location where the target stimulus will occur (e.g., in Figure 1.1b, there is only a single asterisk in the location where the target will later appear). This type of cue allows the participant to prepare for a target in a specific location, perhaps "covertly," or without an eye movement, shifting attention to the cued location in anticipation of the emergence of the target at that location.

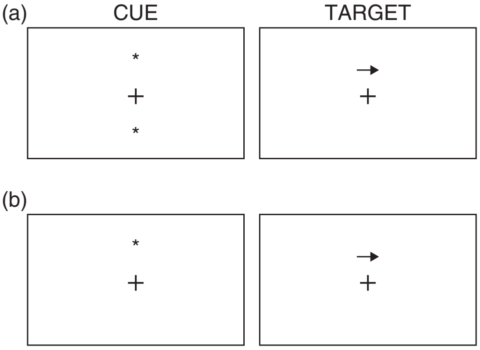

Figure 1.1 A schematic depiction of the Attention Network Task (ANT) (e.g., Fan et al., 2002). In each figure, the cross represents the fixation point, the asterisk is a cue, and the arrow is the target. The figures in (a) illustrate an alerting trial in which the asterisks act as a cue and alert the participant to prepare to respond to a target stimulus but provide no information to the location of that target. The figures in (b) illustrate a valid trial in which the cue indicates both that a target stimulus will occur and also the location in which it will occur, offering the participant the opportunity to covertly orient to that location and prepare a response.

Cuing is not the only way in which researchers have examined orienting attention. A common task used to understanding orienting is visual search (e.g., Treisman & Gelade, 1980). In such tasks, a target item is cast in the midst of varying numbers of

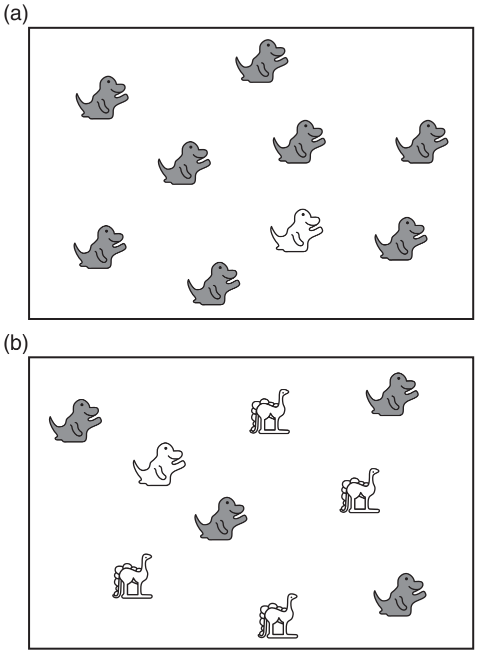

Figure 1.2 Examples of visual search arrays. In (a) the target is defined by a single feature (color), whereas in (b) the target is defined by the combination of two features (color and shape).
SOURCE: Reprinted from Gerhardstein & Rovee-Collier (2002). Copyright (2002) with permission from Elsevier.

distractors. If the target and distractor vary along only one feature dimension, as in Figure 1.2a, the target pops out and is considered preattentive (e.g., Treisman & Gelade, 1980); that is, the target can be detected and located even without the use of attention. One key characteristic of pop-out search is that increasing the number of distractors in the display does not result in longer search times to the target. When the target and distractors share a conjunction of features (Figure 1.2b), in contrast, visual search is effortful and requires attention. In this case, target identification is made progressively more effortful, as indexed by increasing target search times, by increasing the similarity (or competition) between the distractors and the target, or by increasing the number of distractors in the scene (e.g., Treisman & Gelade, 1980), suggesting that participants take longer to detect the target when they have to shift their attention to larger numbers of items. Variants of visual search have become widely used to understand attentional processes in infants (Adler, 2005), toddlers (Gerhardstein & Rovee-Collier, 2002; Scerif, Cornish, Wilding, Driver, & Karmiloff-Smith, 2004), and children (Donnelly et al., 2007). Indeed, some work has explored changes in attention across the life span by examining performance in visual search over a wide age range (Trick & Enns, 1998).

Assessment of executive attention requires that some perceptual conflict be resolved, and such tasks engage midline frontal areas and the lateral prefrontal cortex (Fan et al., 2002). In the ANT, for example, executive attention is assessed using a version of the Eriksen Flanker task (Eriksen & Eriksen, 1974). In this task, a target is an arrow presented in the center of a display. In the simple version of this task, the subject simply has to determine whether the arrow points to the right or the left. However, to assess executive attention, trials are presented in which the central arrow is “flanked” by distracting arrows. Figure 1.3 illustrates child-friendly versions of this task. In the “Fish” adaptation, for example, the trials presented on the left do not require executive attention because all the fish point in the same direction and thus no conflict needs to be resolved. On the trials presented on the left of the figure, in contrast, the flanking fish point one direction and the central fish points in the opposite direction. In this case, the central target and the flanker are conflicting. Because the child’s task is to report the direction the central fish (or arrow) is pointing, accurately responding in the flanker tasks requires inhibiting responding to the flanker fish (arrows) and focusing attention

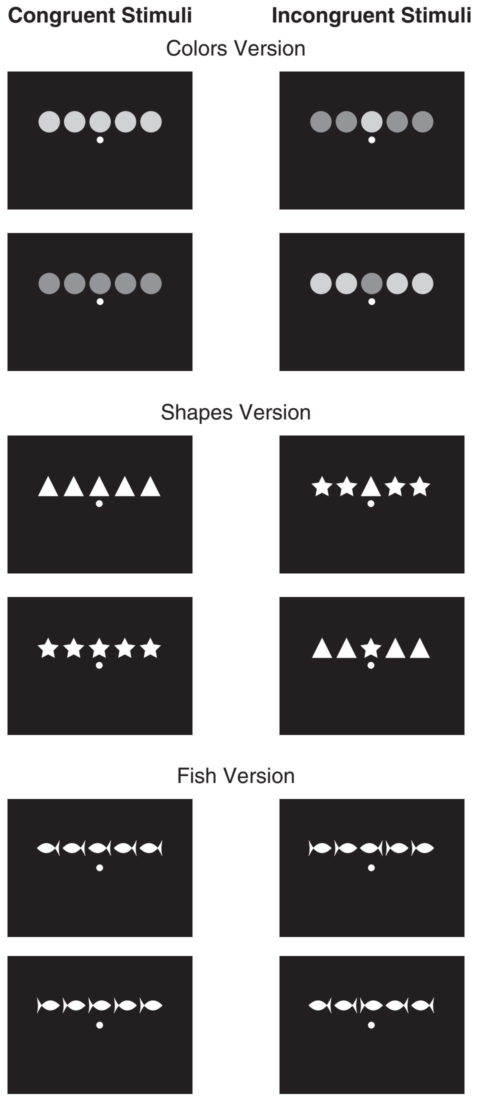

Figure 1.3 Examples of flanker tasks for children.
Source: Reprinted from McDermott, Perez-Edger, & Fox 2007. Copyright 2007 Psychonomic Society, Inc., with permission of Springer.

on the central fish (arrow). Fan et al. (2005) confirmed that the executive attention portion of the ANT engage different brain regions from the other portions of the ANT and that this flanker task engages frontoparietal and anterior cingulate regions generally thought to be involved when dealing with conflict. To better assess young children's performance on this task, McDermott, Perez-Edgar, and Fox (2007) used the variations presented in Figure 1.3 (see also Rueda et al., 2004) and demonstrated behavioral effects of the flankers on the performance of children between 4 and 6 years of age.

In sum, there is a large body of research presenting tasks to assess the development of attention. These tasks have been strongly influenced by the traditional model of attentional networks, originally proposed by Posner and Petersen (Petersen & Posner, 2012; Posner & Petersen, 1990). These visual attention tasks have proven to be powerful for studying visual attention beginning in infancy and extending to adulthood, as described next.

Development of Attention

Attention in Infancy

Different visual attention processes emerge beginning in infancy. However, our description of the ANT task and spatial cuing more generally should make it clear that many aspects or processes of attention are extremely difficult to measure and study in infancy. As a result, historically, the study of attention in infancy conflated attentional processes with measures used to index them, including looking times and oculomotor control, making the early study of visual attention in infancy actually the study of visual behavior in infancy. Indeed, a large number of studies were published in the 1960s and 1970s examining models of infant attention, the effect of stimulus properties on infant attention, and the relation between infant attention and memory.

In the first postnatal weeks, infants have difficulty initiating and maintaining an alert, attentive state, which Colombo (2001) argued is related to the *alertness* function of attention. Changes in this function are related to the amount of time infants are in an awake alert state and reflect noncortical developmental changes (see Colombo, 2001, for a review). It is plausible that changes in infants' regulation of their state (e.g., awake and alert, drowsy, asleep) contribute to alerting as defined by Posner and Petersen (1990). Indeed, Posner and Rothbart and their colleagues have argued that behavioral regulation—and executive attention—are related developmentally to the alerting and orienting network (Posner & Rothbart, 2009; Sheese, Rothbart, Posner, White, & Fraundorf, 2008). But it is difficult to determine how visual attention versus other more general aspects of nervous system regulation determines how much of the time young infants spend fixating a stimulus.

Moreover, studies in the 1960s and 1970s on infants' visual attention focused on stimulus properties that elicit sustained attention (Fantz & Nevis, 1967). Indeed, this emphasis and body of literature led to theories such as Cohen's (1973) highly influential two-process theory of infants' visual attention. Cohen argued that how quickly young infants orient (attention-getting) to a stimulus is related to the physical properties of the stimulus (e.g., its size) whereas how long infants continued to look at a stimulus (attention-holding) is related to its complexity or how difficult it was for infants to process, form a memory, and the like. The relation between visual attention and aspects of processing or one's ongoing cognitive goals has for decades been a focus of research on visual attention across the life span (Desimone & Duncan, 1995; Folk, Remington, & Johnson, 1992; Lavie, Hirst, de Fockert, & Viding, 2004). These questions remain at the forefront of the study of visual attention. However, as we discuss later, the developmental science community now recognizes that they reflect interactions between attention and other psychological processes rather than solely visual attentional processes.

It is also important to note that the terms "attention" and "looking" historically were used interchangeably. Although the conflation of these constructs is intuitive, looking time is not the same as attention. Looking is a very gross metric of attention per se and likely reflects a conglomeration of other processes, for example, processing or learning rates, memory, and visual preference. Disentangling visual attention and looking has been difficult because of a lack of measurement tools. Historically, researchers could measure only coarse aspects of infants' looking behavior—evaluating the direction of the eyes (and head) to determine whether infants looked at a particular image, object, or person, and how long infants continued to look at an item once fixated. Developments in eye tracking (Gredebäck, Johnson, & von Hofsten, 2010) and event-related potential (ERP) methods (Reynolds, Guy, & Zhang, 2010; Richards, 2001) have opened new possibilities for examining infants' attention. In particular, such methods provide insight into infants' covert attention shifting. For example, it is now possible to determine whether infants more quickly fixate a validly cued location than an invalidly cued location (Markant & Amso, 2015; Ross-Sheehy, Schneegans, & Spencer, 2015). By measuring where and how quickly infants orient to an object or location, we can establish whether infants look more quickly at a target appearing at a cued location than at a target appearing at an uncued location, for example. If this pattern emerges, we conclude that infants must have shifted their attention to the cued location before making an eye movement; thus, such effects provide evidence of covert attentional shifts. Other work has examined the neural circuitry supporting covert attentional shifts using ERP methods (Richards, 2000, 2005).

Richards and colleagues (Richards & Casey, 1992; Richards, 1989) measured heart rate variability in young infants as a physiological index of attentional engagement during periods of looking. Specifically, Richards and Casey (1992) described heart rate defined phases of attention during periods of sustained looking at dynamic, complex video clips (e.g., moving shapes, clips from *Sesame Street*). Infants' heart rates undergo a predictable and systematic pattern of changes during looks to visual stimuli, indicating changes in the infants' level of attention engagement. Specifically, soon after initiating a fixation of a stimulus, infants' heart rates begin to decline, indicating that they are entering a state of sustained attention, where infants are found to be more resistant to distraction. After a period of sustained low heart rate, infants' heart rates increase and return to the prestimulus level, indicating sustained attention termination. These data suggest that at least by 8 weeks of age, infants' sustained fixations actually reflect several phases and that only some proportion of individual looks reflects the kinds of attentional processes discussed in the context of other procedures, at other ages, and so on. Because the stimuli used in this research are complex and often multimodal (e.g., several studies used clips from *Sesame Street*), we must be cautious about concluding that the observed patterns reflect only visual attentional processes; as with much infant work, the findings may reflect a combination of visual attentional processes in conjunction with other perceptual and cognitive processes, such as visual perceptual skill control over eye movements, learning, and memory.

