

Early development of visual attention: Change, stability, and longitudinal associations.

Running title: Early development of visual attention

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Abstract

Visual attention is a basic mechanism of information gathering and environment selection, and consequently plays a fundamental role in influencing developmental trajectories. Here, we highlight evidence for predictive associations from early visual attention to emotion regulation, Executive Function, language and broader cognitive ability, mathematics and literacy skills, and neurodevelopmental conditions. Development of visual attention is also multifaceted and non-linear. In daily life, core functions such as orienting, selective filtering and processing of visual inputs are intertwined, and influenced by multiple other cognitive components. Further, the demands of an attention task vary according to the experience, motivation, cognitive, and physical constraints of participants, whilst the mechanisms underlying performance may change with development. Thus, markers of attention may need to be interpreted differently across development, and between populations. We summarise research that has combined multiple measurements and techniques to further our understanding of visual attention development, and highlight possibilities for the future.

Introduction

While the development of visual attention can be studied like any other domain of cognition, it is arguably of fundamental importance due to its role in influencing developmental trajectories. This is because it is a basic mechanism of information gathering and environment selection, and this selection influences development across a variety of cognitive domains. In other words, attention towards a particular class of stimuli determines the targets for subsequent learning. Thus visual attention research has potential to make meaningful contributions to education, economic, and public health policy, by informing our understanding of early visual attention's role in typical and atypical development, and as a target for future interventions.

Attention as a construct comprises multiple functions and processes. We have structured this review in terms of four functions considered to be particularly important in early development: orienting towards and away from objects; selective filtering of visual inputs; processing visual inputs; and maintaining focus on a target – but it should be noted firstly that this is by no means an exhaustive list, and secondly that in day-to-day life these functions are often closely intertwined. As summarised in Table 1, performance on marker tasks for even these relatively basic functions are linked in the literature to multiple cognitive components.

Drawing on longitudinal data, we show that the interpretation of performance and underlying processes on putative marker tasks for these different attentional functions during the first few years of life often needs to change with development. These data are drawn from studies of both typically- and atypically-developing populations. Not only is understanding development key to understanding developmental disorders (Karmiloff-Smith 1998),

mapping the trajectories and consequences of atypical attention development can give us insights into these developmental mechanisms more broadly.

[INSERT TABLE 1 HERE]

Orienting towards and away from objects at various spatial locations

The first topic of focus for this review is the ability to orient towards and away from objects, people or visual cues at various spatial locations (henceforth, spatial orienting). Spatial orienting has substantial impact on what we take in about the world. The transition from relatively inflexible and sluggish attention to a system that is fully responsive to new stimuli entering the visual field is a key development in early visual attention. As we discuss below, individual differences in this basic function may be implicated in a cascade of developmental effects.

Gap/Overlap task performance as a marker of orienting and disengagement

A classic marker task for the ability to disengage visual attention from one location, in order to shift it to another, is the Gap/Overlap task. In the Gap/Overlap task the latency to orient toward a peripheral target from a central fixation stimulus is measured in two key conditions: Gap (the central stimulus disappears before the peripheral target appears); and Overlap (the peripheral target appears whilst the central stimulus remains on display, thus incurring competition). Even amongst adults, orientation to the peripheral target is faster on Gap trials than Overlap trials (Fischer & Weber 1993), but these effects are particularly marked in infancy. During the Overlap condition, 1½ - to 2-month-olds are slow to disengage from the central stimulus in order to fixate the peripheral target and sometimes do so only once the central stimulus has disappeared from the screen (Hood & Atkinson 1993, McConnell &

Bryson 2005). Newborns, too, are faster to look to a peripheral target during Gap versus Overlap conditions; however newborns show a smaller difference between conditions than at 1-2 months (Farroni et al 1999). By 3-4 months of age, typically-developing infants are able to disengage from a central stimulus to orient to a competing peripheral stimulus relatively easily, albeit slower than in Gap trials (Holmboe et al 2018, Johnson et al 1991b). A longitudinal study between ages 6 and 26 weeks, amongst infants born full- and pre-term, shows that the most rapid reduction in latency to fixate the peripheral stimulus during Overlap trials occurs between 10-14 weeks of age (Hitzert et al 2015).

Early developmental changes in Gap/Overlap performance have been attributed to developments in cortical and subcortical visual systems. From birth, saccade production is believed to be mainly controlled by the superior colliculus, but by 1 month of age, when the baby is fixating a central stimulus, inhibition by the substantia nigra may prevent the superior colliculus from initiating a saccade to a peripheral stimulus (Farroni et al 1999, Johnson 1990). From around 1 month of age, increasing cortical control over saccades contributes to reductions in disengagement latencies. By 3-4 months of age, saccade generation is likely influenced by the frontal eye fields along with other higher cortical areas such as the parietal cortex (Johnson 1990, Johnson 1995). Throughout development, it is also likely that phasic alerting plays a role in Gap/Overlap performance. The disappearance of the central stimulus in the Gap condition is a spatially-nonspecific alerting cue which helps the participant to prepare to make a saccadic response: When spatially non-predictive audio cues are added to Overlap trials, saccadic reactions are facilitated (i.e., reaction times are reduced) for children and adults (Kleberg et al 2017), as well as for infants (Nakagawa & Sukigara 2019).

However, Overlap latencies do not necessarily decrease steadily with the development of cortical control. Nakagawa and Sukigara (2019) have reported that 12-month-olds respond slower than 6-month-olds on both Gap and Overlap trials. By 18 and 24 months, longer latencies to shift to peripheral targets in the Overlap condition are associated with higher concurrent parent-reported regulatory abilities (operationalised as ‘effortful control’; a composite of attentional and impulse control, low intensity pleasure and cuddliness scores) – and longer latencies at 24 months are predictive of higher effortful control a year later (Nakagawa & Sukigara 2013). This would seem to indicate that for toddlers the most adaptive response in the Gap/Overlap task is sustained processing of the central target, such that at this age the task may be most sensitive to variation in executive attention; specifically, the ability to *inhibit* orienting to a peripheral distractor, as discussed further in the section on Maintaining attentional focus. These findings illustrate a point we return to throughout this review; that developmental change involves interactions between multiple systems and is frequently non-linear as new processes mature.

