Infant information processing across the visual field: from visual perception to social cognition

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Declaration

I hereby declare that no portion of the work referred to in this thesis has been submitted in support for the award of a higher degree elsewhere. This thesis is the product of my own work that was completed under the supervision of Professor Vincent Reid and Dr Michelle To. The experimental studies included in this thesis that were published or submitted for publication in academic journals are clearly identified at the beginning of the relevant sections.

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Abstract

Detecting information from our rich visual environment is fundamental to guide our attention and to act in the surrounding space. Thus far, infant visual information processing has been primarily studied presenting images within limited visual areas on standard computer displays. This is a simplification of a much richer visual environment in which information derives from a wide space including more peripheral locations. Evidence shows that infants' peripheral vision is developing during the first postnatal year of life. Nevertheless, most studies used flashing lights and little is known about social and non-social information processing at high eccentricities. The aim of this thesis was to understand how low- and high-level visual information is processed across the developing visual field and how it then translates into social behaviour and more naturalistic environments. This aim was achieved by exploring infants' sensitivities to different visual information - such as Gabor patches, face-like stimuli and faces expressing emotions - across a wide visual field extending to mid-peripheral locations (up to 60° eccentricity) and by investigating social behaviour during virtual interactions. In Chapter 1, the literature on infant information processing ranging from visual perception to social cognition was presented and the objectives of the thesis were described. In Chapter 2, the extent of the peripheral visual field in response to basic low-level visual stimuli was measured in 9-month-old infants and adults. In Chapter 3, the influence of stimulus content on peripheral information detection was investigated by presenting 9-month-old infants with face-like targets across the visual field. In Chapter 4, a tool for gaze and head tracking beyond standard screen sizes was described. In Chapter 5, attention-getting and attention-holding mechanisms towards different facial emotional expressions appearing at the edge of the developing visual field were investigated in 9-month-olds. In Chapter 6, the gaze following skills of 11- to 12-month-old infants during virtual social interactions were explored. Overall, the results of these studies showed that low- and high-level visual content affects visual field sensitivities and attention. The implications of the results for visual information processing were presented in Chapter 7.

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Chapter 1

General introduction

1.1 VISUOSPATIAL ATTENTION AND INFORMATION PROCESSING IN EARLY DEVELOPMENT

Our world includes a surprisingly rich amount of visual information, with objects of various types localised in space and often moving across the visual field. However, neural resources are limited so only a selection of information is selected for further processing. The infant's visual capabilities undergo a massive development during the first postnatal year (e.g., Atkinson, 2000). Images are initially fuzzy, visual acuity is reduced and voluntary control is limited, but adult-like visual capacities are fast approached after a few months of development (Braddick & Atkinson, 2011). In this context, eye movements and orienting behaviours have a prominent role in understanding early development before children develop verbal abilities. Many developmental paradigms are based on behaviours and physiological responses that infants reliably produce to overcome the need for following instructions or the requirement to respond to verbal indications. Among these responses, visual orienting is an easy to observe behaviour that measures where and what infants look at and is illustrative of experimental procedures which shed light on the developing mind (Aslin, 2007, 2012). Investigations have often presented visual images to young participants on display monitors and, thus, with a focus on central areas and a relatively narrow visual field. But how sensitive are infants to peripheral information? How are different types of visual information (low- vs. high-level visual features) detected and processed in space? How can we investigate early visual orienting beyond limited areas of a standard computer display? The literature reviewed in this initial chapter presents perceptual and attentional mechanisms across the visual field and outlines how different types of visual stimuli are processed in space.

1.1.1 The eye and visual brain development

The visual system is aimed at transducing the reflected light that reaches the eye into neural signals that allow us to see. The light from a particular location in space reaches a different region of the retina that includes specific photoreceptors - the rods and the cones (see Kefalov, 2010, for an overview on visual receptors). The fovea is the most central region of the retina and it is packed with cones, which provide the best visual detail (acuity) and colour vision. The presence of three types of cones with different spectral sensitivities enables us to discriminate colour. Moving away from the fovea the cone density progressively declines and rods become prominent in the peripheral retina. Rods have a higher sensitivity to light and mediate dim light vision. The lower spatial resolution of peripheral vision compared to central vision is due to the fact that the signals of multiple rods are pooled before these are integrated and sent to the brain. In contrast, signal integration is minimal with cones, leading to better spatial and temporal resolution in central vision. Whilst the newborn infant is equipped with fairly mature rods, the fovea is not fully mature and this leads to poor visual acuity (Banks & Dannemiller, 1987). In turn, contrast sensitivity is also poor and, thus, the contrast between two levels of light must be higher to detect any difference (Banks & Salapatek, 1978). Together with retinal maturation, other capacities undergo progressive development during the first postnatal weeks, such as the ability to focus over a greater range of distances (allowing accommodation; Braddick et al., 1979), the ability to look with both eyes at the same direction (producing 3D stereoscopic vision; Held, 1985) and the sensitivity to different spectral sensitivities (enabling colour vision; Teller & Bornstein, 1987). Before central cone vision becomes dominant, the parafoveal and mid-peripheral retina may have a significant role in young infants' visual functions (Hendrickson & Drucker, 1992). Nevertheless, although the peripheral retina appears more mature compared to the central retina at birth, it is still developing during infancy (Hendrickson et al., 2008).

Beyond the optical immaturity of the eye, receptor and post-receptor changes within the brain along visual pathways are an important contributor in the development of vision (Banks & Shannon, 1993; Kiorpes, 2016). In general, the systems that control eye movements in space go from the retina to the lateral geniculate nucleus (LGN) of the thalamus to then reach the primary visual cortex from which different visual modules arise (the so-called geniculostriate system). Additionally, a rapid, reflexive and phylogenetically old subcortical pathway is present but does not reach the cortex (Johnson & de Haan, 2015). Visual functions associated with subcortical structures are among the first to develop in infants (Bronson, 1974). The subcortical pathway receives input mostly from peripheral regions of the visual field and reaches the superior colliculus, enabling the production of rapid and reflexive eye movement behaviours. This subcortical dominance is primarily present during the first postnatal weeks, leading to preferential orientation to the temporal visual field, reflective saccades to abrupt visual changes and inhibition of return later in development (Johnson & de Haan, 2015).

When visual projections travel from the retina to the brain, retinotopic mapping in the LGN and primary visual cortex maintains neighbourhood and directional relations of the visual signal, but there is an increased signal representation allocated to central, foveated, regions as the signal proceeds for further downstream processing (e.g., Azzopardi & Cowey, 1993). This transformation results in disproportionately emphasised central locations compared to peripheral locations. In experimental paradigms in which visual stimuli are presented at different eccentricities, images may be scaled to control for *cortical magnification*. This refers to the fact that the area of the brain dedicated to processing 1° of foveated space is disproportionately larger than the brain area dedicated to processing the same visual angle in peripheral locations (Horton & Hoyt, 1991; Wong & Sharpe, 1999). A peripheral stimulus can be scaled by a cortical magnification factor so that the same amount of cortex is devoted to the processing as a foveal stimulus. As more peripheral visual locations are explored, a bigger stimulus would be needed to equate cortical processing among stimuli.