A larger literature has been devoted to developmental changes in aspects of looking behavior that reflect spatial orienting processes. A primary focus has been to understand changes in voluntary control over visual attention in the first 12 postnatal months (see Ruff & Rothbart, 1996, for a review). Specifically, several researchers have concluded that attention in very young infants is *stimulus bound*, or externally controlled (Colombo, 2001); it has even been stated that their attention is *obligatory* (Stechler & Latz, 1966). These conclusions are based on the observation that in the first postnatal weeks, infants seem to be unable to disengage attention from a fixated stimulus in order to fixate another stimulus. In the gap-overlap task—in which a peripheral stimulus is presented when the infant is fixating a central stimulus— fixations of very young infants' appear to be *sticky*. In this task, infants look at a central stimulus, which then disappears and is followed by a peripheral stimulus to either the left or the right of center. (See Figure 1.4.) Reaction times to orient to the peripheral stimulus indicate infants' ability to flexibly shift orienting. In *overlap* trials, the central stimulus—the target the infant is fixating—remains visible when the peripheral stimulus is presented. Under these conditions, young infants have significant difficulty disengaging from that central stimulus and shifting their fixation to the peripheral target (Hood & Atkinson, 1993). Because, as described earlier, looking behavior is thought to reflect attention, the conclusion has been that this apparent stickiness arises from infants' inability to voluntarily shift the direction of their attention.

At about 4 months, there appears to be a shift in this "stickiness" in infants' looking behavior. Smooth pursuit rapidly develops from birth to 4 months, and at 4 months smooth pursuit dominates visual tracking (Rosander, 2007). In the overlap task just described, infants more easily shift attention by 4 months (M. H. Johnson, 1995). Recall, however, that our understanding of visual attention in infancy reflects our evaluation of

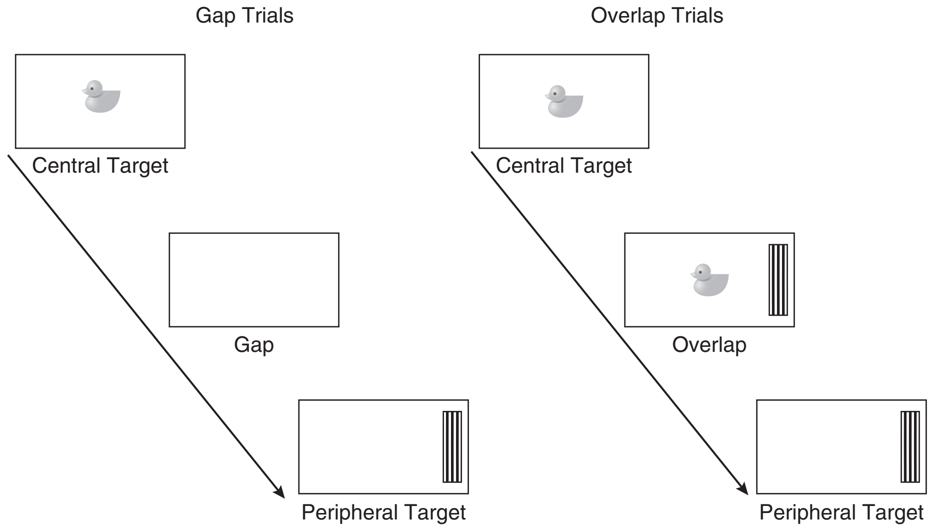

Figure 1.4 A schematic depiction of a gap-overlap task. There are two trial types: Each trial begins with a central target presented at fixation (the duck here); after some period of time the central target disappears and a peripheral target (the black and white bars here) appears. The difference between the two types of trials is whether the two targets are presented at the same time (in overlap trials) or separated by a brief blank screen (in gap trials). Color version of this figure is available at http://onlinelibrary.wiley.com/book/10.1002/9781119170174.

visual behavior. Between birth and 4 months of age, there are significant changes in oculomotor control, and as a consequence, at 4 months, infants have sufficient control over eye movements such that they are reliable research participants. Although there have been discussions about the role of attention in oculomotor control (e.g., Theeuwes, Kramer, Hahn, Irwin, & Zelinsky, 1999) and saccadic eye movements (Canfield & Kirkham, 2001; Hoffman & Subramaniam, 1995), there is evidence that even in adults, performance on some attention tasks requiring eye movements involves multiple neural systems and does not reflect solely attentional processes. (See, e.g., Csibra, Johnson, & Tucker, 1997.) We therefore must be cautious when drawing conclusions about infants' attention from behavior that taxes oculomotor control (Nakagawa & Sukigara, 2007).

The change at 4 months in infants' ability to shift their attention in the overlap task does not mean that this aspect of visual attention is fully developed. In the second half of the first postnatal year, infants' ability to shift attention in this context varies as a function of the content of the central, fixated stimulus (Peltola, Leppänen, Palokangas, & Hietanen, 2008). This variation in the second half of the first year perhaps reflects the fact that infants' processing of the meaning or significance of the central stimulus influences their ability to detect or respond to a peripheral or distracting stimulus. In a very different context, Oakes and colleagues (2002) observed that when playing with toys, 10-month-old infants are less easily distracted by an external stimulus when they are engaged in deeper processing of those toys than when they are less engaged. At 6 months, infants show similar levels of distraction in different states of engagement, suggesting that infants' ability to control their attentional focus—and resist distraction during information processing—shows developmental change during this time.

The literature just described suggests important development in the spatial orienting of attention during the first postnatal year. More precise understanding of this development derives from work using tasks that are more closely related to the tasks developed for older populations. Specifically, a number of studies have used tasks that allow more sensitive measures of spatial orienting that are not conflated with measures of looking. These studies use a task like that illustrated in Figure 1.5. In this task, infants first are induced to fixate a central location (e.g., an interesting stimulus is presented in this location). Next, as infants fixate this centrally presented item, a peripheral cue is briefly presented to the left or right of fixation. Finally, a visual target is presented either in the validly cued location (i.e., where the cue appeared when the infant was fixating the central stimulus) or in an uncued or invalid location (i.e., on the side opposite to where the cue appeared).

Studies using this procedure have documented that visual attention orienting is facilitated to the cued location relative to the uncued location if the interval between cue and target is short. That is, the subject will detect, perceive, and process the target faster or better if it is presented in a validly cued location than if it is presented in a location that is not cued (Carrasco, 2014). Adapting this procedure for use with infants, Johnson, Posner, and Rothbart (1994) observed adult-like responses in such a task by 4-month-old infants. Infants, like adults, responded more quickly to a target that appeared in a cued location. Ross-Sheehy and colleagues (2015) recently introduced an adaptation of this method in which infants are exposed to a variety of cue conditions (e.g., validly cued targets, invalidly cued targets, and neutrally cued targets). Ross-Sheehy et al. observed that older infants showed more effective use of the cues than did younger infants, experiencing less competition between irrelevant cues.

However, spatial cuing does not always result in facilitated or faster response to the cued location. Critically, when the delay between the cue and the target is long (e.g., > 200 ms), people are actually worse at responding to a target that appears in the cued location relative to a target that appears in the uncued location. This effect, termed “inhibition of return” (IOR), presumably reflects the system inhibiting returning attention to a previously attended location. That is,

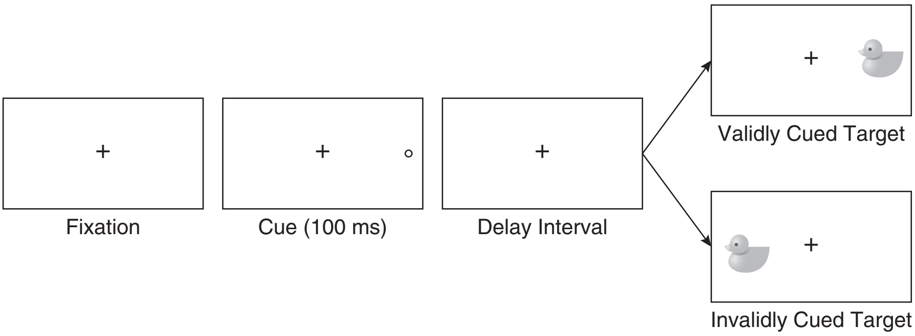

Figure 1.5 An illustration of spatial cueing attention task. When the infant is fixating the central target (the fixation cross), a cue is briefly presented in the periphery. Following a brief delay, in validly cued trials (the top frame), the target is presented in the same location as the cue. In invalidly cued trials (the bottom frame), the target is presented in the opposite location from the cue. Color version of this figure is available at http://onlinelibrary.wiley.com/book/10.1002/9781119170174.

IOR has been described as an adaptation of attentional mechanisms such that once a location is attended and no target occurs, the system inhibits that location in order to encourage orienting to new locations (Klein, 2000). As a result of inhibiting the cued location during the delay, any target that is presented in the cued location is also inhibited, resulting in slower eye movements to that item. There is evidence of IOR in newborns (Simion, Valenza, Umiltà, & Barba, 1995; Valenza, Simion, & Umiltà, 1994) when they are allowed to make overt shifts of attention to the cue. However, when the cue is too rapid and only a covert attention shift can be made, IOR appears to emerge at 5 to 6 months of age (Richards, 2000) and is stable by 9 months (Markant & Amso, 2013, 2015). Richards (2000) paired this task with presaccadic ERPs to show more cortical involvement of parietal and frontal sites with behavioral developmental change from infants 3 to 7 months old. This task, therefore, is a critically important addition to the available tools to assess visual attention. It offers insight into inhibitory processing, an important component of distractor suppression during target selection.

Another task that also provides insight into these inhibitory processes is the *negative priming* task. In this task, a target and a distractor initially are presented together, presumably eliciting attention to the target and inhibition to the location of the distractor. (Maintaining attention to the target presumably requires inhibiting the distractor.) Then, during a second or probe display, the target is presented alone, either in a novel (previously empty) location or in location previously occupied by the distractor. Because the location previously occupied by the distractor was ignored or inhibited, the reasoning is that infants will have more difficulty orienting to a target presented in that location. Indeed, consistent with the data from studies using IOR tasks, infants' responses to targets appearing in previously inhibited locations is slowed compared to their responses to targets appearing in previously empty locations. Thus, performance on these tasks can be used to draw conclusions about infants' ability to inhibit attention to a particular location. Moreover, the developmental changes in this task converge with those obtained when using IOR; infants show developmental change in inhibitory processing across the first postnatal year, with 3-month-olds showing no sign of inhibition but rather facilitation and with inhibitory processing being robust by 9 months (Amso & Johnson, 2005, 2008; Nakagawa & Sukigara, 2007).

Other work has attempted to evaluate infants' visual selective attention orienting more broadly by assessing their performance on visual search tasks. For example, visual search requires shifting attention to a target and inhibiting attending to distractors. A hallmark of effortful visual search is that target identification takes longer with increasing numbers of distractors—because the viewer must attend to individual items or regions of space that contain items, the more items there are, the longer (on average) it will take to find the target. (See discussion in the previous section, "Influential Models and Common Tasks.")

Variations of visual search tasks have been used to study visual attention processes in infants. Very early in infancy, we can ask what stimulus features automatically capture attention by examining visual pop-out. For example, Dannemiller (2005) observed 2-month-old and 4.5-month-old infants' orienting to a singleton oscillating target in a field of static bars. The moving target should capture infants' attention, and their ability to fixate the target and inhibit looking at the nonmoving distractors provides insight into the nature of their visual attention processing. Dannemiller found the pop-out effect in 4.5- but not yet in 2-month-old infants.

Using eye tracking, Amso and Johnson (2006) observed that 3-month-old infants effectively selected both a moving target in a field of nonmoving targets and an oriented bar in a field of vertical bars more often than would be expected by chance. Performance on the moving target search was significantly better than on the more difficult orientation-based search. Frank, Amso, and Johnson (2014) showed developmental improvement in both search tasks from 3 to 10 months of age.