Gap/Overlap task performance and concurrent emotion regulation

Individual differences in latencies to shift attention during infancy appear to be concurrently associated with the ability to regulate emotion. An initial finding that 4-month-olds better able to disengage during Overlap trials were less susceptible to distress and more easily soothed (Johnson et al 1991b) was not replicated in two cohorts of similar-aged infants (Holmboe 2008, McConnell & Bryson 2005). However, saccadic reaction times in the Gap (and to a lesser extent the Overlap) conditions were positively associated with parent-reported fear amongst 4-month-olds (Holmboe 2008, McConnell & Bryson 2005). Longer latencies to disengage during Overlap trials at 6 months of age have been associated with greater parent-reported distress and less smiling (McConnell & Bryson 2005) and with less

soothability (Nakagawa & Sukigara 2019). Longer latencies to disengage during Overlap trials at 12 months are associated with lower concurrent parent report of an orienting-regulation composite that includes report of cuddliness and soothability (Nakagawa & Sukigara 2013). In a sample of 12-month-olds with and without a familial history of autism, longer latencies to disengage to the left specifically are associated with high concurrent parent report of distress to limitations and difficulty to soothe (Bryson et al 2017). These findings appear to indicate that Gap/Overlap performance in the first year of life indexes – at least in part – an orienting system that is implicated in infant state regulation (Rothbart et al 2011). However, to reach a clear consensus on the generalisability and robustness of these associations, the field would benefit from adoption of more-consistent methodology in the collection and interpretation of disengagement data.

Longitudinal correlates of Gap/Overlap task performance

Individual differences in spatial orienting ability in infancy are associated with later cognitive function, but the specificity of associations to later attentional and regulatory processes versus general cognitive ability may change with development, and with certain risk factors such as pre-term birth. In a sample of infants born full-term, poorer disengagement ability at 4 months is associated with lower performance on the Mullen Scales of Early Learning – a standardised test of general cognitive development – at 9 months, but does not associate with performance at 9 months on either the Freeze-Frame or A-not-B tasks (two different measures of executive attention) (Holmboe et al 2018). Further, neither effortful control (measured through a composite of parent report and performance on a delay of gratification task) nor compliance during a tidy-up task at 28 months are predicted by the size of the Gap effect amongst full-term 10-month-olds (Geeraerts et al 2019).

Since the outcome measures in the studies summarised above are considered to rely in part on the executive attention system (Hendry et al 2016), these data do not support the argument that early orienting processes underpin later development of the executive attention system. Yet, in a cohort of pre-term and full-term infants, a slower decrease in latency to disengage between 10 and 26 weeks in the Overlap condition is predictive of poorer performance on a measure of executive attention ability at age 9-11 years (the Opposite Worlds inhibitory control task) (Hitzert et al 2014). Previously it was observed that, as a group, pre-term infants tend to show faster development of attentional disengagement compared with full-term infants of equivalent gestational age – a phenomenon thought to be linked to their additional visual experience (Hunnius et al 2008). Hitzert et al (2014) went on to show however that the pre-terms who benefit least from their additional visual exposure have the lowest executive attention scores at school age. This preliminary evidence of an association between early orienting and later executive processes merits further research, and illustrates the importance of taking a longitudinal individual differences approach to research with clinical populations.

Gap/Overlap task performance and autism

A developmental individual differences approach may be particularly fruitful in research with infants with a familial history of autism. Autism is a notoriously heterogeneous condition, likely involving multiple interacting causal and moderating factors (Happé et al 2006). Extant research indicates that spatial orienting may be one such factor, but that atypicalities in this function may become apparent only at certain points in development, and in conjunction with only certain types of visual stimuli. For example, siblings of autistic children who are later diagnosed with autism themselves tend (at the group level) to show prolonged disengagement latencies on Overlap trials featuring repeating, dynamic non-social stimuli at age 12- to 14-

months, compared with peers with a similar familial history of autism who do not receive a diagnosis by age 3 years (Bryson et al 2017, Elsabbagh et al 2013, Zwaigenbaum et al 2005). Elison et al (2013) report longer Overlap latencies at 7 months of age for infants later showing elevated autism traits, when static images of faces and objects that varied across trials were used. In contrast, Fischer et al. (2016) also used static images of faces and objects and found no group differences between autistic 21- to 37-month-olds and age-matched typically-developing controls with regards to disengagement cost. To date, Gap/Overlap performance has been studied predominantly in terms of associations with the core autism phenotype, and it has been observed that disengagement difficulties are additive with early atypicalities in social attention in terms of predictive associations with autism (Bedford et al 2014). The next challenge is to better understand what, if any, the implications of early differences in disengagement are for infants with a familial history of autism in terms of broader cognitive or regulatory skills past infancy. For example, do the previously-described associations from disengagement latencies to emotion regulation amongst 12-month-olds with and without a familial history of autism extend to predictive associations to later regulatory function (which is often disrupted in autism; (Mazefsky et al 2013))?

Spatial cueing task performance as a marker of covert orienting

So far, we have discussed overt orienting to peripheral targets. Another important aspect of spatial orienting is the ability to orient attention towards a stimulus without an overt eye movement; known as *covert* or *cued* orienting. Functionally, this type of orienting is likely to be important during early development – in exploring their environment, infants need to be able to detect a sudden event in the periphery of their visual field, and to focus processing on this spatial location if needed. Covert orienting can be measured with spatial cueing paradigms in which attention is centrally directed (either through verbal instruction to fixate a

central point on the screen for adults, or presentation of an engaging central stimulus for infants), and subsequently a brief visual cue is presented, followed by the target itself in the cued location.

Two basic covert attention mechanisms are facilitation and inhibition of return (IoR).

Facilitation is when a participant looks faster to a peripheral target which is preceded by a brief visual cue. Here, attention is covertly shifted to the new location just before the target appears, facilitating the response. In order for facilitation to occur, the interval between cue and target onset (stimulus-onset asynchrony; SOA) must be short, typically max. 150 ms in adults (Posner & Cohen, 1984) and max. 450 ms in infants (Richards 2000). If the interval between the cue and the target is longer (e.g., > 300 ms in adults, > 800 ms in infants; (Posner & Cohen 1984, Richards 2000)), IoR occurs, that is, the participant takes longer to look to the subsequent target. It is thought that this effect is due to the participant covertly orienting to the peripheral cue before any eye movement is made, but once attention is back at the centre, the previously-attended peripheral location is inhibited, thus causing a lengthening of saccadic reaction time to the subsequent target.

Developmental change in covert orienting

Facilitation and IoR appear to follow a separable course of development. Facilitation effects have been observed as early as 3 months (Richards 2000), with no further strengthening of facilitation effects after 5 months of age once basic differences in reaction time are taken into account (Ross-Sheehy et al 2015). However, IoR appears to have a slower developmental onset, with mixed evidence for an effect before 6 months of age (Richards 2000, Xie & Richards 2017). This delayed onset may indicate that IoR is a more mature form of covert orienting, which allows the infant to be less distracted by just-processed information and

thereby better able to engage effective visual exploration of the environment. In fact, Markant and Amso (2016) demonstrated that 4-month-olds who *do* show evidence of IoR (about 44% of their sample) are more proficient learners than infants who rely more on facilitation during encoding.