Between 2 and 6 months of age, the developing cortical structures start to interact and become progressively more myelinated, allowing the infant to develop smooth pursuit, increased nasal sensitivity and attention disengagement (Atkinson, 1984; Atkinson, 2000; Johnson, 1990; Johnson & de Haan, 2015). In terms of visual cortical processing, two separate systems develop: a ventral (or parvocellular) system and a dorsal (or magnocellular) system (Atkinson, 1992, 2000; based on the adult work by Goodale and Milner, 1992, 1995). The ventral pathway processes the “what/who” information and details of visual forms that are useful for recognition, including shape, orientation, pattern and colour (Atkinson, 1992, 2000; Atkinson & Nardini, 2008). The dorsal pathway processes the “where” information and is essential in localising objects in space; it also involves the development of different action modules that enable the control of eye and body movements (Atkinson, 1992, 2000; Atkinson & Nardini, 2008). While parvocellular and magnocellular layers are distinguishable prenatally in the LGN, they only reach full maturation by the second postnatal year (Hickey, 1977; Hitchcock & Hickey, 1980). Cortical and subcortical visual modules are progressively more integrated during development, allowing the infant to develop object recognition, the creation of a spatial layout of the visual world, and the control of eye movements and actions (e.g., Atkinson, 2000). The studies presented in this thesis focused on eye and head orienting behaviours in response to changes in a wide visual space that involve these developing neural structures.

1.1.2 Peripheral vision in infancy

Encoding and perceiving visual information across the visual field enable us to perform essential activities such as detecting visual changes in the environment, performing goal-directed actions and moving in space. When referring to peripheral vision, the convention for identifying a location in the peripheral visual field is *eccentricity*. Eccentricity is defined as the distance from the point of fixation and the point in periphery under consideration expressed in degrees of visual angle (Millodot, 2014). Outside of foveated spatial locations, peripheral vision can be classified as *near-peripheral* (up to 30° eccentricity), *mid-peripheral* (30° to 60° eccentricity) and *far-peripheral* (beyond 60° eccentricity). In consideration of the increased density of rod photoreceptors in peripheral regions discussed above, peripheral vision is specialised in detecting movement, flicker and abrupt visual changes, but is less capable of perceiving fine details and colour information than central vision. Also, it is more vulnerable to clutter (referred to as visual crowding) than central vision, in part due to signal pooling of rods and to limited cortical resources dedicated to peripheral areas (e.g., Pelli, 2008, for a review). Importantly, peripheral vision provides appropriate information to the visual system for planning orienting behaviours and subsequent foveation.

In early development, peripheral vision can already rapidly detect salient visual information from the surroundings. Detecting peripheral information allows for the foveation towards and further processing of the selected visual stimuli. As such, assessing visual orienting behaviours towards peripheral stimuli is relevant to understand information processing through development. Further to visual orienting and attention, peripheral information processing is relevant to motor and balance development (Berthenthal & Bai, 1989; Lee & Aronson, 1974). Notably, visual orienting across the visual field is one of the earliest sensory functions that the newborn infant can rely on (e.g., Richards & Hunter, 1998). In infancy, perception across the central and peripheral regions has been investigated systematically with the pioneering methods introduced by Robert Fantz (1958, 1961, 1964). These works examined infants’ eye and head movements, or shifts of gaze, in response to the presentation of visual displays with different visual features and relied on visual preferences for one display over the other. In general, various methods assessing vision and infant perception have included the presentation of visual information across the whole of the visual field. The clinical method used to investigate the peripheral information detection is often referred to as *perimetry* (see Johnson, Wall, & Thompson, 2011, for a review on the history of visual field testing). Perimetry investigations have mostly focused on the extent of the peripheral visual field, that is the spatial limit of visual attention and perception. Conversely, attentional mechanisms in response to different peripheral information have been investigated in the developmental cognitive neuroscience literature, as outlined in the next paragraph. Whilst perimetry studies have investigated spatial information (i.e., eccentricity) with a limited variety of stimuli (mostly flashing lights), the literature in the attention domain has focused on what kind of information elicits gaze shifts but has not investigated high eccentricities beyond near-peripheral locations.

Perimetry investigations have systematically measured peripheral information detection across the visual field. They adopted different methodologies (i.e., static, kinetic or hybrid presentation procedures, which are better described in the next chapter) and presented visual stimuli with different saliency and low-level visual features. Most of these studies have utilised flashing lights at high luminance (e.g., Courage & Adams, 1995; Harris & Macfarlane, 1974; Lewis & Maurer, 1992; Mayer, Fulton, & Cummings, 1988). Perimetry has shown that the extent of the visual field increases with age in parallel with gains in peripheral sensitivity (including a progressive development of visual acuity and contrast sensitivity at peripheral locations), improved attention shifting mechanisms and the development of neural systems associated with eye movements (Maurer & Lewis, 1998). For instance, visual acuity progressively increases in both central and peripheral locations after the first postnatal month up to 12 months of age (Allen, Tyler, & Norcia, 1996; Courage & Adams, 1990; Jones, Kalwarowsky, Atkinson, Braddick, & Nardini, 2014). Also, as discussed previously, neural structures including the retina, the LGN and the cortex undergo significant developmental changes during infancy. As a result, although newborns already show remarkable orienting abilities up to 30° (Lewis & Maurer, 1992), during the first six months of infancy the peripheral field extent undergoes rapid expansion and infants seem to detect peripheral information almost as far in the periphery as adults sometime between 6 and 30 months of age (e.g., Dobson, Brown, Harvey & Narter, 1998; Lewis & Maurer, 1992; van Hof-van Duin & Mohn, 1987). This age variability in attaining the final resting mature visual field may well be related with different target characteristics and experimental procedures (see Maurer & Lewis, 1998, for a review). The majority of past perimetry studies with infants have, however, focused on the first 6-7 postnatal months of infancy (e.g., Aslin & Salapatek, 1975; Courage & Adams, 1995; de Schonen, McKenzie, Maury, & Bresson, 1978; Harris & MacFarlane, 1974; Tronick, 1972). This makes it difficult to establish an endpoint of peripheral vision development.