Adler and Orprecio (2006) provided additional evidence that at least some aspects of visual search in infancy are similar to those in adults. They presented 3-month-old infants with two types of visual search arrays: one that should elicit a preattentive target detection for adults (detecting a + in an array of Ls, or target-present arrays) and another that should be elicit more effortful attention (an array of all Ls, or target-absent arrays). Indeed, Adler and Orprecio observed that both 3-month-old infants and adults had similar latencies to find the + in the target-present trials regardless of the number of distractors, but their performance varied considerably by the number of items in the target-absent trials. Similar results were reported by Adler and Gallego (2014). Thus, although we must be cautious about concluding that similar patterns of behavior in infants and adults necessarily reflect the same underlying processing (particularly as adults are given instructions in this task and infants are not), these findings show some similarities in how infants and adults search for targets in cluttered visual arrays.

Work using computational modeling provides insight into the developmental mechanisms behind this development, in particular the neural development that may support developmental changes in orienting during visual search early in infancy. Specifically, work using computational modeling has identified increases in the size of horizontal connections in primary visual cortex and the duration of recurrent posterior parietal activity as critical to effective visual attention orienting performance in infant visual search data (Schlesinger, Amso, & Johnson, 2007, 2012).

In a different type of visual search experiment, Kwon et al. (2016) presented 4- to 8-month-old infants with an array of 6 different photographs of familiar items (shoe, flower, vehicle). One item in each array was a human face. Whereas 4-month-old infants were drawn to the most physically salient item in the array (as defined by brightness and orientation), 6- and 8-month-old infants looked at the human faces. Studies like these uncover spontaneous behavior by infants when presented with visual search arrays and begin to reveal how infants' looking behavior (and visual attention) is controlled by external stimulus factors (such as movement or physical salience) versus other, nonphysical features (such as familiarity or meaning). Consistent with other work examining visual attention in infancy, the results of Kwon et al. showed that by 6 months, infants could use top-down content, such as familiarity or meaning inherent in a human face, to endogenously guide visual attention orienting in the presence of distraction. Data like these are consistent with the general conclusion that processes engaged in voluntary control of attention increase during the first postnatal year.

Recall that Colombo (2001) described two orienting functions of attention, one based on location and the other based on object features. As just described, most of the work on visual attention in infancy has focused on the spatial orienting function of attention. But there is a small emerging literature on object-based attention in infancy. The term "object-based visual attention" refers to attention to one of many features or objects at a particular location at the expense of others. Using cuing methods, adults have been shown to have object-based attention. For example, Egly, Driver, and Rafal (1994) presented a cue on a part of an object; this cue helped adults attend to the object, facilitating their detection of a target that subsequently is presented on that object compared to an equally distant target presented on a different object.

Bulf et al. (2013) used a variation of this task to examine object-based attention in infants. (See Figure 1.6.) In this variation, infants first saw two identical bars for a brief period of time. Then, a cue appeared on one of the two bars. After a delay (200 ms interstimulus interval [ISI] in Figure 1.6), infants then saw a target presented in the cued location or in one of two uncued locations—both equally distant from the cue. However, one kind of the uncued items (the "Invalid same-object" array in the figure) was presented on the cued object, whereas the other kind of uncued item (the "Invalid different-objects" array in the figure) was presented on the other object. Eight-month-old infants also showed object-based attention cuing benefit; they were faster to detect targets in the same-object displays relative to targets in the between-objects displays. (See also Valenza, Franchin, & Bulf, 2014.) In general, researchers agree that object-based attention effects depend heavily on the strength of object representation and recognition as well as object characteristics, such as goodness (Chen, 2012). Although object-based attention is not yet well studied in developmental science, the study of object perception and recognition enjoys a long history of developmental research beginning with Piaget.

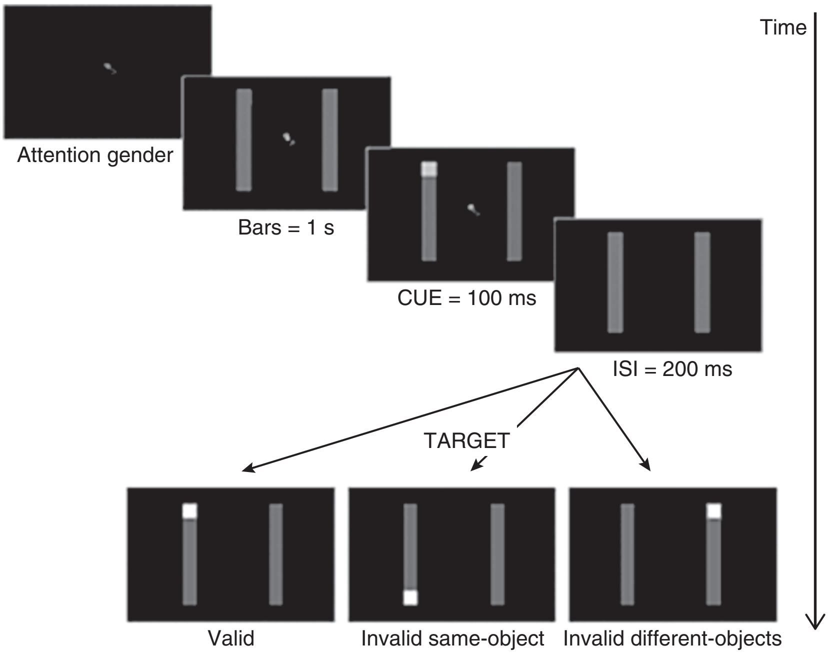

Figure 1.6 Illustrates the procedure used by Bulf & Valenza (2013) to examine object-based visual attention in 8-month-old infants.

Source: Bulf & Valenza (2013), published by APA. Reprinted with permission.

Thus, future research may build on this foundational work on infants' object-based attention and work on object perception and recognition to provide deeper insight into the development of attention more broadly.

Attention in Early Childhood

The transition from infancy to early childhood comes with continued development of visual attention processes. Notably, the relevant changes are not solely in visual attention processes. These processes in childhood operate in a different body than they had in infancy. Young children are mobile, willful, and have strong emerging language skills. Thus, visual attention processes become integrated into a larger set space of competing exploratory skills. It follows that while both alerting and orienting show some measurable developmental change into childhood, it is the executive processes that become a critical component of managing or regulating the now-dynamic opportunities facing the growing child.

Although not explicitly focused on understanding visual attention per se, early studies of toddlers' and preschool children's sustained attention during television watching provide some insight into attentional abilities, at least in the context of watching a complex, dynamic, multimodal stimulus. The findings suggest developmental changes in the *alerting* network during this period. For example, children's attention to television programming increased between age 1 and 4 years (Anderson & Levin, 1976), and children's sustained attention during television viewing was related to their comprehension of the content (Lorch, Anderson, & Levin, 1979). Such findings provide a foundation for understanding how children's sustained attention develops during early childhood and suggests that, as with infants (e.g., Cohen, 1991), the duration of periods of sustained attention is related to children's processing of the stimulus content. Moreover, 5-year-old children are less distractible—and presumably more engaged—when the content being viewed is comprehensible than when it is not (Lorch & Castle, 1997). During the preschool years, there continue to be developmental changes in children's ability to maintain an alert and engaged attentional state, and this ability is enhanced by their ability to understand the content of the stimulus being visually attended.

In addition, the study of children's general attention processes while viewing television—and to some extent during toy play—led to conclusions about the development of attentional inertia, or the process by which attention becomes more engaged over time (Richards & Anderson, 2004). The notion is that sustained attention builds and engagement with the stimulus deepens over the period of sustained attention. This conclusion is supported by the fact that children become less easily distracted as a period of sustained attention continues (Anderson, Choi, & Lorch, 1987; Oakes, Ross-Sheehy, & Kannass, 2004) and by physiological changes, including reductions in heart rate, that occur over prolonged periods of sustained attention (Richards & Cronise, 2000; Richards & Gibson, 1997). This characteristic of increasing engagement over periods of sustained attention is not specific to the preschool years; there is evidence of this process in infancy (Oakes et al., 2004) through the preschool period (Richards & Cronise, 2000). Of course, developmental changes in attention occur during this time period. Given the same stimulus, periods of sustained attention increase over age, and comprehension appears to have an increasing influence on children's sustained attention during the preschool period (Richards & Anderson, 2004).

Other work examined developmental changes in sustained attention in other contexts. For example, in a longitudinal study, Ruff et al. (1998) showed increases in children's duration of looking and focused attention between 2.5 and 4.5 years of age during free play and watching a puppet show, suggesting changes in children's ability to sustain an engaged attentional state. Moreover, the context—particularly the number of toys present—may influence whether sustained attention increases or decreased from infancy through the preschool years (Ruff & Capozzoli, 2003). Such effects underscore the close connection between attention and other cognitive processes and how attention is differentially engaged depending on the cognitive load imposed by the task. During the preschool period, there appear to be changes in the level of engagement during attention, with older children being more resistant to distraction than younger children are during periods of sustained attention during toy play (Ruff & Capozzoli, 2003). Taken together, this research has revealed changes during early childhood in the duration and the level of engagement during periods of sustained attention. Because sustained attention is related to information processing—and the comprehensibility and complexity of the stimulus content—developmental changes must be evaluated taking into consideration the nature of the stimuli, task, context, and other factors.

The work during early childhood also reveals changes in orienting. For example, Gerhardstein and Rovee-Collier (2002) used a visual search task (their stimuli are illustrated in Figure 1.2) to examine orienting in children between 1 and 3 years of age. In this task, children were taught to touch the target. Recall that in Figure 1.2a, the target is different from the distractors only by a single feature, and therefore the feature task should be easy and not require attention. Recall that the target in Figure 1.2b is defined by a conjunction of features—it is the instance that is defined by a specific color/shape combination—and search for this target should require attention and should be effortful. Indeed, Gerhardstein and Rovee-Collier found the number of items in the arrays in the feature task had no effect; the only significant effect was that younger children were slower to find the target. Thus, detecting the target did not appear to require effortful attentional orienting. In contrast, children's performance in the conjunction task varied with the number of distractors—children had more difficulty identifying the target when there were more distractors. In both tasks, younger children were generally less efficient and less accurate than older children, but the effect of attention seemed to be the same across this age range, suggesting that the only developmental effects observed here were those that reflect developmental change in young children's *general* attentional abilities, or something related to making a response. Scerif and colleagues (2004) observed similar results in a touch-screen visual search task with children in this same age range. However, because Scerif et al. also included some of the displays without targets, they could examine not only search times but also other variables, such as search paths and perseverative errors to nontargets. The inclusion of such variables may have yielded more sensitivity to developmental differences in this age range. Other work using more traditional visual search tasks (pressing a key when a target is found within an array) revealed developmental differences in somewhat older children (6–10 versus adults) in conjunction searches (Trick & Enns, 1998). Future work comparing different types of visual search tasks may reveal the source of such discrepancies.

Finally, the increased awareness that developmental changes in attention during early childhood reflect, at least in part, changes in executive attention or cognitive control has led to the development of new tasks to tap those developing systems. As described earlier, variations of the flanker task have been developed for use with children as young as 4 (McDermott et al., 2007). This task, which is depicted in Figure 1.3, simplifies the traditional flanker task by reducing the perceptual demands of the stimuli and increases the child's ability to apply existing knowledge to their processing of the stimuli. The Track-It task developed by Fisher et al. (2013) is also argued to examine executive attention.

By manipulating features of the distractors (e.g., whether they are all the same or vary), Fisher et al. (2013) argued that this task allows assessment of endogenous and exogenous factors on children's sustained selective attention.

In summary, during the toddler and preschool years, there continue to be significant changes in attentional processes, with evidence that children are becoming increasingly more efficient in their visual attention orienting and more capable of sustained attention.

Attention in Later Childhood and Adolescence

The transition into later childhood brings modest developmental change in visual attention alerting and orienting but more robust change in executive attention. Indeed, much of the work in later childhood and early adolescence has focused on cognitive control, which is closely related—and may overlap with—executive attention.