At the neural level, source localisation of Event Related Potentials (a time-locked measure of neural processing) has established a facilitation effect in inferior occipital and ventral temporal regions, with the very earliest brain response, the P1 (onset approximately 100 ms after target onset), being larger when the target is preceded by a brief cue on the same side (Richards 2005, Xie & Richards 2017). This effect is present already at 3 months (Xie & Richards 2017), confirming that facilitation is an early-developing type of attentional cueing. Interestingly, the P1 effect is further amplified when infants are in heart rate-defined sustained attention (see Maintaining focus section), suggesting that sustained attention, even early in infancy, may impact on the fundamental dynamics of covert orienting (Xie & Richards 2017). However, Xie and Richards' (2017) findings also indicate important changes in this sustained attention modulation: by 4½ months of age, the effect is only present at a short SOA, whereas a long SOA results in a reversed effect (smaller P1 during sustained attention compared to during inattention). This suggests that the interplay between sustained attention and covert shifts of attention changes rapidly during the first 6 months of life.

Section summary

The ability to shift attention towards and away from objects at various spatial locations may involve either overt or covert orienting. Covert orienting can be further disaggregated in terms of facilitation and inhibition of return, of which the former develops rapidly during the first months of life, while the latter is more evident after 6 months of age. Meanwhile, overt

orienting and disengagement draw on different brain processes across development: from subcortical circuits in early infancy, through to the cortical orienting network, and later-developing executive control processes.

We now move from considering how infants orient to stimuli to considering how infants filter those stimuli.

Selective filtering of visual inputs

From the moment of birth, our visual system is assailed with competing environmental inputs, which contain more information than can be processed at once. A core function of visual attention then, is to act as a filter; to discriminate between different inputs and selectively bias our limited cognitive resources to a subset of those inputs (Amso & Scerif 2015). In this way, a young child in a busy room becomes able to monitor for the presence of her parent, rapidly scan the room for the most appealing toy, and then proceed to target her attention to that toy.

Preferential tracking of faces

A dominant selective bias for human infants is the preference for social stimuli, which is activated according to low-level characteristics common to faces, and interacts with early experience. Studies showing preferential looking towards and tracking of face-like stimuli in newborns demonstrate that the ability to discriminate stimuli on the basis of certain low-level characteristics is present from birth (Goren et al 1975, Johnson et al 1991a). Brain imaging work using functional Near Infrared Spectroscopy (fNIRS) with newborns indicates that the extent of selective activation of the bilateral posterior temporal cortex in response to a dynamic face stimulus versus a moving human arm correlates with age in hours since birth

(Farroni et al 2013). Preferential tracking of faces declines post birth, but may still be detectable under specific circumstances – such as signals of threat – in adults (see Johnson et al (2015) for review). Thus, although the suppression of rapid orienting to faces during development may be attributable to the increasing dominance of cortical control of visual attention, its residual function into later life may have survival relevance.

Visual search task performance as a marker of selective attention

The ability to exert selective attention extends above and beyond social biases, and is often measured with visual search tasks in which participants must locate (by tapping or fixating) target objects or features among distractors. Research indicates that visual search performance may engage common underlying mechanisms with biases for social stimuli.

Amongst 3- to 9-month-olds, performance on a visual search task is strongly associated with the duration of looking to faces in video and animation clips (Frank et al 2014). The association is stronger for the total amount of looking at faces compared with the duration of individual epochs of attention to faces (i.e., visual search performance is primarily associated with finding faces rather than sustaining attention to them), indicating that associations are driven by a common selective attention mechanism rather than an association between visual search and social orienting more broadly. Accuracy and reaction times in visual search improve with age (Frank et al 2014), and between 4 and 8 months visual search profiles demonstrate a decreasing influence of physical salience properties over socially-relevant content during attention to static stimuli (Kwon et al 2016). Using a computational modelling approach to simulate infant visual search performance data under varying conditions, Schlesinger and colleagues (2007, 2012) argue that, just as in adults, the posterior parietal cortex plays a critical role in infant visual selective attention, and suggest that developmental change might be linked to maturational increases in the duration of recurrent activation in the

parietal cortex (i.e. feedback loops which sustain activation in that region, leading to greater accuracy, but also longer search times) as well as feedback from developing areas in prefrontal cortex which allows for modulation of recurrent parietal activity.

Longitudinal correlates of visual search task performance

So far there is limited evidence for stability and developmental consequences of variation in selective attention in the first year of life, but more research is needed. One study, in a large sample of infants from a low-resource setting (where variation in factors linked to cognitive development, such as nutrition and cognitive stimulation, can be expected to be greater than in the high-resource Western populations that comprise most infant research) has reported that visual search performance shows no stability between 7 and 9 months and no associations with nutritional status or characteristics of the rearing environment (Pyykkö et al 2018). In part, however, null results may be attributable to difficulties in reliably measuring individual differences in selective attention in the first year of life using current methods and, perhaps, an over-reliance on screen-based measures which may under-estimate the full range of selective attention capabilities of infants (Slater et al 1984).

Stability and predictive associations from selective attention are found from around 2 years of age. Performance on a touchscreen visual search task shows moderate stability from age 2½ to 3 years in a socio-economically diverse sample (Veer et al 2017). Moreover, better visual search performance at age 2½ is associated with enhanced working memory and response inhibition performance at age 3 (Veer et al 2017), and greater mathematics and literacy skills at age 5 (Mulder et al. 2017). These results indicate that selective attention processes in toddlerhood are implicated in developmental cascades relating both to executive attention, and to cognition more broadly.