Peripheral target characteristics require some consideration within this context. Low-level visual features such as luminance, contrast, flicker rate, spatial frequency but also stimulus size and distance may play a role in estimating the peripheral field extent and the associated orienting behaviours of an infant to a target. Studies have reported that increased flicker rate (Lewis, Maurer, Burhanpurkar, & Anvari, 1996), luminance (Guez, 1978), contrast (Van Hof-van Duin & Mohn, 1987) or object size (Lewis & Maurer, 1992) enhance orienting performances for stimuli in the periphery. As such, perimetry studies during development have mostly adopted highly salient lights with peak low-level visual features. Those stimuli with enhanced features are suitable to elicit responses in the visual periphery but our visual experience in everyday life is not limited to highly salient information. Perimetry studies provide useful information about the extent of the peripheral visual field using specific stimuli (where information), but not about how different stimuli and high-level visual information can be detected (what information). Therefore, a fairly open research question is whether different kinds of low- and high-level visual information would differentially affect the boundaries of our visual field. In this thesis, we explored peripheral sensitivities to both Gabor patches (Chapter 2) and face-like targets (Chapter 3). Maintaining the same procedures and low-level visual features of the stimuli allowed us to compare non-social and social information detection at high eccentricities. In addition to perimetry works, studies framing peripheral processing in terms of attention have provided some additional insight into what kind of stimuli influences visual orienting in the visual field, as outlined in the next section.

1.1.3 Spatial orienting and attention

Attention is a broad concept that includes several components. An influential anatomical model of attention was described by Posner (1980). It distinguished three attentional systems: one network to maintain an alert state, one network to orient to sensory inputs, and one executive network to detect signals for processing (Posner & Petersen, 1990). According to this framework, orienting is the operation of aligning attention with a sensory input or a structure stored in memory, whereas detecting happens when the subject is aware of the stimulus (Posner, 1980). The moment of target detection has been differentiated from orienting also because it generates interference across the attention system. For instance, it slows down detection of another stimulus (Duncan, 1984). Visual orienting can be *exogenous* (reflexive), thus related to the abrupt onset of a stimulus that automatically captures attention, or *endogenous* (central), that is a voluntarily-controlled allocation of attention in space. According to Yantis and Hillstrom (1994), a low-level mechanism such as a luminance change alone is not enough to capture exogenous attention, while the onset of a new object equiluminant with the background does.

Orienting often implies disengagement from the foveated object and location to shift the eyes to another object and location. During this process, a sensory input produces a motor response that allows the subject to bring an image to the fovea and gather high-acuity visual information for further processing (e.g., Aslin, 2007). Posner (1980) used the spatial cueing paradigm to provide evidence that this is not always the case and attention can be oriented in space even in the absence of eye movements. This paradigm showed that detection is enhanced when the participant receives an endogenous cue (e.g., a flashing light) that is informative of the location where the target will appear, as opposed to instances in which the target appears in a non-cued location (Posner, 1980). Thus, attentional orienting can be either overt or covert. *Overt* attention implies an action, that is an orienting behaviour including eye and other body movements towards the target, whilst *covert* attention does not include orienting towards the sensed object. Covert and overt shifts of attention have been described as anatomically independent mechanisms (Posner & Petersen, 1990). Accordingly, attention precedes eye movements (Posner, 1980). At the same time, Rizzolati and collaborators (1987) have argued that saccade planning and execution are mediated by the same system. In infancy, covert attention may be signalled, for instance, by heart rate deceleration when the infant is foveating a central stimulus and some peripheral information appears without causing an overt behaviour (Finlay & Ivinskis, 1984). Another example of covert attention comes from developmental adaptations of the spatial cueing paradigm in which a brief peripheral cue is presented while the infant is foveating a central stimulus. Although the cue presentation is too brief to elicit an overt behaviour, the number of saccades to a following target presented in the cued location are often increased (Clohessy, Posner, Rothbart, & Vecera, 1991).

A developmental perspective to study attention can help investigating the relation between objects and locations in space. It is also relevant to study the origins of attention and the mechanisms underlying orienting and detection. Over the last decades, there have been efforts to develop suitable behavioural tasks for use with infants and also to derive predictions based on developmental neuroanatomy (Atkinson, 1984; Bronson, 1974; Johnson, 1990). With evidence suggesting that the primary visual cortex is not fully functional over the first postnatal trimester, Bronson was among the first to argue that early visual orienting is characterised by a shift from subcortical to cortical visual processing (Bronson, 1974). Johnson (1990) extended Bronson's developmental model by elaborating Schiller's work (1985) on the adult neuroanatomical pathways from a maturational viewpoint. In fact, Schiller (1985) proposed a model of pathways that allow oculomotor control in primates. This model included: (a) a subcortical pathway for rapid exogenous saccades via the superior colliculus, (b) a cortical projection to the superior colliculus for its regulation, (c) a cortical pathway for motion detection and smooth tracking via the middle temporal area, and (d) a cortical pathway for complex scanning patterns via the frontal eye fields. Johnson (1990) proposed the sequential development of these networks during infancy, that is from pathway (a) to pathway (d).

Past research has indicated a relation between overt attention and eccentricity. In particular, beyond 30° field of view (or 15° eccentricity – the so-called *eye field*) an overt eye change is required to orient attention, whereas beyond 90° field of view (or 45° eccentricity – the so-called *head field*) eyes alone are not sufficient and a combination eye and head movements becomes necessary (Sanders, 1963). In the head field, a shift in processing mode happens so that two simultaneously presented stimuli are perceived as two separate percepts (Sanders & Houtmans, 1985). Notably, the vast majority of developmental research that has investigated early attentional mechanisms has looked at the narrow visual space that could be explored with standard computer displays, which often do not reach Sanders' *eye field*. Instead, most research has focused on the so-called *stationary field* (Sanders, 1963), with targets appearing within 15° eccentricity. In consideration of the importance of spatial orienting for the development of action control (involved, for instance, in reaching or locomotion), it is relevant to consider a wider visual field that reflects everyday visual experience. In this thesis, different peripheral visual attributes were investigated across high eccentricities that require both eye and head movements.

In the attention domain, relevant methods to study orienting and peripheral information processing are the fixation shift paradigm (e.g., Atkinson, Hood, Braddick, & Wattam-Bell, 1988; Hood & Atkinson, 1993) or the gap/overlap paradigm (e.g., Csibra, Tucker, & Johnson, 1998; Matsuzawa & Shimojo, 1997). Both paradigms measure overt shifts of attention from a central stimulus to a peripheral target. In the former, once the participant looks at a central stimulus a peripheral target appears. The central stimulus can disappear before the peripheral target onset or can remain on screen and compete for attention. A time interval between central stimulus offset and peripheral target onset is included in the gap paradigm. In circumstances in which there is no competition of attentional resources (i.e., one visual target is visible at the time) the orienting system seems most likely mediated by the subcortical pathway in a rapid alerting mechanism. On the other hand, disengagement and more cortical control mechanisms are necessary when more visual information competes for attention (Atkinson & Nardini, 2008). The increased extent of the visual field during the first year of infancy may also be linked with improved control of eye movements and attentional capacities. This includes the ability to disengage attention from salient stimuli and to overcome obligatory attention, often referred to as *sticky fixations* (Atkinson, Hood, Wattam-Bell, & Braddick, 1992; Hood & Atkinson, 1993). Shifts of attention to a peripheral target have been compared in conditions in which a central stimulus remains visible during target presentation and in conditions in which the central stimulus disappears before peripheral onset. One-month-olds failed to orient towards the peripheral target or were slower if the central stimulus was not extinguished during peripheral presentation (Atkinson et al., 1992; Harris & Macfarlane, 1974). This difficulty in disengaging from a foveated stimulus seems to emerge with inhibitory mechanisms that develops around the first month of age which then become attenuated around 3-4 months of age when cortical structures (especially parietal and frontal) are more mature and, in turn, subcortical structures are then further influenced by cortical processing (Atkinson et al., 1992).