Work with older children and adolescence suggests that there is little change in orienting attention in late childhood. Enns and Brodeur (1989) showed that 5- to 9-year-old children are more influenced by an orienting cue than are adults—both in terms of the benefit of a valid cue on their attention performance and the interference from an invalid cue. (See also Konrad et al., 2005.) However, several studies have shown that by 8 to 10 years, children's orienting is adult-like. Rueda et al. (2004) showed that in the ANT by age 10, children receive the same benefit as adults from an alerting cue. Other work has shown that visual attention orienting is adult-like by 8 to 10 years (Goldberg, Maurer, & Lewis, 2001; Rueda, Rothbart, McCandliss, Saccomanno, & Posner, 2005; Waszak, Li, & Hommel, 2010). Using a spatial cuing task, Markant and Amso (2014) did not observe developmental change in visual attention orienting, with either facilitation- or IOR-inducing timing, in children 7 to 17 years of age, which suggests stable visual attention orienting in this age range. Thus, any changes in these attention networks beyond early childhood are subtle and much less dramatic than the development that occurs in infancy and early childhood.

In contrast to alerting and orienting, the development of executive attention processes is more protracted, with changes into adolescence Executive attention processes are involved when contexts or tasks require inhibition of conflicting or interfering sources of information in the visual environment. Resolving such conflict requires some overarching rule to guide visual attention. For example, executive attention is engaged when a target is flanked by distractors that present a conflict (see Figure 1.3)—such as when the direction of flanking arrows is different from the direction of a central arrow target. Research using tasks that require attention in the context of such conflict has revealed that executive attention is not yet adult-like in childhood (Goldberg et al., 2001) and continues to develop into adolescence (Konrad et al., 2005; Waszak et al., 2010).

Additional insight into the development of executive attention comes from work using the anti-saccade task (Guitton, Buchtel, & Douglas, 1985). In this task, children are taught a rule: When a cue appears on a screen, inhibit attending to it and instead orient to the opposite side of the screen. Evidence of some competence on anti-saccade tasks is available in infants (Johnson, 1995) as well as in toddlers and young children (Scerif et al., 2005). Despite these developmental changes early in childhood, as is true for other aspects of executive attention, anti-saccade development has a prolonged developmental time course, becoming adult-like by roughly 14 years of age (Luna, Garver, Urban, Lazar, & Sweeney, 2004).

Moreover, neuroimaging data have exposed the neural networks underlying these visual attention processes; these findings confirm and provide additional insight into the behavioral changes described. For example, Konrad et al. (2005) showed that 8- to 12-year-old children had less activation than did adults in frontal-midbrain regions during alerting, less activation in the temporoparietal junction during orienting, and less activation in the dorsolateral prefrontal cortex during executive attention tasks. Using anti-saccade, Luna and colleagues (2004) have shown that developmental change in top-down executive control of visual attention involves frontoparietal engagement and emerging long-range connections between these regions and develops into adolescence (Crone, 2009; Hwang, Velanova, & Luna, 2010).

EMERGING TRENDS AND FUTURE DIRECTIONS IN THE STUDY OF THE DEVELOPMENT OF VISUAL ATTENTION

As illustrated by the preceding discussion, much work in the study of the development of visual attention has focused on demonstrating the state of the system at different developmental points. This has been a fruitful approach and has yielded significant understanding of both the limitations and the capabilities of visual attention across development.

With this work as a foundation, two trends have emerged in the literature that have and will continue to shape our understanding of the development of visual attention. The first emerging trend derives from the fact that the process-oriented focus in the study of attention has highlighted the connections between attentional processes and other processes, in particular learning and memory. Second, there has been an explosion of new tools available for studying attention. Many of these tools are further refinements of older tools or involve the application of tools used with adults or in neuropsychological contexts. However, the availability of new imaging techniques—as well as methods for analyzing the data from those techniques—has yielded significant insight into how developing neural structures influence attentional processes. We discuss each of these trends in the following paragraphs.

Attention and Its Interactions with Learning and Memory

Attention as a process interacts with learning and memory processes in intimate and complex ways. Historically, researchers have asked how cognitive processes influence attention—for example, how children are more engaged and less distractible when attending to content they understand than when attending to content that is more difficult to understand (Lorch et al., 1979). However, it is important to keep in mind that one part of the definition of attention is that, because it functions to filter distraction, it increases the efficiency of other cognitive processes. An emerging trend in the literature is a deep recognition of this connection. For example, attentional processes may differ depending on the content of information in particular location. Also, and relatedly, visual attention dynamics—such as the facilitation of processing of some information or such facilitation in combination with inhibition of competing distractors—can impact how attended items are learned and remembered.

One way attention is related to learning and memory is that how perceivers distribute their attention to a stimulus can determine what they learn about that stimulus. For example, using eye tracking, researchers have asked how people distribute their attention to specific parts of a visual scene (ignoring other parts of the scene) and how that pattern of attention relates to their learning about the objects in those scenes. These relations have been demonstrated even in infancy. Johnson, Slemmer, and Amso (2004) found a relation between where infants oriented on a visually ambiguous display (a rod divided by a central box) and whether infants perceived the central rod object in the display as complete or broken. Infants who oriented to (looked at) the object parts and their movement perceived the rod and box in an adult-like manner, whereas those who oriented randomly did not. This and other work has collectively identified a role for efficient attention-guided orienting in bootstrapping both object and face perception (Amso, Fitzgerald, Davidow, Gilhooly, & Tottenham, 2010; Amso & Johnson, 2006; Emberson & Amso, 2012; Johnson et al., 2004).

Moreover, at least in infancy, previous learning can shape how viewers orient to a stimulus, presumably influencing what they learn about those stimuli. For example, 4-month-old infants who live with a pet distribute their looking differently to images of dogs and cats than do infants who do not live with pets (Hurley & Oakes, 2015; Kovack-Lesh, McMurray, & Oakes, 2014; Markant & Amso, 2015). Similarly, infants looking at faces distribute their visual attention differently when viewing relatively familiar, own-race faces than when viewing relatively unfamiliar, other-race faces (Xiao, Quinn, Pascalis, & Lee, 2014; Xiao, Xiao, Quinn, Anzures, & Lee, 2013). Thus, not only does orienting influencing learning in the moment, but the strategies that infants use to guide their attention to a stimulus reflects their past experience.

In addition, visual attention can bias what infants learn about available content. As noted, IOR emerges by the time infants are 5 to 6 months of age. Recent work has identified a novel role for IOR, during visual attention orientating, in learning and memory (Markant & Amso, 2013, 2014; Markant, Oakes, & Amso, 2015; Markant, Worden, et al., 2015). Using spatial cuing tasks, these studies showed a benefit for objects that were attended to and encoded in the IOR condition. Recall that IOR is elicited when subjects are cued to a location, but there is a relatively long delay between the offset of the cue and the onset of the target. On these trials, participants simultaneously suppress or inhibit the cued location—that is, the distractor location—and increase attention to the noncued location—that is, the target location. Studies with infants show that when the timing elicits IOR, infants more effectively learn objects presented in the noncued (target) location than objects in the cued (distractor) location, illustrating suppression of the object in the distractor condition and facilitation of attention and learning to the object in the target location.

Moreover, functional magnetic resonance imaging (fMRI) data in adults showed that this memory benefit was linked to attentional modulation of visual cortex activity: Recognition accuracy for objects encoded in the context of IOR was predicted by cortical activity associated with target location enhancement and by the extent to which competing distractor locations were inhibited during initial encoding (Markant, Worden, et al., 2015). These data suggest that, in filtering distraction, visual attention provides a less noisy representation of the attended item for learning and memory.

Markant, Oakes, and Amso (2015) provided a powerful demonstration of this effect. They observed that they could influence how infants processed items within a category of objects by biasing infants to attend to that category. A number of studies have shown that infants orient attention differently to informative parts of own-race versus other-race faces, in particular the eyes (Wheeler et al., 2011; Xiao et al., 2013). Markant, Oakes, and Amso (2015) asked a different question; they asked how biasing infants to attend to some types of stimuli (but not to other types of stimuli) could influence asymmetries in processing faces based on race. They used a spatial cuing procedure to bias Caucasian 9-month-old infants to attend to either own- or other-race faces. (All infants were exposed to the same own- and other-race faces; some infants were biased to attend to the own-race faces, and other infants were biased to attend to the other-race faces.) Infants showed stronger discrimination of and memory for faces from the race that was the focus of the attention bias, regardless of whether those faces were from their own-familiar race or a different, unfamiliar race. Thus, the extent of attention engagement, and distractor suppression, at initial stimulus encoding—not the familiarity of the race—determined the asymmetry in processing in this case. These results extend other attentional explanations of the other-race effect in both adult (Hills, Cooper, & Pake, 2013) and infant literatures (Wheeler et al., 2011; Xiao et al., 2013) on how attention (as measured by eye movements) is distributed to different facial areas influences the other-race effect.

Finally, research using very different methods and procedures has also shown that attention can contribute to what infants learn in cluttered visual scenes. Specifically, when presented with an array of multiple objects, learning about any individual object requires selecting that objects, attending to it, and inhibiting distracting objects. This may be especially difficult for young infants. Ross-Sheehy and colleagues (2011) observed that facilitating young infants' attention to an individual item in a multiple item array allowed them to encode that individual item into visual short-term memory (VSTM) and detect when it changed. Importantly, this effect was observed at a point in development when infants appear to be unable to encode or store in VSTM individual items in multiple-item arrays (Oakes, Baumgartner, Barrett, Messenger, & Luck, 2013; Ross-Sheehy, Oakes, & Luck, 2003). These relations appear to continue across development. For example, Astle, Nobre, and Scerif (2012) observed that individual differences in attentional control were related to VSTM in 7- to 10-year-old children, providing support for the idea that developmental changes in attentional control contribute to developmental changes in VSTM. In sum, attention and memory are reciprocally interactive, and a great deal is gained by examining their development as such.

New Tools to Study Visual Attention

Behavioral Tools

Many new behavioral tools have been developed to study attentional processes in infancy and childhood. The availability of eye trackers with adaptations for calibrating and tracking younger children's eye gaze have opened the door for the introduction of new tools as well as the refinement of existing tools.

Consider the visual search tasks described throughout this chapter. Examining visual search with young children was extremely difficult until new technical tools were developed. For example, Dannemiller (2000) drew conclusions about the role of external stimulus factors on young infants' attention by examining gaze shifts to displays containing a number of static shapes and one moving shape. Using classic forced-choice preferential looking (FPL) procedure (Teller, 1979), observers watched infant behavior and made a judgment (based on head movement, eye direction, facial expression, and other idiosyncratic behaviors) about the side of the moving bar. Because the observers have no information about where the moving bar is, the observer will be accurate (i.e., be able to judge correctly the side of the display containing the moving bar) only if the infant has a strong tendency to look at that bar. This procedure has been extremely successful at evaluating many aspects of young infants' visual behavior (Dannemiller, 2000; Powers, Schneck, & Teller, 1981; Wattam-Bell, 2001), but it allows only a crude measurement of where infants are looking. Thus, it is less useful for assessing complex attentional processes in visual search.

Others have attempted to understand how attention is deployed and used in visual search with habituation or familiarization tasks (Quinn & Bhatt, 1998) or conditioning tasks (Rovee-Collier, Hankins, & Bhatt, 1992). However, these tasks also do not allow evaluation of attentional processes on the same timescale as in traditional visual search (i.e., on a single brief exposure to a stimulus array), and they also do not allow precise measurement of where subjects look.

The availability and accessibility of eye tracking systems that can be used with young children and infants has allowed researchers to ask more sophisticated questions about visual search in these age groups. Specifically, researchers can now measure, with extreme precision, exactly where infants look, how many targets they orient to prior to landing on the target, their scan paths when distractors are nearby, and the latency in milliseconds to target identification. The development of eye tracking methods has given scientists the ability to unconfound visual attention processes from other variables involved in looking behavior.

As discussed throughout this chapter, the development of new tasks also has advanced visual attention research. Tasks have been developed that are explicitly linked to Posner and Petersen's separable networks and the ANT. Of course, the most influential task is the ANT itself (Rueda et al., 2004), which has been used to assess attentional processes in children. Results from this task have shown how attentional abilities are related to executive control and emerging self-regulation (Rueda, Posner, & Rothbart, 2005). Many tasks, such as the NIH Toolbox for the Assessment of Neurological and Behavioral Function (Zelazo et al., 2013) and the Early Childhood Attention Battery (ECAB), developed by Breckenridge, Atkinson, and Braddick (Atkinson & Braddick, 2012; Breckenridge, Braddick, & Atkinson, 2013), have examined these types of relations to assess different aspects of attention in early childhood—particularly those related to executive attention and cognitive control—that are predictive of atypical developmental trajectories. For example, the ECAB has revealed deficits in attentional processes of children with Down syndrome and Williams syndrome (Breckenridge, Braddick, Anker, Woodhouse, & Atkinson, 2013) and may help both understanding and early identification of such disorders (Atkinson & Braddick, 2012).