Bottom-up and top-down modulators of visual search task performance

Often overlooked however, is the notion that individual and developmental differences in top-down selective attention operate in interaction with variation in other processes and functions. These might include top-down executive processes, bottom-up processes such as visual acuity, colour processing and face preference, as well as phasic and tonic variation in arousal. This point can be illustrated by comparing populations who show atypical performance on visual search tasks, and who have specific profiles relating to some of the factors listed above. For example, toddlers with Fragile X Syndrome and Williams Syndrome (conditions of known genetic etiology, which are both associated with intellectual disability and differing profiles of attentional difficulties) show poorer group-level performance on visual search tasks compared with typically-developing controls – but little difference in search speed or path. Further examination reveals that toddlers with Williams Syndrome are more likely to confuse distractors with targets than the comparison groups, and are more affected than the other groups by increases to the perceptual load of the task, consistent with a subtle visuo-perceptual impairment. In contrast, toddlers with Fragile X Syndrome produce more repeat touches to previously-selected targets than the other groups, consistent with general inhibitory difficulties (Scerif et al 2004). Meanwhile, children with, or later diagnosed with, autism (which, as previously described, has been linked to difficulties with attentional disengagement in infancy) sometimes show *advantages* in visual search, from as young as age 2 years (Cheung et al 2018, Gliga et al 2015). Although a recent meta-analysis indicates that this visual search advantage is not as pervasive in older children and adults with autism as first thought (Van der Hallen et al 2015), various arguments have been proposed to account for the advantage, when it does occur, including enhanced perceptual discrimination (Joseph et al 2009), a preference for bottom-up processing (Amso et al 2014), and hyper task-

evoked-arousal (Blaser et al 2014). Amongst typically-developing 6½-month-olds, accuracy of locating a target distinct from 3 distractor stimuli is highest at intermediate levels of arousal (Kleberg et al 2018). Thus, whilst visual search may be a useful marker for selective attention, it must also be considered whether variation in performance might be attributable to other factors, particularly amongst populations where bottom-up or arousal processes may function atypically and play a predominant role in task performance.

Finally, we should not be complacent that selective attention necessarily develops in a consistent way across cultures. Amongst adults and children, attention allocation is characterized as more relational in Eastern cultures, and more object-focused in Western cultures (Kuwabara & Smith 2012, Nisbett & Miyamoto 2005). Preliminary evidence suggests that the attentional biases of Chinese versus American toddlers are already diverging in response to dynamic scenes at around age 2 years (Waxman et al 2016). Further research is required to establish whether culturally-specific profiles of selective attention are robust across contexts and can be identified in infancy.

Section summary

Infants are able to exercise a limited form of selective attention – to faces – from birth, and by 3 months are also able to deploy selective attention processes to non-social stimuli. Selective attention develops rapidly during infancy, and individual differences in this skill may not be stable prior to age 2 years. By toddlerhood, selective attention skills show some stability over time, as well as predictive associations to later executive attention and academic skills. Nevertheless, even in toddlerhood and beyond, performance on putative selective attention tasks such as Visual Search is influenced by the low-level properties of

task stimuli, top-down executive processes, variation in arousal, and, potentially, by culturally-accumulated biases.

We move now from selecting the focus of attention via orienting and/or filtering, to processing the focus of attention.

Processing visual inputs

By looking towards a specific stimulus we are able to take in information about that stimulus. Both the duration and the manner (pattern of looking) of attention influence the information that is taken in. Conversely, the more-efficiently information is processed, the shorter the period of attention required to reach the maximal information threshold for that stimulus; thus when an infant looks away from a particular stimulus, we might assume that they have obtained all the information they need from that input. Infant research has a long history of using looking time as a marker for processing efficiency on the basis of this logic; such is the approach used in habituation paradigms in which a stimulus is presented to an infant until their attention has declined to an absolute or relative level, and the amount of time spent attending to the stimulus until that point is recorded (Colombo & Mitchell 1990).

Look durations as a marker of processing efficiency

During the first 5-to-6 months of life, look durations to novel stimuli during habituation paradigms tend to decrease with age (Colombo et al 2004, Courage et al 2006), changing particularly dramatically between 1½ and 4½ months (Colombo et al 2004). Whilst changes in look durations may in part be attributable to increases in *speed* of processing, short look durations may also be an index of efficient attentional *style*. Colombo and colleagues have demonstrated that infants who are ‘short lookers’ show a bias towards initially encoding the

global features of a stimulus (i.e., automatically segregating the visual field into coarse or global regions) before attending to the local or fine features of a stimulus, whereas long lookers show no such bias and do not exhibit any systematic pattern of visual selectivity. In this way, global-to-local lookers demonstrate a form of selective attention that benefits their performance on subsequent recognition memory tests (Colombo et al 1995). Indeed, 6-month-old short lookers demonstrate significantly greater amplitude for the Nc event-related potential (ERP) component (which, in adults, has been localised to frontal areas such as anterior cingulate and inferior prefrontal cortex; areas implicated in an executive attention network and in memory retrieval) to novel global stimuli compared to novel local stimuli, whereas no significant differences in Nc amplitude are found across stimulus types for long lookers (Guy et al 2013). Meanwhile, at a behavioural level, the causal association between attentional style and processing efficiency has been demonstrated in an elegant study in which long-looking infants were induced to exhibit a more global-to-local scanning style by means of a red light guiding their visual path – and subsequently performed equivalently to short-looking infants in the test phase (Jankowski et al 2001).

Early differences in look duration have been shown to have both immediate and long-term cognitive correlates. These correlates include broad measures of childhood intelligence (Kavšek 2004), information processing (Sigman et al 1991) and top-down cognitive control and self-regulation (known as Executive Function) (Cuevas & Bell 2014). However, recent studies indicate that predictive associations may be limited to performance on certain types of Executive Function tasks; specifically those relating to working memory, cognitive flexibility or complex inhibition (sometimes known as ‘cool Executive Function’ tasks), and not those measuring the ability to comply with an instruction not to touch a desirable toy, or to resist chewing a snack (‘hot Executive Function’ tasks) (Devine et al 2019, Kraybill et al 2019).

Look durations as a marker of disengagement ability

Disengagement of attention may also play a key role in look durations during infancy. In the Sigman et al (1991) study mentioned above, pre-term infants were tested at a gestational age of approximately 42 weeks (where typical gestational age at birth is 38 to 42 weeks), having been born 3 to 15 weeks previously. In the section on Orienting above we referred to studies showing how infants of less than 2 months of age (gestational age of around 48 weeks) are susceptible to sticky fixation. Infants who take longer to outgrow sticky fixation – i.e., who continue to show long latencies to disengage from a target – show executive attention difficulties later in life (Hitzert et al 2014). Thus, the long look durations to habituation stimuli shown by some pre-term infants in the Sigman et al., (1991) study may have been driven by disengagement difficulties as well as by poor processing efficiency. Consistent with this argument, in full-term 3- to 4-month-olds peak look duration is strongly correlated with latency to fixate a peripheral stimulus in Overlap, but not Gap, trials of a Gap/Overlap task (Frick et al 1999).