The tasks investigating overt and covert spatial orienting during development, such as the above-mentioned fixation shift paradigm and spatial cueing task, have been used to assess the time course of different attention processes and the brain areas associated with these processes. Additionally, some studies in the attention domain have looked at the attributes of the stimuli that may bias visual orienting, and these are described further in the next section. For instance, Hunnius and Geuze (2004) found that the attributes of the central stimulus and peripheral target had an effect on infant’s shifting gaze during competing presentations. At the same time, although peripheral visual information is always involved in spatial orienting studies, little consideration has been given to the effect of specific eccentricities to attentional mechanisms. The spatial aspect of visual orienting is often reduced to a generic peripheral space. Thus far, the effect of eccentricity on attentional mechanisms during development has been rarely investigated (e.g., Farzin, Rivera, & Whitney, 2010), and investigations have not gone beyond near-peripheral visual locations. At the same time, the perimetry clinical investigations and the studies assessing the extent of the visual field (described above) have explored spatial information but have failed to investigate the effect of the attributes of the visual targets across the visual field. In fact, lights stimuli were mostly adopted in the past. Better characterising infants’ spatial orienting in response to different targets is a fundamental issue because visual attention grounds information selection and, in turn, any downstream action related to these targets in the visual world.

1.2 ORIENTING TOWARDS DIFFERENT PERIPHERAL INFORMATION

Some visual patterns alert the visual system more than others from the very early stages of development. Newborn infants can already discriminate a range of stimuli. Notably, faces represent a special visual input to humans. The developing sensory systems appear to be attuned to some aspects - such as movement, contrast, shape and pattern configurations - that make face-like stimuli particularly salient (e.g., Bushnell, 1998). During the first postnatal year, face preference and face recognition skills are refined following prolonged exposure to faces and perceptual learning mechanisms (e.g., Pascalis, de Haan, Nelson, 2002). In this section, the influence of social and non-social stimuli on orienting behaviours is presented. One aim of this thesis was to understand how the extent of the visual field is influenced by target attributes, considering both low- and high-level visual features. So far, how the different locations across the visual field (eccentricity) interact with the attributes of the target has been very rarely investigated during development.

1.2.1 Social and non-social information across the visual field

Face perception differs from the perception of other objects. This specificity was initially suggested with the discovery of an inversion effect that was significantly greater for face rather than for object recognition (Yin, 1969). Although an inversion effect has been found also when processing other stimuli where the viewer has substantial expertise (Diamond & Carey, 1986), there is no doubt that faces convey unique and diverse information to the observer. Face processing has been referred to as *holistic* or *configural*, such as it does not require a decomposition into parts (Tanaka & Sengco, 1997). In contrast, scrambled or inverted faces (together with other objects) would involve the processing of parts and of the relationships among these parts (Biederman, 1987). In addition to behavioural responses to faces, specialised brain networks are also specifically activated during face processing and recognition (e.g., Kanwisher, McDermott, & Chun, 1997).

Newborn infants attend to some visual patterns more than others. As already discussed, reduced visual acuity makes fine discrimination of details difficult at early stages in development. Nevertheless, human infants are already biased to attend to some specific visual features. Intriguingly, even prenatally light patterns directed at the mother's abdomen and arranged in face-like configurations are more salient when compared with inverted face-like light patterns (Reid et al., 2017). Newborn infants track a schematic face stimulus further and for longer in comparison to a scrambled or blank stimulus (Johnson, Dziurawiec, Ellis, & Morton, 1991). It has been suggested that face perception may involve rapid visual orienting via a subcortical system (Johnson & Morton, 1991; Colombo, 2001). Interestingly, some cortical involvement in response to face stimuli may be already functional shortly after birth (Buiatti et al., 2019). Whether face biases are due to face-specific mechanisms (Johnson & Morton, 1991) or more general perceptual mechanisms responding to all visual information that shares some characteristics typical with faces (Simion, Macchi Cassia, Turati, & Valenza, 2001), these biases will set the stage for the later face expertise that develop via a combination of structural, environmental and learned constraints (Oakes & Rakinson, 2020). An early bias to salient visual information conveyed by faces allows increased visual exposure to faces and, in turn, increasingly better face processing skills that allow recognition of facial features and expressions.

The development of face expertise is built upon a constant exposure to diverse face stimuli in our social environment. Face-to-face dyadic interactions with the caregivers are undoubtedly very frequent, but faces are also visible from multiple locations in space. The way that infants look at faces changes as a function of posture and motor development (e.g., Libertus & Needham, 2014). Moreover, an investigation looking at how faces are viewed from an infant perspective showed that faces appear progressively at increased distances from the infant face over the first postnatal year (Jayaraman, Fausey, & Smith, 2015). Accordingly, the more the infant can act and explore the visual environment, the more visual information comes from a wider space. But how is social and non-social information detected in space during infancy? We already discussed how some visual features of a peripheral target may affect both the visual field extent and attentional mechanisms, but do low- and high-level visual information (especially socially relevant information and non-socially relevant information) differentially affect visual sensitivities? Measures of the extent of the visual field have primarily adopted salient lights as visual stimuli (e.g., Dobson et al., 1998; Harris & Macfarlane, 1974; Lewis & Maurer, 1992). In the classic attention shift paradigm by Atkinson and colleagues, a schematic face-like configuration was always presented centrally and some bars were used as peripheral targets (e.g., Hood & Atkinson, 1993). Hence, the peripheral target was not manipulated.

In this thesis, we asked whether the attributes of the peripheral target are influential in early orienting behaviours. Evidence seems to suggest that orienting behaviours are affected by stimulus attributes and also by age. A set of experiments manipulating the nature of the peripheral target is described by Farroni and colleagues (1999). They presented newborns with either an upright schematic face, an inverted schematic face, or flashing lights at two different eccentricities as peripheral targets in a gap-overlap paradigm. A gap effect was present in all conditions with the exception of the inverted peripheral schematic face. Further, reaction times were faster for the upright face than the flashing light (presented either at 20° or 30° eccentricity). The effect of social and non-social stimuli has also been investigated in older infants. Hunnius & Geuze (2004) compared visual orienting of 6- to 26-week-old infants using different combinations of faces and abstract patterns as central and peripheral stimuli. They found more frequent gaze shifts presenting a familiar face as central stimulus and an abstract pattern as peripheral target rather than the opposite condition (i.e., central abstract and peripheral familiar face; Hunnius & Geuze, 2004). In this study, infants may have disengaged more easily when the central stimulus was a familiar face in order to seek new unfamiliar visual information (the abstract patterns). Further, a study by Valenza and collaborators (2015) suggested that two attributes of peripheral faces, namely orientation and motion, differentially affect visual orienting during the first postnatal months. In particular, newborn orienting behaviour towards a peripheral target was primarily led by motion, whereas at 4 months of age the role of orientation of the stimulus becomes prominent (Valenza et al., 2015). These paradigms mostly focused on a relatively narrow horizontal visual field, often up to near-peripheral eccentricities.