In addition to these broad tasks, other tasks have been developed to assess specific aspects of visual attention. Ross-Sheehy and colleagues (2015) developed an attentional cuing task for use with infants and young children that takes advantage of infants' and young children's interest in moving, dynamic stimuli and presents young children with several types of cuing. In each trial, an attractive central stimulus (a looming smiley face) is presented. As infants fixate that stimulus, a cue is presented—a single cue in one of two peripheral locations, a neutral cue, or a tone—then, after a brief delay, a target is presented in one of the peripheral locations. By comparing how quickly infants fixate the target in different cuing conditions, Ross-Sheehy et al. have identified different attentional profiles in infancy and have examined developmental changes in how effective infants are in controlling their attention. Similarly, Markant and Amso (2013, 2015) have adapted a spatial cuing paradigm to examine IOR in infancy. Although IOR has been studied in infants—in particular, to document whether IOR exists in infancy (Butcher, Kalverboer, & Geuze, 1999; Valenza et al., 1994; Varga, Frick, Kapa, & Dengler, 2010)—Markant and Amso's work reflects a change in focus. As described earlier, this newer work examines the attentional processes engaged in different types of cuing and the effect of those differences on learning.

Finally, it has recently been recognized that attentional processes—particularly in infancy—can be understood through training procedures. By manipulating features of tasks and the presence or absence of reward, researchers have developed contexts in which infants and young children can be trained to use their attention in particular ways. Individual and developmental differences in how easily and effectively children can learn the contingencies and/or specific behaviors can provide insight into the systems that underlie visual attention and may help identify children at risk for developmental disorders. One such task is the Freeze Frame task developed by Holmboe and colleagues (Holmboe, Pasco Fearon, Csibra, Tucker, & Johnson, 2008; Holmboe et al., 2010b) in which children are trained to inhibit responding to a peripheral distractor. When children fixate an attractive, animated centrally presented stimulus, a peripheral stimulus is presented; when children shift their gaze to that peripheral stimulus, the central stimulus freezes. This task presumably reflects infants' emerging frontal control over visual attention, and performance at 9 months predicted performance at 24 months. Moreover, performance on this task is related to risk of later developing autism spectrum disorder (ASD; Holmboe et al., 2010a).

Similarly, Wass, Porayska-Pomsta, and Johnson (2011) found that they could use tasks like this, as well as tasks that reinforced some types of shifts of attention, to train infants' attentional control. Training had an effect on other aspects of visual attention. Specifically, training children to inhibit distractors and to follow targets increased the ability of 11-month-old infants to sustain and shift attention relative to control participants who did not receive the training.

Neuroimaging Tools

As the introduction of eye tracking technology helped bring precision the study of visual attention in infancy, so now has the introduction of novel neuroimaging tools and statistical methods provided some precision to the study of the neural architecture underlying visual attention development. Electroencephalogram (EEG) methods historically have been powerful tools for the study of the temporal dynamics of neural signals relevant to visual attention orienting (Astle, Scerif, Kuo, & Nobre, 2009; Hopf et al., 2000; Richards, 2001). One significant limitation of the EEG method is that although it has good temporal resolution, it has limited spatial resolution. Some methods have been developed to localize the source of specific ERP and EEG signals (e.g., Reynolds & Richards, 2009), but source localization of such signals is extremely coarse and subject to inaccuracies (Luck, 2014). Thus, these techniques can provide only gross indications of differences—and age-related differences—in the involvement of different neural networks during attentional processes.

The introduction of near-infrared spectroscopy (NIRS) allows better spatial precision (Aslin, 2012; Aslin, Shukla, & Emberson, 2015; Ferreri, Bigand, Perrey, & Bugaiska, 2014) and may be an essential tool for better understanding the development of cortical attention networks. NIRS uses infrared light to measure cortical activity precisely beneath the locus of the measuring optodes and emittors. The variable offered is effectively a blood-oxygen-level-dependent (BOLD) signal, which is a measurement of relative oxygenated to deoxygenated hemoglobin in response to a stimulus or event. In this way, and for the first time, the scientific community can document functional brain activations while infants are awake and performing tasks. NIRS can also be combined with tools like eye tracking to provide even more precision. Using NIRS in concert with eye tracking, for example, a recent study showed that infants engaged the dorsomedial prefrontal cortex more during a social interaction, peek-a-boo, when their partner looked directly at them rather than when the partner averted the gaze (Urakawa, Takamoto, Ishikawa, Ono, & Nishijo, 2015) Clearly, therefore, the use of NIRS is an important emerging trend in the study of visual attention, and even deeper understanding will be gained as new tasks are developed for use with NIRS. This technique also has significant limitations, however. Because the technique involves measuring how light moves through the brain, it is limited to measuring only the outermost few millimeters of the cortex.

For this reason, NIRS is unlikely to replace fMRI in child and adult participants who can perform tasks comfortably in a scanner. FMRI and diffusion tensor imaging (DTI; used to measure white matter microstructure) have long been used to study the neural underpinnings of cognitive processes in children (Amso & Casey, 2006; Qiu, Mori, & Miller, 2015). Several emerging advances mean that these techniques will be even more useful for understanding the development of visual attention networks.

Anatomical data and functional resting state data are gathered while infants and toddlers are naturally asleep. These data often can be coupled with separate behavioral data collections on tasks such as those described earlier. With respect to visual attention, for example, Elison et al. (2013) used this strategy to show that visual attention orienting as well as white matter microstructure at 7 months of age predicted later emergence of autism in an at-risk cohort. Using a similar approach, Stjerna et al. (2015) examined the relationship between visual fixations and gaze behavior and white matter microstructure at birth. Not only were better visual fixations at birth related to indices of better white matter microstructure (fractional anisotropy), visual fixation behavior related to visuocognitive task performance at 2 and 5 years of age. Thus, by combining behavioral and MRI techniques, we gain understanding into how those systems and measures are related across development.

In concert with resting-state data collection in infants and young children, advances in data analysis and modeling allow insight into the development of the neural structures that support visual attention. For example, one novel approach to fMRI research, connectomics (Di Martino et al., 2014; Sporns, 2013), has added important insight into developmental processes in particular. One view of brain development, namely interactive specialization (Johnson, 2000), holds that neural development is not the growth of any particular region but rather changes in connectivity among regions and pathways. With respect to the networks that support visual attention, connectomics data have shown that dorsal attention and frontoparietal network connectivity shows measurable strengthening even as early as 6 to 12 months (Pruett et al., 2015). Similarly, developmental improvements in executive attention are shown to be supported by strengthening of long-range connectivity from parietal to frontal regions and decreases in short-range connectivity within parietal and frontal regions (Hwang et al., 2010). These data have led many to argue that brain development is consistent with interactive specialization and that brain development involves a shift from local to long-range connections supporting increasingly mature cognition.

Semi-Naturalistic Measurement in the Study of Visual Attention

Most of the findings described here reflect results from tightly controlled, well-designed experimental procedures. The findings from such studies are invaluable for understanding cognitive processes such as those of visual attention. As evident from the preceding pages, we have gained significant understanding of visual attention across the life span using this approach. However, this approach is limited because it can provide little understanding into the ways in which visual attention operates in complex contexts, such as those encountered everyday. That is, children do not simply use visual attention to find a black circle in an array of gray squares—they use it to process the information being written on the chalkboard in a busy classroom where other children are talking, wiggling, and chewing gum, and the chalkboard is surrounded by posters, student work, and important announcements. How can we understand how the kinds of attentional processes described in this chapter translate to children's behavior in such environments?

One solution is to use semi-naturalistic measurement of visual attention, and increasingly in developmental science, methods and procedures are being developed to conduct semi-naturalistic assessments of visual attention. Technological advances allow us to take the large body of findings from tightly controlled, but relatively sparse, experimental procedures and further examine the processes using semi-naturalistic data collection techniques. One approach to semi-naturalistic data collection is to develop a laboratory space that is designed to look and function like a school classroom or room in a home. This encourages play, exploration, oculomotor engagement, locomotor action, and social interaction with others. In this way, visual attention data collection proceeds as children engage in naturalistic behaviors.

A second approach is to use high-tech solutions to systematically evaluate children's visual attention in these contexts or "in the wild," such as at home or school. For example, a number of studies have provided significant insight into attention in real-world contexts simply by recording the visual world from the infants' perspective. These studies have explored what visual information infants actually *can* attend to by simply asking what visual information is *there*. Answering this question is possible with the availability of lightweight, remote (and wireless) video recording devices that can be mounted on an infant's' forehead. Sugden, Mohamed-Ali, and Mouleson (2014), for example, placed a small camera inside an infant-size headband and asked parents of 1- and 3-month-old infants to place the headband on their infant's head whenever the infant was awake during a 2-week period. This procedure yielded hundreds of hours of recordings of what information was available to these infants, and conclusions could be drawn about how often infants could actually attend to faces in their daily lives. Such information is invaluable in understanding the real-world contexts in which infants actually use their attentional processes.

In an extension of this method, Aslin (2009) presented infants with recordings obtained from a different infant's forehead. Because the head-mounted cameras provide information only about the information infants might look at, Aslin used eye-tracking methods to record infants' eye gaze when watching the video recordings. This work shows how infants direct their gaze at scenes recorded from an infant's' viewpoint.

Such work is important for understanding how infants look at more naturalistic stimuli, but it still does not allow conclusions about how infants direct their attention during more naturalistic interactions with objects and others. That is, a key question is how infants and children deploy attention, control, inhibit, and select as they reach for objects, navigate environments, interact with others, learn the names of objects, and other activities. The development of head-mounted eye trackers has made possible the evaluation of visual attention under a range of naturalistic contexts. For example, Franchak and Adolph (2010; Franchak, Kretch, Soska, & Adolph, 2011) used head-mounted eye trackers to understand developmental changes in visual attention during developmental changes in motor abilities. Franchak and Adolph (2010) found that children and adults attended differently to obstacles as they walked around a space. Kretch et al. (2014) found that crawling and walking infants directed their gaze differently at caregivers as they approached them (e.g., crawled or walked toward them). These semi-naturalistic observations allowed researchers to understand how changes in locomotor ability—as well as age—corresponded to changes in visual attention. Similarly, Yu and Smith (2011, 2013) have used head-mounted eye trackers to examine how children's attentional processes constrain, shape, and interact with their learning of new object labels.

CONCLUSION

Visual attention is one of many attention processes that operate over sensory modalities. As is clear from the work reviewed here, a great deal of research effort has been aimed at understanding the development of visual attention beginning in infancy and at uncovering the neural mechanisms that support these processes and their development. Visual attention involves both excitatory and inhibitory mechanisms, and its development has functional significance for other cognitive and social domains in the developing child. Indeed, visual attention processes give us a window into the developing brain, are of the earliest emerging processes that are measurable in young infants, and are critical in determining what information enters the system for subsequent perception and learning. As such, visual attention processes are building block processes for perception and cognition, and their impairment has cascading effects on brain and cognitive development. The work reviewed in this chapter collectively serves an additional purpose of informing the community of scholars engaged in improving the lives of children with neurodevelopmental disorders. Visual attention processes are impaired in a variety of neurodevelopmental disorders including ASD, fragile X, and attention-deficit/hyperactivity disorder (ADHD) (see Amso & Scerif, 2015, for review).

A recent trend in the study of disorders with known impairments in visual attention is to use the described developmental trajectories of visual attention processes to predict whether an infant at familial risk for disorders will deviate from typical trajectories (Gliga, Bedford, Charman, & Johnson, 2015; Jones & Klin, 2013). For example, Elsabbagh et al. (2009) observed that infant siblings of children with ASD showed reduced attentional disengagement in comparison to siblings of children without ASD. Similarly, infants at risk for ADHD have been shown to have some differences in sensory processing as measured by ERP that later related to ADHD symptomology (externalizing behavior, attentional problems; Hutchinson, De Luca, Doyle, Roberts, & Anderson, 2013). These data provide evidence of a broader endophenotype associated with differences in visual attention modulation in infants and children at familial risk for both neurodevelopmental disorders. Thus, visual attention processes are starting to serve as biomarkers of need for early intervention.