Analysis of infant heart rate during habituation tasks may give further insight into the role of disengagement in look durations. Richards and Casey (1992) have posited that consideration of heart rate indices during infant looking to visual stimuli can allow for a parsing of attention into three different “phases”: Orienting – in which a stimulus is fixated and the heart rate declines rapidly; Sustained Attention – in which the decelerated heart rate is maintained, heart rate variability is low, and information processing is expected to occur; and Attention Termination – in which the look towards the stimulus continues, but information is no longer being processed, and the heart rate returns to at least the pre-stimulus median baseline level. Amongst 4-month-old infants, longer look durations are associated with more time spent in Sustained Attention (Colombo et al 2001) – which may indicate that longer-looking infants

need more time to process stimuli (i.e., their information processing is less-efficient) compared with their short-looking peers. Additionally, longer look durations are associated with more time spent in Attention Termination (Colombo et al 2001); which would support the previous argument that looking time is also associated with disengagement of attention.

Novelty preference and arousal as modulators of look durations

Another important but variable characteristic in infancy, and potential driver of look durations, is preference for novelty (Sternberg 1981). Infants who habituate quickly and have a preference for novel over familiar stimuli will, over time, experience a greater variety of input. Measures of habituation (decrement of attention to a repeatedly- or continuously-presented stimulus) correlate with measures of dishabituation (reactivation of attention towards a novel stimulus following habituation), and both measures share similar predictive associations with IQ (Kavšek 2004). In the ERP study previously described, short-looking 6-month-olds showed increased Nc response to novel global stimuli compared with familiar global stimuli. Whilst the Nc component is associated in later development with brain regions associated with executive attention, at age 6 months it is suggested that high amplitude Nc may be indicative of activation of a general arousal system (Guy et al 2013). Thus, habituation measures may be sensitive to arousal linked to individual differences in novelty-preference, as well as to variation in processing efficiency.

Arousal may also modulate look durations in a more general sense. Twelve-month-olds with increased reactivity (greater increases in heart rate relative to baseline) to a moderate stressor (a video of another infant crying) show shorter look durations and greater novelty preference in a habituation paradigm (de Barbaro et al 2016). In a related study, de Barbaro et al (2017) found that that short-term increases in arousal (using a composite of heart rate, electrodermal

response and movement indices) for 12-month-old infants precede decreases in look duration to photographs and cartoon clips. And, in the same study, infant-by-infant individual look durations to static face stimuli could be predicted by the arousal level within that particular look; higher arousal levels were associated with shorter look durations. In conjunction, these findings indicate that increases in arousal trigger a faster, more stimulus-ready attentional profile in infants – similar to that observed in adults (Duffy 1962, Vaez Mousavi et al 2007).

Developmental change in look durations

Not only does it seem likely on the basis of the evidence described above that look durations tap multiple processes in infancy, to complicate matters further the relative impact of individual differences in processing efficiency appears to change during early development. In particular, evidence from multiple research programmes indicates that a key change in looking behaviour occurs between 7 to 9 months. Firstly, meta-analyses have shown that predictive associations from habituation task look durations to broad cognitive outcomes, such as IQ scores, are generally weaker when look durations are measured in infants older than 8 months (Kavšek 2004, McCall & Carriger 1993). Secondly, a cross-sectional study of infants examined at age 3, 5, 6, 9 or 12 months of age, indicates that at around 6 to 9 months, average look durations diverge according to the type of stimulus being viewed; decreasing for simple geometric stimuli, increasing for complex stimuli (Sesame Street clips), and levelling off for face stimuli (Courage et al 2006). Thirdly, longitudinal research by Colombo et al (2004) found that infants could be differentiated according to whether they show a decrease in look durations to face stimuli between 3-6 months and 7-9 months (characteristic of 75% of the sample), or whether they show an increase in look durations during that period (characteristic of 25% of the sample).

One likely explanation for the findings described above is the increased dominance of the executive attention network over looking behaviour from around 7 to 9 months of age. Executive attention enables infants to exert endogenous control over their own looking behaviour and to use that control to explore other aspects of their environment than the stimuli that initially captures their attention (Hendry et al 2016). Greater executive attention in late infancy might be expected to lead to a positive cascade of effects. Consistent with this, those infants in the Colombo et al. (2004) study who showed a decrease in look durations between 3-6 months and 7-9 months exhibited higher cognitive and language scores at age 2 years. Similarly, in a cohort of infants with and without a familial history of autism, infants who showed a decrease in look durations to faces embedded within visual arrays between the age of 8 and 15 months, had higher parent-reported effortful control at age 3 years (Hendry et al 2018).

Section summary

Look durations can be used as a proxy for processing efficiency in infants aged up to 6 months of age – although even early in infancy look durations are moderated by other factors including disengagement ability, novelty preference and arousal. From around 7 months, look durations are more sensitive to individual differences in executive attention. This increasing ability of infants to endogenously control their own attention means that motivational factors may interact with the social and information value of a target stimulus, and any competing stimuli, to influence look durations. The direction of effect of predictive associations from look durations in late infancy may therefore vary across different stimuli, and different contexts. These issues are considered further in the following section, as we address the endogenous control of focused attention.

Maintaining focus on a target

The studies described above have tended to consider visual attention at the level of individual looks to specific targets. However, in the real world, visual attention is engaged towards heterogeneous targets which change with varying degrees of rapidity whilst other stimuli compete for attention. For example, an infant being pushed in a buggy might redirect his attention to every new stimulus that encroaches on his visual field, withdraw active attention altogether by ‘zoning out’ or napping, or alternatively, might maintain active attention on a single visual target such as a new buggy toy; i.e., engage focused attention. In this section we address the construct of focused attention and the related construct of distractibility; the sidebar ‘Genetic mechanisms of attention development’ introduces the potential effects of variation in dopamine genes on this type of attention during infancy.

Toy play task performance as a marker of focused attention

Focused attention entails effortful attentional engagement with a target for the purposes of active information processing. Behavioural markers of focused attention during toy play include simultaneous manipulation and visual exploration of objects, facial expressions of interest or excitement, decreased distractibility to peripheral stimuli, and quieting of motor activity. In contrast, casual attention – during which little if any information regarding the stimulus is processed – can be characterised by looking in the absence of these additional behavioural markers, by manipulation, banging or mouthing without visual exploration, or by stereotyped repetitive activity (Oakes & Tellinghuisen 1994, Ruff 1986, Ruff et al 1996, Ruff & Lawson 1990). Using heart rate indices to parse looking behaviour components in a similar way to that described in the Processing section, Lansink et al (2000) have shown that amongst 6- to 12-month-olds, heart-rate- and behaviourally-defined focused attention are more closely coupled than are heart-rate-defined focused attention and behaviourally-defined

casual attention. Amongst 10- to 12-month-olds, the neural correlates of heart-rate-defined sustained attention in a screen-based paradigm include increased synchronization in the theta (2-6Hz) band and decreased synchronization in the alpha band (6-9Hz) of the electroencephalogram (EEG) – these effects are not observed at 6 or 8 months (Xie et al 2018). Lower frontal alpha power at 10 months during calm viewing of a moving object has been associated with higher Executive Function abilities at ages 4 and 6 years (Kraybill & Bell 2013), whilst increased activation in the theta band during infancy has been interpreted as reflecting activity in the anterior attention system underlying the executive control of attention (Orekhova et al 1999). Taken together, these findings indicate that towards the end of the first year of life infants are able to engage cortically-mediated executive processes to establish and maintain focused attention.