Other studies investigated spatial orienting in response to different visual stimuli using circular arrays, with the advantage of investigating multiple directions and locations in space (e.g., Elsabbagh et al., 2009; Gliga, Elsabbagh, Andravizou, & Johnson, 2009; Simpson, Maylott, Leonard, Lazo, & Jakobsen, 2019). These investigations confirmed an infant bias to attend to faces rather than other objects competing in the array presentation. Further, they suggested that face orientation does not influence attention capture (i.e., latency, detection rate or probability) but only attention-holding mechanisms (i.e., looking duration, number of fixations); thus, configural face properties do not seem influential for initial orienting in complex spatial arrays (Gliga et al., 2009; Simpson et al., 2019). From 7 months of age, an advantage for the upper visual field relative to the lower visual field has also been suggested for face processing and memory (Tsurumi, Kanazawa, Yamaguchi, & Kawahara, 2022). Further, spatial aspects within the face area have also been investigated during development in the "face-space" framework (de Haan, Humphreys, & Johnson, 2002). According to this framework, faces are suggested to be encoded as deviations in terms of points or vector in a multidimensional space (de Haan et al., 2002; Humphreys & Johnson, 2007). This is a relevant spatial aspect to be considered once a face has been foveated. Before the encoding stage, the location in space where a target appeared is relevant for attention selection mechanisms, which are the current focus of the present work. Overall, past developmental studies suggested a relevant role of spatial information in face processing. Still, the eccentricities investigated in all paradigms are either parafoveal or near-peripheral and the measured orienting behaviour is mostly comprised of eye movements. During visual orienting in naturalistic situations, it is not only the gaze that moves from the foveated location to a new location in space. Heads and bodies also move in space. In this thesis, visual field sensitivities were explored across a wide visual space. The influence of different visual attributes was investigated at locations beyond 30° (Studies 1 to 4), where both eye and head/body movements are required.

1.2.2 Complex face information across the visual field: emotion and gaze cues

In naturalistic situations, faces convey rich information to the observer. Here we focused on two types of information that faces convey, namely emotional facial expressions and gaze cues, and how these are processed in space. Some facial expressions can be distinguished and imitated even by newborns (Farroni, Menon, Rigato, & Johnson, 2007; Field, Woodson, Greenberg, & Cohen, 1982) and by 7 months of age a wide range of emotions can be discriminated (e.g., Leppänen & Nelson, 2006). Around this age, infants also allocate more attention to negative rather than neutral or positive emotional expressions (Peltola, Leppänen, Palokangas, & Hietanen, 2008). This bias towards threatening information is early-emerging and seems to be associated with multiple factors, such as brain development (e.g., Peltola et al., 2009), individual differences (e.g., de Haan, Belsky, Reid, Volein & Johnson, 2004) and increased exposure to dangers in the environment over the first postnatal months of life (e.g., Campos et al., 2000). Peltola and colleagues used either a happy, neutral or fearful face as a central stimulus and a checkerboard bar as a peripheral target. Fearful faces maintained more attention and delayed attentional disengagement in 7-month-old infants (Peltola et al., 2008). The effect of an emotional facial expression was only investigated at central locations, manipulating the emotion of the central stimulus while the peripheral target was always a bar. Similarly, Leppänen and collaborators (2018) used a face (happy, angry or fearful) or a non-face pattern as central stimulus and a geometric shape as peripheral target. In this paradigm, a negativity bias was found with fearful but not angry faces in infants aged 7 to 12 months (Leppänen, Cataldo, Bosquet Enlow, & Nelson, 2018). These studies seem to suggest that fearful faces bias sustained attention in infancy. Nevertheless, not only fearful but also angry faces elicit a bias in sustained attention from early childhood (Leppänen et al., 2018), suggesting that a more general bias towards negative emotional expressions develops after the first postnatal year. In infancy, only some physical characteristics of some negative expressions, such as wide-open eyes and mouth, may influence sustained attention (Leppänen et al., 2018). A potential interpretation for this bias may be that fearful expressions warn the infant about an indirect threat and, in turn, longer looking times may enable to retrieve additional information about the threatening source (Kobiella, Grossmann, Reid, & Striano, 2008; LoBue & DeLoache, 2010). The literature investigating the effect of facial emotional expressions on attention mechanisms presented so far did not explore different characteristics of the peripheral targets, which have been often not socially relevant in such studies (e.g., geometric shapes and checkerboard bars).

The attentional negativity bias has also been investigated with paired visual presentations that involve peripheral vision. LoBue and DeLoache (2010) presented 8- to 14-month-old infants with pairs of pictures side by side, one was threatening and the other one was non-threatening. This time, a superior detection of angry compared to happy faces (but not of fearful compared to happy faces) was found (LoBue and DeLoache, 2010). Angry faces may represent a direct source of threat compared to fearful faces. Thus, it may be of biological relevance to rapidly detect angry expressions across the visual field and be prepared for action. A peripheral presentation of angry faces, such as the paired visual presentation just described, might be suitable for investigating attentional mechanisms in response to an incoming threat, as opposed to a central presentation used in developmental study on sustained attention. Although some level of detail and high-spatial frequency information seem to be needed for emotion recognition, adult studies have suggested that some emotions may have an advantage in peripheral vision and may resist peripheral degradation (Bayle, Schoendorff, Hénaff, & Krolak-Salmon, 2011; Calvo, Avero, & Lundqvist, 2006). This sensitivity to threatening faces has been linked with rapid subcortical activity (e.g., Johnson, 2005). Developmental investigations presenting faces at high eccentricities are generally limited and the role of peripheral vision in emotional facial expressions remains largely unexplored. In Chapters 4 and 5, we investigated attention-getting and attention-holding mechanisms in response to emotional facial expressions appearing across a 120° field of view.

Another relevant information that faces convey is gaze information. Detecting and following gaze direction ground social and communicative development.

Gaze is a socially relevant cue to orient attention in space. Gaze *cueing* is present even in newborns and involves an overt attentional shift that can increase the processing of the peripheral target (Farroni, Massaccesi, Pividori, & Johnson, 2004). Gaze *following* behaviour, which includes a shift of someone's eyes and head towards an object, emerges sometime between 3 and 6 months and matures over the first postnatal year (e.g., Butterworth & Jarrett, 1991; D'Entremont, 2000; Gredebäck, Theuring, Hauf, & Kenward, 2008). In everyday situations, the caregiver looks at the infant and then shifts gaze towards a visual object, often naming it. As a result, the baby turns towards the direction of the object of interest. Characteristics of both the social partner and the target objects have been shown to influence gaze following (see Del Bianco, Falck-Ytter, Thorup, & Gredebäck, 2018, for a review).