REFERENCES

Adler, S. A. (2005). Visual search and pop-out in infancy. In L. Itti, G. Rees, & J. Tsotsos (Eds.), *The Neurobiology of Attention* (pp. 207–212). Amsterdam: Elsevier. http://doi.org/10.1016/B978-012375731-9/50038-0

Adler, S. A., & Gallego, P. (2014). Search asymmetry and eye movements in infants and adults. *Attention, Perception & Psychophysics*, *76*(6), 1590–608. http://doi.org/10.3758/s13414-014-0667-6

Adler, S. A., & Orprecio, J. (2006). The eyes have it: visual pop-out in infants and adults. *Developmental Science*, *9*(2), 189–206.

Amso, D., & Casey, B. J. (2006). Beyond what develops when: neuroimaging may inform how cognition changes with development. *Psychological Science*, *15*(1), 24–29.

Amso, D., Fitzgerald, M., Davidow, J., Gilhooly, T., & Tottenham, N. (2010). Visual exploration strategies and the development of infants' facial emotion discrimination. *Frontiers in Psychology, 1*. Article 180. doi:10.3389/fpsyg.2010.00180

Amso, D., Haas, S., & Markant, J. (2014). An eye tracking investigation of developmental change in bottom-up attention orienting to faces in cluttered natural scenes. *PLoS ONE*, *9*(1), e85701. http://doi.org/10.1371/journal.pone.0085701

Amso, D., & Johnson, S. P. (2005). Selection and inhibition in infancy: evidence from the spatial negative priming paradigm. *Cognition*, *95*(2), B27–B36. http://doi.org/10.1016/j.cognition.2004.08.006

Amso, D., & Johnson, S. P. (2006). Learning by selection: visual search and object perception in young infants. *Developmental Psychology*, *42*(6), 1236–1245.

Amso, D., & Johnson, S. P. (2008). Development of visual selection in 3- to 9-month-olds: Evidence from saccades to previously ignored locations. *Infancy: Official Journal of the International Society on Infant Studies*, *13*(6), 675–686. http://doi.org/10.1080/15250000802459060

Amso, D., & Scerif, G. (2015). The attentive brain: insights from developmental cognitive neuroscience. *Nature Reviews*, *16*(10), 606–619. http://doi.org/10.1038/nrn4025

Anderson, D. R., Choi, H. P., & Lorch, E. P. (1987). Attentional inertia reduces distractibility during young children's TV viewing. *Child Development*, *58*(3), 798–806.

Anderson, D. R., & Levin, S. R. (1976). Young children's attention to "Sesame Street." *Child Development*, *47*(3), 806–811. http://doi.org/10.2307/1128198

Aslin, R. N. (2009). How infants view natural scenes gathered from a head-mounted camera. *Optometry and Vision Science*, *86*(6), 561–565.

Aslin, R. N. (2012). Questioning the questions that have been asked about the infant brain using near-infrared spectroscopy. *Cognitive Neuropsychology*, *29*(1–2), 7–33. http://doi.org/10.1080/02643294.2012.654773

Aslin, R. N., Shukla, M., & Emberson, L. L. (2015). Hemodynamic correlates of cognition in human infants. *Annual Review of Psychology*, *66*(1), 349–379. http://doi.org/10.1146/annurev-psych-010213-115108

Astle, D. E., Nobre, A. C., & Scerif, G. (2012). Attentional control constrains visual short-term memory: insights from developmental and individual differences. *Quarterly Journal of Experimental Psychology*, *65*(2), 277–294. http://doi.org/10.1080/17470218.2010.492622

Astle, D. E., Scerif, G., Kuo, B.-C., & Nobre, A. C. (2009). Spatial selection of features within perceived and remembered objects. *Frontiers in Human Neuroscience*, *3*, 6.

Atkinson, J., & Braddick, O. (2012). Visual attention in the first years: typical development and developmental disorders. *Developmental Medicine & Child Neurology*, *54*(7), 589–595.

Awh, E., Vogel, E. K., & Oh, S.-H. (2006). Interactions between attention and working memory. *Neuroscience*, *139*(1), 201–208. http://doi.org/10.1016/j.neuroscience.2005.08.023

Bertenthal, B., & Von Hofsten, C. (1998). Eye, head and trunk control: The foundation for manual development. *Neuroscience and Biobehavioral Reviews*, *22*(4), 515–520. http://doi.org/10.1016/S0149-7634(97)00038-9

Breckenridge, K., Braddick, O., Anker, S., Woodhouse, M., & Atkinson, J. (2013). Attention in Williams syndrome and Down's syndrome: performance on the new early childhood attention battery. *British Journal of Developmental Psychology*, *31*(2), 257–269. http://doi.org/10.1111/bjdp.12003

Breckenridge, K., Braddick, O., & Atkinson, J. (2013). The organization of attention in typical development: a new preschool attention test battery. *British Journal of Developmental Psychology*, *31*(Pt 3), 271–88. http://doi.org/10.1111/bjdp.12004

Bulf, H., & Valenza, E. (2013). Object-based visual attention in 8-month-old infants: evidence from an eye-tracking study. *Developmental Psychology*, *49*(10), 1909–1918. http://doi.org/10.1037/a0031310

Bunge, S. A., Dudukovic, N. M., Thomason, M. E., Vaidya, C. J., & Gabrieli, J. D. E. (2002). Immature frontal lobe contributions to cognitive control in children: evidence from fMRI. *Neuron*, *33*(2), 301–311.

Butcher, P. R., Kalverboer, A. F., & Geuze, R. H. (1999). Inhibition of return in very young infants: a longitudinal study. *Infant Behavior and Development*, *22*, 303–319. http://doi.org/10.1016/S0163-6383(99)00013-2

Canfield, R. L., & Kirkham, N. Z. (2001). Infant cortical development and the prospective control of saccadic eye movements. *Infancy*, *2*, 197–211. http://doi.org/10.1207/S15327078IN0202_5

Carrasco, M. (2011). Visual attention: the past 25 years. *Vision Research*, *51*(13), 1484–1525. http://doi.org/10.1016/j.visres.2011.04.012

Carrasco, M. (2014). Spatial attention: perceptual modulation. In K. Nobre & S. Kastner (Eds.), *The Oxford Handbook of Attention* (pp. 183–230). Oxford, UK: Oxford University Press. http://doi.org/10.1093/oxfordhb/9780199675111.001.0001

Chen, Z. (2012). Object-based attention: a tutorial review. *Attention, Perception, & Psychophysics*, *74*(5), 784–802. http://doi.org/10.3758/s13414-012-0322-z

Cohen, L. B. (1973). A two-process model of infant attention. *Merrill-Palmer Quarterly*, *19*, 157–180.

Cohen, L. B. (1991). Infant attention: an information processing approach. In M. J. Weiss & P. R. Zelazo (Eds.), *Newborn Attention: Biological Constraints and Influence of Experience* (pp. 1–21). Norwood, NJ: Ablex.

Colombo, J. (2001). The development of visual attention in infancy. *Annual Review of Psychology*, *52*, 337–367.

Crone, E. A. (2009). Executive functions in adolescence: inferences from brain and behavior. *Developmental Science*, *12*(6), 825–830. http://doi.org/10.1111/j.1467-7687.2009.00918.x

Csibra, G., Johnson, M. H., & Tucker, L. A. (1997). Attention and oculomotor control: a high-density ERP study of the gap effect. *Neuropsychologia*, *35*(6), 855–865.

Dannemiller, J. L. (2000). Competition in early exogenous orienting between 7 and 21 weeks. *Journal of Experimental Child Psychology*, *76*(4), 253–274.

Dannemiller, J. L. (2005). Motion popout in selective visual orienting at 4.5 but not at 2 months in human infants. *Infancy*, *8*, 201–216.

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience*, *18*, 193–222.

Di Martino, A., Fair, D. A., Kelly, C., Satterthwaite, T. D., Castellanos, F. X., Thomason, M. E., . . . Milham, M. P. (2014). Unraveling the miswired connectome: a developmental perspective. *Neuron*, *83*(6), 1335–1353. http://doi.org/10.1016/j.neuron.2014.08.050

Donnelly, N., Cave, K., Greenway, R., Hadwin, J. A, Stevenson, J., & Sonuga-Barke, E. (2007). Visual search in children and adults: top-down and bottom-up mechanisms. *Quarterly Journal of Experimental Psychology*, *60*(1), 120–136. http://doi.org/10.1080/17470210600625362

Egly, R., Driver, J., & Rafal, R. D. (1994). Shifting visual attention between objects and locations: evidence from normal and parietal lesion subjects. *Journal of Experimental Psychology: General*, *123*(2), 161–177. http://doi.org/10.1037/0096-3445.123.2.161

Elison, J. T., Paterson, S. J., Wolff, J. J., Reznick, J. S., Sasson, N. J., Gu, H., . . . Piven, J. (2013). White matter microstructure and atypical visual orienting in 7-month-olds at risk for autism. *American Journal of Psychiatry*, *170*(8), 899–908. http://doi.org/10.1176/appi.ajp.2012.12091150

Elsabbagh, M., Volein, A., Holmboe, K., Tucker, L., Csibra, G., Baron-Cohen, S., . . . Johnson, M. H. (2009). Visual orienting in the early broader autism phenotype: disengagement and facilitation. *Journal of Child Psychology and Psychiatry*, *50*(5), 637–642. doi:10.1111/j.1469-7610.2008.02051.x

Emberson, L. L., & Amso, D. (2012). Learning to sample: eye tracking and fMRI indices of changes in object perception. *Journal of Cognitive Neuroscience*, *24*(2006), 2030–2042. http://doi.org/10.1162/jocn_a_00259

Enns, J. T., & Brodeur, D. A. (1989). A developmental study of covert orienting to peripheral visual cues. *Journal of Experimental Child Psychology*, *48*(2), 171–189. http://doi.org/10.1016/0022-0965(89)90001-5

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics*, *16*(1), 143–149. http://doi.org/10.3758/BF03203267

Fan, J., McCandliss, B. D., Fossella, J., Flombaum, J. I., & Posner, M. I. (2005). The activation of attentional networks. *NeuroImage*, *26*(2), 471–479. http://doi.org/10.1016/j.neuroimage.2005.02.004

Fan, J., McCandliss, B. D., Sommer, T., Raz, A., & Posner, M. I. (2002). Testing the efficiency and independence of attentional networks. *Journal of Cognitive Neuroscience*, *14*(3), 340–347. http://doi.org/10.1162/089892902317361886

Fantz, R. L., & Nevis, S. (1967). Pattern preferences and perceptual-cognitive development in early infancy. *Merrill Palmer Quarterly: Journal of Developmental Psychology*, *13*(1), 77–108.

Ferreri, L., Bigand, E., Perrey, S., & Bugaiska, A. (2014). The promise of Near-Infrared Spectroscopy (NIRS) for psychological research: a brief review. *L’Année psychologique*, *114*(3), 537–569. http://doi.org/10.4074/S0003503314003054

Fisher, A., Thiessen, E., Godwin, K., Kloos, H., & Dickerson, J. (2013). Assessing selective sustained attention in 3- to 5-year-old children: evidence from a new paradigm. *Journal of Experimental Child Psychology*, *114*(2), 275–294. http://doi.org/10.1016/j.jecp.2012.07.006

Folk, C. L., Remington, R. W., & Johnson, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 1030–1044.

Franchak, J. M., & Adolph, K. E. (2010). Visually guided navigation: Head-mounted eye-tracking of natural locomotion in children and adults. *Vision Research*, *50*(24), 2766–2774. http://doi.org/10.1016/j.visres.2010.09.024

Franchak, J. M., Kretch, K. S., Soska, K. C., & Adolph, K. E. (2011). Head-mounted eye tracking: a new method to describe infant looking. *Child Development*, *82*(6), 1738–50. http://doi.org/10.1111/j.1467-8624.2011.01670.x

Frank, M. C., Amso, D., & Johnson, S. P. (2014). Visual search and attention to faces during early infancy. *Journal of Experimental Child Psychology*, *118*, 13–26. http://doi.org/10.1016/j.jecp.2013.08.012

Gerhardstein, P., & Rovee-Collier, C. (2002). The development of visual search in infants and very young children. *Journal of Experimental Child Psychology*, *81*(2), 194–215. http://doi.org/10.1006/jecp.2001.2649

Gibson, E. J. (1988). Exploratory behavior in the development of perceiving, acting, and the acquiring of knowledge. *Annual Review of Psychology*, *39*(1), 1–41.