Longitudinal correlates of toy play task performance

The ability to sustain focused attention rapidly improves over the second half of the first year of life (Lawson & Ruff 2004a) and on into ages 2 and 3 years (unlike casual attention, which does not show an increase) (Ruff & Lawson 1990). The literature on stability of focused attention from infancy through to the preschool years is mixed, with some studies showing continuity from infant focused attention to measures of the ability to sustain attention during a structured task in the toddler and preschool years (Gaertner et al 2008, Lawson & Ruff 2004b, Ruff 1986), and other studies showing little evidence for stability in focused attention between 10 and 18 months (Bono & Stifter 2003) and from 7 or 9 months through to 31 months (Kannass et al 2006) – although these null results may in part be attributable to analyses being under-powered to detect small-to-moderate associations.

Nevertheless, a number of studies have now demonstrated that predictive associations from focused attention towards the end of the first year of life can be found with a range of outcomes considered to relate to executive attention more generally. For example, individual differences in focused attention amongst 9- to 12-month-olds show a positive predictive association with effortful control and Executive Function (Frick et al 2017, Johansson et al 2015a, Johansson et al 2015b, Kochanska et al 2000) and a negative association with later Attention Deficit Hyperactivity Disorder (ADHD) symptoms (Lawson & Ruff 2004b), particularly for infants born pre-term (Ruff et al 1990).

Distractibility task performance as a marker of focused attention

In day-to-day life, maintaining attentional focus on a target also involves inhibiting looks to the alternative stimuli that have encroached on infants' visual field. This second component can be indexed by distractibility tasks. In distractibility tasks the infant is presented with a target stimulus (e.g., a toy or dynamic cartoon or shape) whilst a distracting event is presented intermittently in the periphery (Holmboe et al 2008, Kannass et al 2006, Lansink & Richards 1996, Oakes et al 2002, Oakes et al 2004, Ruff et al 1996). The measure of distractibility is the latency and/or frequency of orientation to the distractors.

It appears to be possible to detect stable individual differences in distractibility from slightly earlier in infancy than focused attention. Seven-month-olds' latency to look to a peripheral audio-visual distractor presented whilst they play with a toy is predictive of their distractibility in the same task at 9 months (Kannass et al 2006). In the same study, 9-month-olds' performance is also predictive of distractibility at 31 months. Using an alternative measure of distractibility in which an engaging central animation stimulus is intermittently

interrupted by white distractor squares in the periphery, the proportion of looks to distractors at 6 months of age predicts distractibility on the same task at 9 months (Holmboe et al 2018).

Distractibility and focused attention appear to be closely-related functions, and may rely on the same neural processes. Infants exhibiting behaviourally- or heart-rate-defined indicators of focused attention are less distractible compared with when they are considered to be in a state of casual attention, and they are most resistant to distraction when they have maintained attention on the target for a sustained period of time (Lansink & Richards 1996, Oakes et al 2004, Richards & Turner 2001, Ruff et al 1996). At 31 months (but not 7 or 9 months), performance on focused attention and distractibility tasks is significantly correlated, such that children who are effective at inhibiting responding to the distractor in the distractibility task also tend to maintain their attention for longer durations during object exploration (Kannass et al 2006). Kannass and colleagues (2006) attribute this coherence to the common influence of endogenous attentional control in both tasks, and others have specifically highlighted the role of the executive attention network (Colombo 2001, Conejero & Rueda 2017). Consistent with this, Holmboe et al. (2018, 2008) have shown that distractibility at 9 months is moderately associated with concurrent performance on a classic infant Executive Function measure (the A not B task, in which infants are tasked with retrieving an object that is hidden repeatedly first in one location, A, and then in an alternate location, B) at 9 months, even after controlling for general cognitive ability. However, further research is required to test whether associations between distractibility and focused attention can be directly attributed to individual differences in executive attention.

Section summary

From around 7-9 months of age, infants are able, in some contexts, to use top-down attentional control to maintain attentional focus on a target and to inhibit looks to a peripheral distractor. This top-down control engages cortical processes linked to the executive attention network, becomes stronger and more coherent in the second year of life, and is associated with behavioural measures of executive control.

Although executive attention skills continue to develop well into adolescence and beyond, by the end of the second year of life the typically-developing infant is able to use top-down control mechanisms to allocate processing resources and to modulate their orienting response to spatial cues. With this ability, the cornerstones of visual attention are in place.

Sidebar: Genetic mechanisms of attention development

Genetic polymorphisms (i.e., common variations), in particular in monoaminergic neurotransmitter systems, have been associated with attentional development during the first few years of life. One such polymorphism is the Val¹⁵⁸Met polymorphism in the catechol-O-methyltransferase (COMT) gene, which impacts on dopamine break-down primarily in the prefrontal cortex (Chen et al 2004). Holmboe et al (2010) found that infants carrying the lower-expressing Met variant of the gene (leading to higher dopamine availability in the prefrontal cortex) were less distractible when engaged with an interesting central stimulus. Similar results were reported by Markant et al (2014) in 7-month-olds. These findings suggest that in infancy carrying the Met-allele results in a higher level of sustained attention and reduced distractibility; findings that are also consistent with research in adult populations where the Met-allele has been associated with more efficient processing in the prefrontal cortex during executive function task performance (Mier et al 2010), which by definition

places high demands on attentional control. However, results have not always been consistent across different age groups and between different populations; specifically, some studies have found that the Val-allele confers an advantage in some ethnic groups and in certain high-risk samples (for further discussion, see Fiske & Holmboe (2019), p. 51-52). More research is therefore needed to track the impact of this polymorphism, and polymorphisms with similar impacts in the brain, beyond infancy and within different contexts, in particular as infants gain further skills in more-controlled forms of attention.

Future directions and challenges

Advances in eye-tracking technology

Within the space of 15 years, the identification of the target and duration of visual attention has transitioned from a time-intensive process based on manual coding of video footage at resolutions between 25 and 50 Hertz, to a largely automated process in which eye-tracking hardware can record gaze co-ordinates to an accuracy of around 1 degree of visual angle at up to 1000 Hertz, ready for processing. Both proprietary (e.g. Tobii (2016)) and open source (e.g. GraFIX; de Urabain et al (2015)) software is available to aid the eye-tracking processing stage, although some degree of manual checking is still advisable and data quality is still, with current technology, vulnerable to movement and variation in infant physiology (e.g. eye colour and position) (Hessels et al 2015).