Interestingly, among all target characteristics, the location of the target has a relevant role during the first year of infancy. In fact, at 6 months of age infants can successfully follow the direction of gaze but they often look at the first object they encounter in that direction, even if it is a distractor (Butterworth & Jarrett, 1991). Only around 12 months of age infants look at the appropriate target and ignore distractors in the same direction/hemifield, thus understanding both direction and location of the target (Butterworth & Jarrett, 1991). Up to this age, gaze following and the ability to spatially infer the target of someone's attention depends on the infant's effective visual field. Twelve-month-olds can orient even beyond their visual field if gaze information is reinforced by pointing gestures (Deák, Flom, & Pick, 2000). Most studies investigating the influence of target location on gaze following skills have been live laboratory investigations. The adult sat facing the infant in a room with plain walls and no distractors. Infants were presented with sets of identically shaped objects that were mounted on stands at different locations in space (e.g., Butterworth & Jarrett, 1991; Deák, Flom, & Pick, 2000). Another common way of investigating gaze following was via video-based presentation, with a pre-recorded video of an actor turning towards some targets on screen (e.g., Senju & Csibra, 2008; von Hofsten, Dahlström and Fredriksson, 2005). Video-based paradigms enable more precise eye-tracking measures of the infant responses to different manipulations of both the gazer and the target object, although there is no contingent social interaction with the partner as in live paradigms. In the final study of this thesis, a video-based presentation is merged with a live social interaction by transitioning gaze following research online. This transition was due to COVID-19 and extensive laboratory closure, but it provided the opportunity to investigate a new space, the virtual space that has become increasingly predominant in everyone's life during lockdown and beyond. Further, as this new testing space can't be as controlled as the laboratory, this provides a more naturalistic investigation of infant capacities in the home environment when contrasted with lab-based studies.

1.3 WAYS TO MEASURE ATTENTION AND PERCEPTION ACROSS THE VISUAL FIELD AND IN NATURALISTIC SITUATIONS

We have already outlined the small literature which has investigated how infants orient towards different visual information and processed this information across a wide visual field beyond near-peripheral locations. In this section, we explore those methodologies that have been employed to examine the infant's visual sensitivities and orienting behaviours that can cover a wide visual area. We also address what limits are present for experiments covering a wide visual space. Further, naturalistic investigations and investigations that do not include a screen-based procedure are also considered.

1.3.1 Measures of orienting and information processing across the visual field

As already mentioned, the clinical method to assess the visual field extent is called perimetry. Traditionally, this involves the presentation of light emitting diodes (LEDs) appearing at different eccentricities and on multiple directions along one or more meridians. Detection is determined by recording a meaningful eye/head movement in the target direction that implies the subject's awareness of the stimulus. Light stimuli and LEDs are highly salient and the participant responds to a very abrupt change in terms of luminance. In everyday life, we constantly experience stimuli covering a range of features and saliency. Beyond clinical and perimetry works, the effect of the visual stimuli characteristics on infant attention has been investigated via developmental cognitive neuroscience using stimuli presented on computer displays. These displays often range between 20 and 30 inches and, considering that the young participant normally sits at a fixed distance from the screen (often 50-70cm, according to the indications of the eye-tracking manufacturer), the field of view that can be explored is limited. Both video recordings of the infant's visuomotor behaviour and eye tracking investigations were adopted to investigate visual attention. Remote eye tracking investigations use high-speed infrared cameras to measure the location the observer is looking at relative to a frame of reference, which is often a standard computer monitor (Aslin, 2012). As a consequence, locations beyond the near periphery (30° eccentricity) are very rarely investigated in laboratories. Still, in everyday life visual information comes from a wide array of peripheral locations.

Some developmental methods to investigate a more extended space beyond screen-based presentations are also available. A way to explore visual orienting in wider and more naturalistic environments is through head-mounted cameras. An advantage of these investigations is that the participant can move more freely in the environment compared to screen-based investigations (Franchak, 2017). Further, researchers can gain insights from the infant's point of view and explore more ecologically valid testing situations (Smith, Yu, Yoshida, & Fausey, 2015). These investigations have enabled researchers to observe how the visual environment changes from the child's perspective during hour-long video recordings that could capture several activities. For instance, considering social information processing discussed above, it was possible to quantify the infant's frequency of face exposure during daily activities (Jayaraman, Fausey, & Smith, 2015) or to compare the exposure to faces of crawling and walking infants (Kretch, Franchak, Brothers, & Adolph, 2012). In case of eye tracking investigations, an infrared camera towards one eye is needed in addition to the camera that records the participant's field of view. Combining information from the head and eye cameras includes several complexities (e.g., Nystrom & Holmqvist, 2010; Wass, Smith, & Johnson, 2012). Further, often preverbal participants are not willing to wear head-mounted devices and attrition rates are higher for these studies than remote eye tracking paradigms (Corbetta, Guan, & Williams, 2012).

Remote eye-tracking investigations beyond near-peripheral locations are very sparse. This is due to the fact that most commercial eye tracking solutions do not track screens beyond 28-30’’. These systems provide a higher sampling rate and better data quality compared to head mounted eye trackers (Corbetta et al., 2012). Also, they do not involve wearing a system on the head, which may not be well tolerated by young participants, and are completely non-invasive. Overall, data from remote eye trackers are also easier to analyse compared to data from head-mounted systems because, with the former, gaze and stimuli have the same frame of reference. To the best of our knowledge, only one developmental remote eye-tracking study by Pratesi and collaborators (2015) investigated mid-peripheral locations up to 120° field of view in infancy. This was achieved presenting stimuli on five display monitors arranged side-by-side and it represents the first successful methodological attempt to investigate infant’s gaze via remote eye tracking in a wide space. As a limit, the infant sample of this investigation was very small (nine infants aged 4 to 10 months). In Chapter 4, an eye tracking methodology for tracking the eyes and head across a single wide curved display covering 126° is presented. In comparison to Pratesi and colleagues, we used a single display/environment and we proposed an eye tracking software that was specifically created according to the infants’ facial proportions. Further, data accuracy was improved by implementing an offline gaze calibration. Overall, gaze movements in isolation are not enough to orient towards a visual target beyond near-peripheral locations and head movements become increasingly relevant in a wider space (Franchak, McGee, & Blanch, 2021; Freedman, 2008). More research is needed to explore infants’ gaze behaviour when the eyes, head and body can move freely in space.