Gliga, T., Bedford, R., Charman, T., & Johnson, M. H. (2015). Enhanced visual search in infancy predicts emerging autism symptoms. *Current Biology*, *25*(13), 1727–1730. http://doi.org/10.1016/j.cub.2015.05.011

Goldberg, M. C., Maurer, D., & Lewis, T. L. (2001). Developmental changes in attention: the effects of endogenous cueing and of distractors. *Developmental Science*, *4*, 209–219. http://doi.org/10.1111/1467-7687.00166

Gredebäck, G., Johnson, S. P., & von Hofsten, C. (2010). Eye tracking in infancy research. *Developmental Neuropsychology*, *35*(1), 1–19. http://doi.org/10.1080/87565640903325758

Guitton, D., Buchtel, H. A., & Douglas, R. M. (1985). Frontal lobe lesions in man cause difficulties in suppressing reflexive glances and in generating goal-directed saccades. *Experimental Brain Research*, *58*(3), 455–472. http://doi.org/10.1007/BF00235863

Günther, T., Konrad, K., Häusler, J., Saghraoui, H., Willmes, K., & Sturm, W. (2014). Developmental differences in visual and auditory attention: A cross-sectional study. *Zeitschrift für Neuropsychologie*,, *25*(3), 143–152. http://doi.org/10.1024/1016-264X/a000126

Hills, P. J., Cooper, R. E., & Pake, J. M. (2013). Removing the own-race bias in face recognition by attentional shift using fixation crosses to diagnostic features: an eye-tracking study. *Visual Cognition*, *21*, 876–898.

Hoffman, J. E., & Subramaniam, B. (1995). The role of visual attention in saccadic eye movements. *Perception & Psychophysics*, *57*(6), 787–795.

Holmboe, K., Elsabbagh, M., Volein, A., Tucker, L. A., Baron-Cohen, S., Bolton, P., . . . Johnson, M. H. (2010a). Frontal cortex functioning in the infant broader autism phenotype. *Infant Behavior & Development*, *33*(4), 482–491. http://doi.org/10.1016/j.infbeh.2010.05.004

Holmboe, K., Nemoda, Z., Fearon, R. M. P., Csibra, G., Sasvari-Szekely, M., & Johnson, M. H. (2010b). Polymorphisms in dopamine system genes are associated with individual differences in attention in infancy. *Developmental Psychology*, *46*(2), 404–416. http://doi.org/10.1037/a0018180

Holmboe, K., Pasco Fearon, R. M., Csibra, G., Tucker, L. A., & Johnson, M. H. (2008). Freeze-frame: a new infant inhibition task and its relation to frontal cortex tasks during infancy and early childhood. *Journal of Experimental Child Psychology*, *100*(2), 89–114. http://doi.org/10.1016/j.jecp.2007.09.004

Hood, B. M., & Atkinson, J. (1993). Disengaging visual attention in the infant and adult. *Infant Behavior and Development*, *16*(4), 405–422.

Hopf, J. M., Luck, S. J., Girelli, M., Hagner, T., Mangun, G. R., Scheich, H., & Heinze, H. J. (2000). Neural sources of focused attention in visual search. *Cerebral Cortex*, *10*(12), 1233–1241.

Hurley, K. B., & Oakes, L. M. (2015). Experience and distribution of attention: pet exposure and infants' scanning of animal images. *Journal of Cognition and Development*, *16*(1), 11–30. http://doi.org/10.1080/15248372.2013.833922

Hutchinson, E. A., De Luca, C. R., Doyle, L. W., Roberts, G., & Anderson, P. J. (2013). School-age outcomes of extremely preterm or extremely low birth weight children. *Pediatrics*, *131*(4), e1053–e1061. http://doi.org/10.1542/peds.2012-2311

Hwang, K., Velanova, K., & Luna, B. (2010). Strengthening of top-down frontal cognitive control networks underlying the development of inhibitory control: a functional magnetic resonance imaging effective connectivity study. *Journal of Neuroscience*, *30*(46), 15535–15545. http://doi.org/10.1523/JNEUROSCI.2825-10.2010

Johnson, M. H. (1995). The inhibition of automatic saccades in early infancy. *Developmental Psychobiology*, *28*(5), 281–291. http://doi.org/10.1002/dev.420280504

Johnson, M. H. (2000). Functional brain development in infants: elements of an interactive specialization framework. *Child Development*, *71*(1), 75–81. http://doi.org/http://dx.doi.org/10.1111/1467-8624.00120

Johnson, M. H., Posner, M. I., & Rothbart, M. K. (1994). Facilitation of saccades toward a covertly attended location in early infancy. *Psychological Science*, *5*(2), 90–92. http://doi.org/10.1111/j.1467-9280.1994.tb00636.x

Johnson, S. P., Slemmer, J. A., & Amso, D. (2004). Where infants look determines how they see: eye movements and object perception performance in 3-month-olds. *Infancy*, *6*(2), 185–201. http://doi.org/10.1207/s15327078in0602_3

Jones, W., & Klin, A. (2013). Attention to eyes is present but in decline in 2–6-month-old infants later diagnosed with autism. *Nature*, *504*(7480), 427–431. http://doi.org/10.1038/nature12715

Klein, R. M. (2000). Inhibition of return. *Trends in Cognitive Sciences*, *4*(4), 138–147.

Konrad, K., Neufang, S., Thiel, C. M., Specht, K., Hanisch, C., Fan, J., . . . Fink, G. R. (2005). Development of attentional networks: an fMRI study with children and adults. *NeuroImage*, *28*(2), 429–439.

Kovack-Lesh, K. A., McMurray, B., & Oakes, L. M. (2014). Four-month-old infants' visual investigation of cats and dogs: relations with pet experience and attentional strategy. *Developmental Psychology*, *50*(2), 402–413. http://doi.org/10.1037/a0033195

Kretch, K. S., Franchak, J. M., & Adolph, K. E. (2014). Crawling and walking infants see the world differently. *Child Development*, *85*(4), 1503–1518. http://doi.org/10.1111/cdev.12206

Kwon, M.-K., Setoodehnia, M., Baek, J., Luck, S. J., & Oakes, L. M. (2016). The development of visual search in infancy: attention to faces salience. *Developmental Psychology*, *52*(4), 537–555. doi:10.1037/dev0000080

Lavie, N., Hirst, A., de Fockert, J. W., & Viding, E. (2004). Load theory of selective attention and cognitive control. *Journal of Experimental Psychology: General*, *133*(3), 339–354. http://doi.org/10.1037/0096-3445.133.3.339

Lorch, E. P., Anderson, D. R., & Levin, S. R. (1979). The relationship of visual attention to children's comprehension of television. *Child Development*, *50*(3), 722–727. http://doi.org/10.1111/j.1467-8624.1979.tb02420.x

Lorch, E. P., & Castle, V. J. (1997). Preschool children's attention to television: visual attention and probe response times. *Journal of Experimental Child Psychology*, *66*, 111–127. http://doi.org/10.1006/jecp.1997.2372

Luck, S. J. (2014). *An Introduction to the Event-Related Potential Technique*. Cambridge, MA: MIT Press.

Luck, S. J., & Vecera, S. P. (2002). Attention. In H. Pashler & S. Yantis (Eds.), *Steven's Handbook of Experimental Psychology (3rd ed.), Vol. 1: Sensation and Perception* (pp. 235–286). Hoboken, NJ: Wiley.

Luna, B., Garver, K. E., Urban, T. A., Lazar, N. A., & Sweeney, J. A. (2004). Maturation of cognitive processes from late childhood to adulthood. *Child Development*, *75*(5), 1357–1372. http://doi.org/10.1111/j.1467-8624.2004.00745.x

Markant, J., & Amso, D. (2013). Selective memories: infants' encoding is enhanced in selection via suppression. *Developmental Science*, *16*(6), 926–940. http://doi.org/10.1111/desc.12084

Markant, J., & Amso, D. (2014). Leveling the playing field: attention mitigates the effects of intelligence on memory. *Cognition*, *131*(2), 195–204. http://doi.org/10.1016/j.cognition.2014.01.006

Markant, J., & Amso, D. (2015). The development of selective attention orienting is an agent of change in learning and memory efficacy. *Infancy*, *21*(2), 154–176. http://doi.org/10.1111/infa.12100

Markant, J., Oakes, L. M., & Amso, D. (2015). Visual selective attention biases contribute to the other-race effect among 9-month-old infants. *Developmental Psychobiology*, *58*(3), 355–365. http://doi.org/10.1002/dev.21375

Markant, J., Worden, M. S., & Amso, D. (2015). Not all attention orienting is created equal:

recognition memory is enhanced when attention orienting involves distractor suppression. *Neurobiology of Learning and Memory*, *120*, 28–40. http://doi.org/10.1016/j.nlm.2015.02.006

McDermott, J. M., Pérez-Edgar, K., & Fox, N. A. (2007). Variations of the flanker paradigm: assessing selective attention in young children. *Behavior Research Methods*, *39*(1), 62–70. http://doi.org/10.3758/BF03192844

Nakagawa, A., & Sukigara, M. (2007). Infant eye and head movements toward the side opposite the cue in the anti-saccade paradigm. *Behavioral and Brain Functions*, *3*, 5. http://doi.org/10.1186/1744-9081-3-5

Oakes, L. M., Baumgartner, H. A., Barrett, F. S., Messenger, I. M., & Luck, S. J. (2013). Developmental changes in visual short-term memory in infancy: Evidence from eye-tracking. *Frontiers in Psychology*, *4* (October). http://doi.org/10.3389/fpsyg.2013.00697

Oakes, L. M., Kannass, K. N. K. N., & Shaddy, D. J. J. (2002). Developmental changes in endogenous control of attention: the role of target familiarity on infants' distraction latency. *Child Development*, *73*(6), 1644–1655. http://doi.org/http://dx.doi.org/10.1111/1467-8624.00496

Oakes, L. M., Ross-Sheehy, S., & Kannass, K. N. (2004). Attentional engagement in infancy: the interactive influence of attentional inertia and attentional state. *Infancy*, *5*(2), 239–252. http://doi.org/10.1207/s15327078in0502_8

Peltola, M. J., Leppänen, J. M., Palokangas, T., & Hietanen, J. K. (2008). Fearful faces modulate looking duration and attention disengagement in 7-month-old infants. *Developmental Science*, *11*(1), 60–68. http://doi.org/10.1111/j.1467-7687.2007.00659.x

Petersen, S. S. E., & Posner, M. I. (2012). The attention system of the human brain: 20 years after. *Annual Review of Neuroscience*, *35*, 73–89. http://doi.org/10.1146/annurev-neuro-062111-150525

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, *32*, 3–25. http://doi.org/10.1080/00335558008248231

Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. *Annual Review of Neuroscience*, *13*, 25–42. http://doi.org/10.1146/annurev.ne.13.030190.000325

Posner, M. I., & Rothbart, M. K. (2009). Toward a physical basis of attention and self-regulation. *Physics of Life Reviews*, *6*(2), 103–120. http://doi.org/10.1016/j.plrev.2009.02.001

Powers, M. K., Schneck, M., & Teller, D. Y. (1981). Spectral sensitivity of human infants at absolute visual threshold. *Vision Research. 21*(7), 1005–1016.

Pruett, J. R., Kandala, S., Hoertel, S., Snyder, A. Z., Elison, J. T., Nishino, T., . . . Piven, J. (2015). Accurate age classification of 6- and 12-month-old infants based on resting-state functional connectivity magnetic resonance imaging data. *Developmental Cognitive Neuroscience*, *12*, 123–133. http://doi.org/10.1016/j.dcn.2015.01.003

Qiu, A., Mori, S., & Miller, M. I. (2015). Diffusion tensor imaging for understanding brain development in early life. *Annual Review of Psychology*, *66*, 853–876. http://doi.org/10.1146/annurev-psych-010814-015340

Quinn, P. C., & Bhatt, R. (1998). Visual pop-out in young infants: convergent evidence and an extension. *Infant Behavior and Development*, *21*(2), 273–288.