One advantage of technological advances is that the increase in granularity that can be recorded at scale enables us to examine the microstructure of looking behaviour – i.e., the individual brief fixations and saccades that make up a look. Wass, Smith and Johnson (2013) have demonstrated that with appropriate data analysis methods that take into account artefacts caused by, for example, infant movement and precision accuracy of the eye-tracker,

fixation duration can be a reliable measure in infants. Preliminary work has found that longer mean fixation durations to a diverse set of stimuli amongst infants aged 4-10 months are predictive of higher levels of effortful control and lower levels of surgency and hyperactivity-inattention at preschool age (Papageorgiou et al 2014). Further investigation of the longitudinal correlates of individual differences in fixation duration may therefore be an interesting line of inquiry – although given the interaction effects between age and stimuli highlighted in this review, follow-up research may benefit from analysing infant fixation data within smaller age bands and with more-consistent stimuli. Another fruitful approach may be to disaggregate looks into individual fixations – and use the shape of the distribution of fixation durations to parse looks into attentional components, such as encoding of information, disengagement and saccade programming, and attentional lapses (de Urabain et al 2017) as a means of calculating indices that are closer to the specific attentional component of interest and thus contain less measurement noise than compound look metrics.

A second advantage of technological advances is that modern eye-tracking systems are increasingly portable, making it possible to extend the diversity of the populations we study beyond those families with the time, motivation and access to laboratories in universities or other large institutions. In the UK, for example, eye-tracking systems have been used with socially-disadvantaged populations in community centres (Ballieux et al 2016), and for home visits to infants with a familial history of ADHD (Goodwin et al 2016). It is also now possible to estimate gaze using the cameras built into tablet devices (Wood & Bulling 2014), albeit at lower levels of accuracy and resolution than bespoke eye-tracking systems. By putting data collection in the hands of participants (or, perhaps more literally, their parents), tablet-based eyetracking could open up possibilities of ‘big data’ research into early development of visual attention as well as research in geographically-dispersed populations;

indeed, field data collection using tablet devices is already underway in India as part of the Screening Tools for Autism Risk using Technology (START) project.

Another area of innovation suitable for research into early development of attention is in the use of head-mounted eye-trackers. By enabling researchers to record infants' gaze to targets other than a two-dimensional screen, this approach allows us to consider variation in visual attention when the infant engages with the world in a more naturalistic way. To date head-mounted eye-trackers have been used to collect data relating to questions as diverse as the interaction between visual attention and manual behaviour during object exploration (Yuan et al 2019) and the impact of joint attention on gaze duration (Yu & Smith 2016), and could be applicable to many other lines of inquiry. However, current limitations in the technology include the requirement for extensive calibration and manual coding, and this limits the applicability to relatively small data sets in the short term.

Directly test questions of causality

As outlined above, researchers have made considerable progress in elucidating the functional and neural mechanisms involved in the development of visual attention and, where longitudinal designs have been employed, the evidence for meaningful developmental consequences of variation in early visual attention development is amassing. However, to increase relevance for public policy, more-direct tests of causality are required, and this is most fruitfully achieved with intervention-based research.

The challenges for large, longitudinal infant visual attention intervention studies are three-fold. The first challenge is to establish how to intervene in such a core, domain-general cognitive function as visual attention with participants who are unable to comprehend

detailed instructions or to execute anything beyond the most basic of motor responses. One approach that shows promise is the use of gaze-contingent, adaptive screen-based tasks in which the infant is rewarded (with appealing visual and sound effects) for making particular gaze responses to a selected visual target. Eleven-month-old infants trained in this way over the course of 15 days on tasks targeting attentional focus, selective attention and visual working memory, showed immediate post-training improvements in sustained attention to complex screen-based stimuli, reaction time in general during the Gap/Overlap task and reduced latencies for disengagement in particular, as well as increased ability to inhibit a previously-learned rule (looking to one side to anticipate a reward) in favour of a new rule (looking to the opposite side). No improvements were observed in visuospatial working memory (Wass et al 2011). When the training was administered to 12-month-olds in a community setting, significant training effects were found for sustained attention to complex screen-based stimuli, reaction time in general during the Gap/Overlap task (but not disengagement specifically), and anticipatory looking generally (but not shifting of anticipatory looks) (Ballieux et al 2016). Following a similar training programme, but with different outcome measures, 9-month-old infants demonstrated little training effects for disengagement, but more-efficient processing of screen-based stimuli and greater response to social cues, both immediately post-training and at 6-week follow up (Forssman & Wass 2018).

The second challenge for intervention research relates to scale and resource demands. Even the ambitious studies described above have been limited to follow up only a matter of weeks post training – therefore, as yet, it is not known whether the promising training effects indicated in the studies above are sustained. A version of the same adaptive-training paradigm described above is currently being used in a randomised control trial with infants

with a familial history of ADHD, with intervention across 9 sessions between 10 and 14 months, and follow up at ages 2 and 3 years (Goodwin et al 2016). The resource demands of recruiting, scheduling, implementing and evaluating an eleven-timepoint study are immense, and a particular challenge for infant intervention research is that during this period of rapid development, infants' routines are in constant flux and thus within-and between-session attrition is high. It must also be considered that such studies are demanding on participant families, and may be simply out of the question for some.

The third challenge for intervention design is that sustained, distal effects are likely best achieved when intervention is embedded in multiple applied contexts, including social interactions (Amso & Scerif 2015, Diamond & Lee 2011). This may be particularly the case during infancy, when motor-, sensory- and socio-communicative domains are developing rapidly in interaction with visual attention. In this review, for space reasons, we have focused on visual attention in isolation, but a growing body of research demonstrates that visual attention interacts with other sensory modalities during infant cognition (Begus et al 2015, de Klerk et al 2015); and indeed it has been argued that multisensory information is prioritized by typically-developing infants (Bahrick et al 2004, Flom & Bahrick 2007). Screen-based interventions are inherently limited in this regard but one solution may be to use advances in technology to enable the parent to act as a partner in the intervention process. This approach could also in part address the scale and resource demand challenge outlined above. Another option could be to augment objects with technology to create tangible user interfaces ('tangibles') for learning. This is an area which is being innovated in education and autism research (Baykal et al 2018, Fleck & Hachet 2016, Francis et al 2019) but has been largely overlooked to date in infant research.