1.3.2 Testing outside of the laboratory: online developmental studies

The bulk of research and knowledge we gathered on early development is mostly grounded on controlled laboratory investigations. Exploring infant and child behaviour using remote testing procedures has been a very recent development in the field. This growing interest is linked with the COVID-19 pandemic and with the effort of finding alternative solutions to acquiring developmental datasets outside the laboratory. Beyond this contemporary need for online investigations, there are several advantages of testing remotely (e.g., Zaadnoordijk & Cusack, 2022). First, a significant advantage is that infants are comfortable in their own environment and do not have to travel and adapt to the laboratory, which often differs from the environments that an infant has experience with. Also, online testing makes it easier and potentially less time consuming to get data from diverse geographical locations (although it does not necessarily make easier to reach a more diverse socio-economic sample, as suggested by Lourenco & Tasimi, 2020). Specific advantages and limitations depend on the online testing procedure. Some recent case studies with different approaches to experimental work with children online have been recently summarised by Kominsky and collaborators (2021).

Two main ways of testing remotely can be distinguished. The former is *unmoderated or asynchronous* testing, which happens via a browser-based web platform at the time that suits the participant best and without any interaction with the experimenter during testing. The other way of testing is *moderated or synchronous* testing, which includes a live interaction with the experimenter, often via video chat platforms. Infants and children have been increasingly exposed to digital media and video chat in recent years (Ribner & McHarg, 2021), and online testing enables an understanding of how young participants process information in a virtual space. Moderated testing opens the possibility to understand how children interact with social online information and whether social learning from media changes with increased online exposure. Lastly, moderated online testing is characterised by a video-based presentation, as it is the case of screen-based studies in the laboratory, but it also includes a contingent experimenter/social partner interacting live with the participant, creating an interesting experimental condition to be explored.

The fact that infants are tested in their own home environment, which is often less controlled than the laboratory, makes it interesting to understand if previous developmental studies can generalise to different environments. A recent study by Bochynska and Dillon (2021) measured 7-month-olds' sensitivities to basic shape discrimination online. The authors failed to replicate the results they collected in a past laboratory study of the same research group (Bochynska & Dillon, 2021). They considered highly controlled settings, large screens and specialised equipment that are available in the laboratory but not online as a potential explanation for non-consistent findings. Another recent investigation compared the detection of audio-visual asynchrony in 4- to 6-month-old infants tested via online webcam and via in-lab eye tracking (Bánki, de Eccher, Falschlehner, Hoehl, & Markova, 2022). Overall, data quality and number of valid trials were better in laboratory rather than online settings and a careful data quality assessment of online data was recommended for future research (Bánki et al., 2022). At the same time, Nelson and Oakes (2021) successfully transitioned in-lab infant research to an online unmoderated procedure with 4- to 12-month-olds and reported results in line with the current literature on object perception and motor development. Further efforts are needed to investigate the generalisability of laboratory findings to online settings. Being a relatively new option for experimental research with infants, there is still room for online testing methods to be further improved and investigated. Even though the studies reported above and, in general, most online studies available in the literature have taken advantage of unmoderated procedures when testing infants, the final study of this thesis presents an infant online study based on a live social interaction between the participant and the experimenter. Evidence with toddlers suggested that learning from media may require rich social agency cues (e.g., Tsuji, Fiévét, & Cristia, 2021) and earlier ages have not yet been investigated.

1.4 THESIS OBJECTIVES

The literature in the preceding sections described what is currently known about the extent of the developing visual field and how eccentricity can influence attentional mechanisms, especially orienting behaviours. Investigating early sensitivities to peripheral visual information is relevant to understand how visual information can guide exploratory behaviours and spatial attention. Thus far, the extent of the developing visual field has often been measured by presenting highly salient stimuli that produced abrupt visual changes, such as flashing lights. In everyday life, we not only face alerting scenarios and orient towards abrupt visual changes, but our visual field encounters a multitude of stimuli covering a range of low- and high-level visual features. Given that perimetry studies have used limited visual stimuli across peripheral locations, the literature in the attention domain during development has looked at the effect of various types of stimuli, but within a relatively narrow visual space that does not go beyond near-peripheral eccentricities.

The general goal of this thesis was to investigate sensitivities to low- and high-level visual information across the developing visual field. To address this question, Study 1 (Chapter 2) aimed to measure the extent of the visual field in 9-month-old infants and in a control group of adults across a wide visual area covering a field of view of 126°. Gabor patches were adopted as peripheral targets to ensure optimal control in terms of low-level visual features. In particular, we aimed to measure sensitivity to peripheral information with stimuli that did not produce abrupt changes across the visual field. As discussed in the previous sections, the characteristics of the visual stimulus have a relevance in peripheral information processing from the first stages of development (Maurer & Lewis, 1991). Thus, a second goal of this thesis was to understand if social information may influence visual peripheral processing during development. Although visual acuity is reduced at peripheral locations, orienting to biologically relevant stimuli may have an advantage over non-relevant stimuli even beyond foveated locations (e.g., Johnson, Senju, & Tomalski, 2015).

To explore this issue, Study 2 (Chapter 3) measured sensitivities to face-like stimuli across peripheral eccentricities. The same set up and low-level visual features of the stimuli adopted in Study 1 were used in Study 2. This way, social and non-social peripheral targets differed only by their configuration. Further, the presentation of face-like stimuli enabled us to investigate if target orientation can be influential outside foveated areas or not. Sensitivity to peripheral information was studied in 9-month-old infants as past perimetry work with infants has mostly focused in the first six months of age and there is mixed evidence of whether the visual field is mature or not at this stage of development (Dobson et al., 1998; Lewis & Maurer, 1992; Mayer et al., 1988). In addition, during the second half of the first postnatal year, infants act and explore the surrounding space more extensively and peripheral vision becomes essential for the development of a functional representation of space (Atkinson, 2000).

With the aim of investigating a range of low- to high-level visual information across the visual field, a further focus of this thesis was the more complex information conveyed by intact faces as they enter the developing visual field. While the first two studies focused on detection rates from video recordings, we then proposed a remote eye tracking methodology to track infant gaze and head movements beyond the standard display areas that most commercial eye tracking solutions can provide. Further, a new offline calibration procedure was proposed to improve spatial accuracy and infant data quality throughout the experimental session. This tool and the relative methodological advantages are described in Study 3 (Chapter 4). This method was adopted in Study 4 (Chapter 5) and enabled us to investigate both attention-getting and attention-holding mechanisms associated with the presentation of emotional facial expressions at peripheral locations. In particular, the emotion negativity bias was explored at the edge of the developing visual field in a group of 9-month-old infants. Past evidence has suggested that mature peripheral vision can process some emotion information (e.g., Bayle et al., 2011; Calvo et al., 2006). We suggested that a source of direct threat, such as angry faces, may elicit an early bias even at extreme locations.