Reynolds, G. D., Guy, M. W., & Zhang, D. (2010). Neural correlates of individual differences in infant visual attention and recognition memory. *Infancy*, *16*(4), 368–391.

Reynolds, G. D., & Richards, J. E. (2009). Cortical source localization of infant cognition. *Developmental Neuropsychology*, *34*(3), 312–329.

Richards, J. E. (1989). Development and stability in visual sustained attention in 14-, 20-, and 26-week-old infants. *Psychophysiology*, *26*(4), 422–430.

Richards, J. E. (2000). Localizing the development of covert attention in infants with scalp event-related potentials. *Developmental Psychology*, *36*(1), 91–108. http://doi.org/10.1037/0012-1649.36.1.91

Richards, J. E. (2001). Cortical indexes of saccade planning following covert orienting in

20-week-old infants. *Infancy*, *2*(2), 135–157. doi:10.1207/S15327078IN0202_2

Richards, J. E. (2005). Localizing cortical sources of event-related potentials in infants' covert orienting. *Developmental Science*, *8*(3), 255–278.

Richards, J. E., & Anderson, D. R. (2004). Attentional inertia in children's extended looking at television. *Advances in Child Development and Behavior*, *32*(C), 163–212. http://doi.org/10.1016/S0065-2407(04)80007-7

Richards, J. E., & Casey, B. J. (1992). Development of sustained visual attention in the human infant. In B. A. Campbell, H. Hayne, & R. Richardson (Eds.), *Attention and information processing in infants and adults: Perspectives from human and animal research* (pp. 30–60). Hillsdale, NJ: Erlbaum.

Richards, J. E., & Cronise, K. (2000). Extended visual fixation in the early preschool years: look duration, heart rate changes, and attentional inertia. *Child Development*, *71*(3), 602–620. http://doi.org/10.1111/1467-8624.00170

Richards, J. E., & Gibson, T. L. (1997). Extended visual fixation in young infants: look distributions, heart rate changes, and attention. *Child Development*, *68*(6), 1041–1056. http://doi.org/10.2307/1132290

Rosander, K. (2007). Visual tracking and its relationship to cortical development. *Progress in Brain Research*, *164*, 105–22. http://doi.org/10.1016/S0079-6123(07)64006-0

Ross-Sheehy, S., Oakes, L. M., & Luck, S. J. (2003). The development of visual short-term memory capacity in infants. *Child Development*, *74*(6), 1807–1822. http://doi.org/10.1046/j.1467-8624.2003.00639.x

Ross-Sheehy, S., Oakes, L. M., & Luck, S. J. (2011). Exogenous attention influences visual short-term memory in infants. *Developmental Science*, *14*(3), 490–501. http://doi.org/10.1111/j.1467-7687.2010.00992.x

Ross-Sheehy, S., Schneegans, S., & Spencer, J. P. (2015). The infant orienting with attention task: assessing the neural basis of spatial attention in infancy. *Infancy*, *20*(5), 467–506. http://doi.org/10.1111/infa.12087

Rovee-Collier, C., Hankins, E., & Bhatt, R. (1992). Textons, visual pop-out effects, and object recognition in infancy. *Journal of Experimental Psychology: General*, *121*(4), 435–445.

Rueda, M. R., Fan, J., McCandliss, B. D., Halparin, J. D., Gruber, D. B., Lercari, L. P., & Posner, M. I. (2004). Development of attentional networks in childhood. *Neuropsychologia*, *42*(8), 1029–1040. http://doi.org/10.1016/j.neuropsychologia.2003.12.012

Rueda, M. R., Posner, M. I., & Rothbart, M. K. (2005). The development of executive attention: contributions to the emergence of self-regulation. *Developmental Neuropsychology*, *28*(2), 573–594.

Rueda, M. R., Rothbart, M. K., McCandliss, B. D., Saccomanno, L., & Posner, M. I. (2005). Training, maturation, and genetic influences on the development of executive attention. *Proceedings of the National Academy of Sciences of the United States of America*, *102*(41), 14931–14936.

Ruff, H. A., & Capozzoli, M. C. (2003). Development of attention and distractibility in the first 4 years of life. *Developmental Psychology*, *39*(5), 877–890. http://doi.org/10.1037/0012-1649.39.5.877

Ruff, H. A., Capozzoli, M., & Weissberg, R. (1998). Age, individuality, and context as factors in sustained visual attention during the preschool years. *Developmental Psychology*, *34*(3), 454–64. http://doi.org/10.1037/0012-1649.34.3.454

Ruff, H. A., & Rothbart, M. K. (1996). *Attention in Early Development*. New York, NY: Oxford University Press.

Scerif, G., Cornish, K., Wilding, J., Driver, J., & Karmiloff-Smith, A. (2004). Visual search in typically developing toddlers and toddlers with Fragile X or Williams syndrome. *Developmental Science*, *7*(1), 116–130. http://doi.org/10.1111/j.1467-7687.2004.00327.x

Scerif, G., Karmiloff-Smith, A., Campos, R., Elsabbagh, M., Driver, J., & Cornish, K. (2005). To look or not to look? Typical and atypical development of oculomotor control. *Journal of Cognitive Neuroscience*, *17*(4), 591–604.

Schlesinger, M., Amso, D., & Johnson, S. P. (2007). The neural basis for visual selective attention in young infants: a computational account. *Adaptive Behavior*, *15*(2), 135–148. doi: https://doi.org/10.1177/1059712307078661

Schlesinger, M., Amso, D., & Johnson, S. P. (2012). Simulating the role of visual selective attention during the development of perceptual completion. *Developmental Science*, *15*(6), 739–752. http://doi.org/10.1111/j.1467-7687.2012.01177.x

Sheese, B. E., Rothbart, M. K., Posner, M. I., White, L. K., & Fraundorf, S. H. (2008). Executive attention and self-regulation in infancy. *Infant Behavior & Development*, *31*(3), 501–510. http://doi.org/10.1016/j.infbeh.2008.02.001

Simion, F., Valenza, E., Umiltà, C., & Barba, B. D. (1995). Inhibition of return in newborns is temporo-nasal asymmetrical. *Infant Behavior and Development*, *18*(2), 189–194.

Smith, N. A., & Trainor, L. J. (2011). Auditory stream segregation improves infants' selective attention to target tones amid distracters. *Infancy*, *16*(6), 655–668. http://doi.org/10.1111/j.1532-7078.2011.00067.x

Sporns, O. (2013). The human connectome: origins and challenges. *NeuroImage*, *80*, 53–61. http://doi.org/10.1016/j.neuroimage.2013.03.023

Stechler, G., & Latz, E. (1966). Some observations on attention and arousal in the human infant. *Journal of the American Academy of Child Psychiatry*, *5*(3), 517–525. http://doi.org/10.1016/S0002-7138(09)62098-7

Stjerna, S., Sairanen, V., Grohn, R., Andersson, S., Metsaranta, M., Lano, A., & Vanhatalo, S. (2015). Visual fixation in human newborns correlates with extensive white matter networks and predicts long-term neurocognitive development. *Journal of Neuroscience*, *35*(12), 4824–4829. http://doi.org/10.1523/JNEUROSCI.5162-14.2015

Sugden, N. A., Mohamed-Ali, M. I., & Moulson, M. C. (2014). I spy with my little eye: typical, daily exposure to faces documented from a first-person infant perspective. *Developmental Psychobiology*, *56*, 249–261. http://doi.org/10.1002/dev.21183

Teller, D. Y. (1979). The forced-choice preferential looking procedure: a psychophysical technique for use with human infants. *Infant Behavior and Development*, *2*(1962), 135–153. http://doi.org/10.1016/S0163-6383(79)80016-8

Theeuwes, J., Kramer, A. F., Hahn, S., Irwin, D. E., & Zelinsky, G. J. (1999). Influence of attentional capture on oculomotor control. *Journal of Experimental Psychology: Human Perception and Performance*, *25*(6), 1595–1608. http://doi.org/10.1037/0096-1523.25.6.1595

Treisman, A. M. (1998). Feature binding, attention and object perception. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, *353*(1373), 1295–1306.

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*(1), 97–136.

Trick, L. M., & Enns, J. T. (1998). Lifespan changes in attention: the visual search task. *Cognitive Development*, *13*(3), 369–386.

Ungerleider, L. G., & Pessosa, L. (2008). What and where pathways. *Scholarpedia*, *2*, 5342.

Urakawa, S., Takamoto, K., Ishikawa, A., Ono, T., & Nishijo, H. (2015). Selective medial prefrontal cortex responses during live mutual gaze interactions in human infants: an fNIRS study. *Brain Topography*, *28*(5), 691–701. http://doi.org/10.1007/s10548-014-0414-2

Valenza, E., Franchin, L., & Bulf, H. (2014). How a face may affect object-based attention: evidence from adults and 8-month-old infants. *Frontiers in Integrative Neuroscience*, *8*(March), 1–10. http://doi.org/10.3389/fnint.2014.00027

Valenza, E., Simion, F., & Umiltà, C. (1994). Inhibition of return in newborn infants. *Infant Behavior and Development*, *17*(3), 293–302. https://doi.org/10.1016/0163-6383(94)90009-4

Varga, K., Frick, J. E., Kapa, L. L., & Dengler, M. J. (2010). Developmental changes in inhibition of return from 3 to 6 months of age. *Infant Behavior and Development*, *33*(2), 245–249. doi:10.1016/j.infbeh.2009.12.011

von Hofsten, C. (2004). An action perspective on motor development. *Trends in Cognitive Sciences*, *8*(6), 266–72. http://doi.org/10.1016/j.tics.2004.04.002

Wass, S., Porayska-Pomsta, K., & Johnson, M. H. (2011). Training attentional control in infancy. *Current Biology*, *21*(18), 1543–1547. http://doi.org/10.1016/j.cub.2011.08.004

Waszak, F., Li, S.-C., & Hommel, B. (2010). The development of attentional networks: cross-sectional findings from a life span sample. *Developmental Psychology*, *46*(2), 337–349. http://doi.org/10.1037/a0018541

Wattam-Bell, J. (2001). The effect of contrast on vertical motion processing asymmetries in 11-week-old infants. *Perception*, *30*(2), 159–166. http://doi.org/10.1068/p3098

Wheeler, A., Anzures, G., Quinn, P. C., Pascalis, O., Omrin, D. S., & Lee, K. (2011). Caucasian infants scan own- and other-race faces differently. *PLoS ONE*, *6*(4), e18621. http://doi.org/10.1371/journal.pone.0018621

Xiao, W. S., Quinn, P. C., Pascalis, O., & Lee, K. (2014). Own- and other-race face scanning in infants: implications for perceptual narrowing. *Developmental Psychobiology*, *56*(2), 262–273.

Xiao, W. S., Xiao, N. G., Quinn, P. C., Anzures, G., & Lee, K. (2013). Development of face scanning for own- and other-race faces in infancy. *International Journal of Behavioral Development*, *37*(2), 100–105. http://doi.org/10.1177/0165025412467584

Yu, C., & Smith, L. B. (2011). What you learn is what you see: using eye movements to study infant cross-situational word learning. *Developmental Science*, *14*(2), 165–180. http://doi.org/10.1111/j.1467-7687.2010.00958.x

Yu, C., & Smith, L. B. (2013). Joint attention without gaze following: human infants and their parents coordinate visual attention to objects through eye-hand coordination. *PLoS ONE*, *8*(11), e79659. http://doi.org/10.1371/journal.pone.0079659

Zelazo, P. D., Anderson, J. E., Richler, J., Wallner-Allen, K., Beaumont, J. L., & Weintraub, S. (2013). II. NIH Toolbox cognition battery (CB): Measuring executive function and attention. *Monographs of the Society for Research in Child Development*, *78*(4), 16–33. http://doi.org/10.1111/mono.12032

Zhang, Y., Meyers, E. M., Bichot, N. P., Serre, T., Poggio, T. A., & Desimone, R. (2011). Object decoding with attention in inferior temporal cortex. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(21), 8850–8855. http://doi.org/10.1073/pnas.1100999108