Increase diversity, breadth and depth of studies

We end with two calls to action. Firstly, there is a need for greater diversity in our study participants. We note that the majority of the evidence for the consequences of early variation in visual attention is drawn from the kind of societies that Henrich et al (2010) have termed ‘WEIRD’; Western, educated, industrialized, rich and democratic. Focusing on a narrow population undermines our ability to make claims about the fundamental, generalizable aspects of human cognition (Henrich et al 2010, Nielsen et al 2017), and may limit the range of variability captured in research, masking potentially important longitudinal associations. An increased emphasis on longitudinal research from non-industrialised or low-resource communities also has a more practical imperative; unless we understand what optimal attention development looks like for a specific population we cannot make meaningful progress in understanding and remediating, if needed, the effects of atypical attention development in that population. Promisingly, technological developments which have increased the portability and availability of eye-tracking and imaging techniques, combined with a growing interest in sampling from under-represented populations may slowly begin to redress this imbalance (Boivin et al 2017, Lloyd-Fox et al 2019, Lloyd-Fox et al 2014, Perdue et al 2019).

Secondly, we note the need for more robust and diverse indices of attention. As outlined above, the primary attentional construct driving performance may vary during the course of a given task, and this may interact with other sensory modalities, cultural context, developmental stage and/or neurodevelopmental condition. Using multiple measures as manifest variables loading onto a putative construct to be formally tested through factor analysis is one promising way to address this challenge and is currently under-utilised in the field. A further benefit of this approach is that infant data often has high measurement error

(Frank et al 2017), and factor analysis can be used to partial out this error from the construct of interest.

One consideration that has likely limited the adoption of factor analysis in early visual attention research is that the number of dedicated ‘attention tasks’ that can be fitted into a session without over-loading participants is limited in infant research, particularly in studies with multiple domains of interest. However, researchers are increasingly demonstrating that attention-relevant variables can be extracted from other tasks. Observer ratings of attentive behaviour across a 2- to 3-hour session at 7 and 15 months of age have predictive associations to Executive Function measured at age 5 years (Brandes-Aitken et al 2019). In another example, Miller et al (2018) extracted looking time to screen as an index of sustained attention from two eye-tracking tasks originally designed to measure social preference and emotion processing, and showed that infants with a familial history of autism who were later diagnosed with ADHD did not show the increases in looking time between 3 and 24 months of age characteristic of typically-developing controls. Additionally, parent report can offer insights into aspects of attentional control that are not easily captured in the lab, has been shown to be stable across the first and second year of life (Putnam et al 2006, Putnam et al 2008, Rothbart et al 2000), and can be collected without placing any additional demands on the infants themselves.

A second obstacle to the adoption of factor analysis and other Structural Equation Modelling approaches is the requirement for large sample sizes (MacCallum & Austin 2000) – a particular challenge in a field which suffers with high attrition rates, and compounded still further for developmental studies with rare or hard-to-reach populations such as infants with developmental conditions or in low resource settings. Although technological advances such

as increasing portability of equipment will play a role in addressing this challenge, it seems likely that the major advances are to be made through multi-site collaborations, such as the Many Babies project (Frank et al 2017, ManyBabiesConsortium 2019). The Eurosibs consortium is another example of a multi-site collaboration project which is beginning to yield results. Jones et al (2019) have shown that by adopting a stimulus presentation framework that maintains consistent size and positioning of stimuli across different screen sizes and resolutions, alongside rigorous Standardised Operating Procedures for infant testing, data can be harmonised across sites. Specifically, they demonstrate that despite site differences in indices of eye-tracking data quality, disengagement performance on the Gap-Overlap task appears robust to these lower-level differences.

Conclusions

The neural underpinnings of performance on visual attention tasks change with development; with subcortical bottom-up processes in early infancy being usurped by cortical processes, that, later in development, are moderated by executive attention processes. These changes equip the developing infant with increasing control over their own attention and responses, and are implicated in far-reaching and complex developmental cascades relating to self-regulation, social development and general cognitive ability. The vulnerability of some groups – such as infants born pre-term, or with a family history of autism or ADHD – to disruption to the normative profile of early attention development therefore puts them at greater risk for a range of later cognitive and behavioural difficulties.

A consequence of the complex interactions between rapidly-developing attentional processes and other systems is that age-related changes in performance on any given attention task may be non-linear, and tasks demands may vary according to developmental stage, as well as with

the experience, motivation, cognitive and physical constraints of the individual child. Thus behavioural, neural and physiological markers of attention may need to be interpreted differently at different points in development, and for samples from different populations.

We argue therefore that the role of attention is best understood through judicious use of multiple measurements. This may include taking measurements using multiple techniques within the same task, for example using heart rate or EEG indices to disambiguate attentional processes within an eyetracking task; or applying multiple conditions within the same task, such as the Gap and Overlap conditions of the Gap/Overlap task. Additionally, it may be necessary to use multiple marker tasks of the same putative attentional factor that can be formally tested and integrated within a factor analysis, or to take measurements at multiple points in development with the same marker task. Observer and parent-report measures may offer less stringent, but potentially broader and more ecologically-valid indices of different components of attentional development, which can in turn be related back to performance on laboratory-based tasks. When considering longitudinal associations of attention it may be necessary to collect multiple outcome markers, and to test for individual differences within and between multiple populations, e.g., in different cultures or developmental conditions. Although such studies are major undertakings, a new era of cross-lab collaborations, combined with technological developments, hold promise for an exciting future of consolidation and advancement in attention development research.

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Table 1: Attentional functions and associated marker tasks discussed in this review

Broad function	Marker tasks	Cognitive components of performance on marker tasks
Orienting towards and away from objects at various spatial locations	Gap/Overlap	Oculomotor control Overt orientating and disengagement Performance is likely also modulated by alerting and, in later infancy, by executive processes (distractibility/focus)
	Spatial cueing tasks	Covert orientating and inhibition of return Performance is likely also modulated by sustained attention
Selective filtering of visual inputs	Preferential looking and tracking of social stimuli	Bottom-up discrimination of stimuli characteristics Motivational factors (e.g., social preferences) Selective attention
	Visual search	Bottom-up discrimination of stimuli characteristics Selective attention Motivational factors (e.g., social preferences, task goal) Performance is likely also modulated by arousal and, in later infancy, by executive (e.g., inhibitory) processes
Processing visual inputs	Habituation / Novelty preference tasks	Information processing Selective attention Disengagement Executive attention Motivational factors (e.g., novelty preference) Performance is likely also modulated by arousal processes
Maintaining focus on a target	Toy play tasks Attention to screen-based stimuli Distractibility tasks	Information processing Executive attention Motivational factors (e.g., engagement with the stimuli chosen)