Finally, this thesis explored an emerging way of conducting research with developmental populations, that is online testing. Study 5 (Chapter 6) used an online synchronous testing procedure to investigate gaze following skills in different experimenter's eye status conditions. This final study enabled us to investigate more complex face information (i.e., gaze cues) and to transition infant research to a virtual space and a less controlled home environment. If the original idea for this thesis was to transition from screen-based paradigms to more naturalistic live testing situations in the laboratory, this latter naturalistic in-person step was constrained due to the COVID-19 outbreak and the subsequent closure of the laboratory. In order to explore these issues, we developed an online testing procedure suitable for infants that included a live interaction with the experimenter, which is normally not possible during screen-based studies. Further, online testing enabled us to study infants' behaviour in their everyday home environment without adapting the space to match stringent experimental settings, as is typically the case in the laboratory. Hence, testing online represented an alternative way of conducting research in a more natural space. This final study also aimed to understand whether past developmental findings generalised to a less controlled setting outside of the laboratory. In particular, Study 5 explored how infants oriented in a digital space in response to gaze cues.

Overall, this dissertation describes five studies that aim to investigate how different types of peripheral information is processed across the developing visual field. Visual information under investigation ranged from low- to high level (Gabor patches, face-like stimuli, faces expressing emotions, human gaze directed towards objects) and the visual space we considered was either a wide visual area covering up to 126° field of view in a laboratory setting or a more variable virtual space. The thesis commences in the following chapter with a study that examined the visual field extent of 9-month-old infants and a control group of adults. Sensitivities to peripheral information were mapped presenting Gabor patches up to 60˚ eccentricity.

Chapter 2

Identifying the limits of peripheral visual processing in 9-month-old infants

Text as it appears in Capparini, C., To, M.P.S., & Reid, V.M. (2022). Identifying the limits of peripheral visual processing in 9-month-old infants. *Developmental Psychobiology*, *64*(4), e22274. https://doi.org/10.1002/dev.22274

With the exception of the following paragraph added on page 45:

> *“In the present work, the central stimulus faded away before peripheral target onset. This way, we avoided that detection could be influenced by the participant’s willingness to look away from the central stimulus. In fact, the presence of a central stimulus in perimetry studies may inhibit orienting towards peripheral targets and the degree of this inhibition varies during development (e.g., Maurer & Lewis, 1991). For this reason, we started investigating a simple situation where there was no competition for attentional resources (i.e., the onset of the peripheral target followed the offset of the central stimulus). However, future studies could investigate if the present detection measure is influenced by the continuous presence of a central stimulus. In real world, visual information is unlikely to fade away and, thus, investigating a competing condition could reflect a more naturalistic situation.”*

Abstract

Most fundamental aspects of information processing in infancy have been primarily investigated using simplified images centrally presented on computer displays. This approach lacks ecological validity as in reality the majority of visual information is presented across the visual field, over a range of eccentricities. Limited studies are present, however, about the extent and the characteristics of infant peripheral vision after 7 months of age. The present work investigates the limits of infant (9-month-olds) and adult visual fields using

a detection task. Gabor patches were presented at one of six eccentricities per hemifield, from 35° up to 60° in the left and right mid-peripheral visual fields. Detection rates at different eccentricities were measured from video recordings (infant sample) or key press responses (adult sample). Infant performance declined below chance level beyond 50˚, whereas adults performed at ceiling level across all eccentricities. The performance of 9-month-olds was unequal even within 50˚, suggesting regions of differential sensitivity to low-level visual information in the infant’s periphery. These findings are key to understanding the limits of visual fields in the infant and, in turn, will inform the design of future infant studies.

2.1 INTRODUCTION

Detecting information from our rich visual environment is essential to guide exploratory fixations and to register spatial information. Although we rely heavily on central vision for everyday tasks as it offers the most spatial resolution (Curcio, Sloan, Kalina, & Hendrickson, 1990), a large amount of visual information is delivered to more peripheral regions. Interestingly, as much as 99.9% of the visual field lies outside the fovea, so much of visual processing is required in the peripheral field (Rosenholtz, 2016). In our everyday life, peripheral vision is crucial for planning eye movements (Nuthmann, 2014), for visual search in natural scenes (Boucart, Moroni, Thibaut, Szaffarczyk, & Greene, 2013; David, Beitner, & Võ, 2021) and for orienting our attention towards an incoming threat or a sudden change in the environment (Bayle, Schoendorff, Henaff, & Krolak-Salmon, 2011; Rigoulot, D'Hondt, Honoré, & Sequeira, 2012). Peripheral vision also processes optic flow patterns that contribute to balance control and postural adjustments (Berencsi, Ishihara, & Imanaka, 2005; Dickinson & Leonard, 1967).

Although most developmental research has investigated attention and information processing in a relatively narrow portion of the visual field, a number of classic infant paradigms have involved the visual periphery to some extent, mainly within near-peripheral regions (up to 30° eccentricity). Examples include the preferential looking method pioneered by Fantz (1958) or the forced-choice preferential looking method by Teller (1979), together with other experimental variations that have measured gaze-shifts behaviour through the presentation of pairs of stimuli to the left and right of a central spot. Additional examples of well-established methods that involve the presentation of stimuli across the visual field come from the attention domain, with the fixation shift paradigm (e.g., Butcher, Kalverboer, & Geuze, 2000; Hood & Atkinson, 1993) and the gap-overlap paradigm (e.g., Farroni, Simion, Umiltà, & Barba, 1999; Matsuzawa & Shimojo, 1997). Nevertheless, although we have an idea of what is normative in terms of the extent of the mature visual field and its characteristics, significantly less is known about it throughout development. In addition, eccentricity is quite rarely factored in when designing studies such as the ones mentioned above. Beyond near-peripheral locations, it seems that vision at high eccentricities was not really thought of as being a particularly relevant field of infant research. In fact, with the exception of some early perimetry works mostly between the 1970s and 1990s (de Schonen, McKenzie, Maury, & Bresson, 1978; Dobson, Brown, Harvey, & Narter, 1998; Harris & MacFarlane, 1974; MacFarlane, Harris, & Barnes, 1976; Lewis & Maurer, 1992; Mayer, Fulton, & Cummings, 1988; Maurer & Lewis, 1991; Mohn & van Hof-van Duin, 1986; Tronick, 1972), little consideration to locations beyond the near periphery was given in many recent infant research paradigms, possibly due to the difficulty of performing studies across a wide visual field.

In adults, the visual field can extend to over 90-100° temporally from the line of sight, and only moving stimuli are visible in the outermost visual areas (To, Regan, Wood, & Mollon, 2011). With collaborative participants, the visual field has been investigated with a wide range of clinical tools (i.e., perimetry) and research studies have also taken advantage of sophisticated psychophysics techniques (see Simpson, 2017, for a review). Some methodological adaptations have emerged when exploring the development of peripheral vision in infancy (Atkinson, Anker, Rae, Hughes, & Braddick, 2002; Porro et al., 1998). Intriguingly, we know that the newborn infant preferentially orients to the temporal visual field, showing the so-called “externality effect” from birth (Johnson & de Haan, 2015; Lewis, Maurer, & Blackburn, 1985). Nonetheless, the visual field is very restricted at birth when compared to the adult visual field. In fact, previous research suggests that peripheral vision is still developing during the first postnatal year of life with evidence to suggest a progressive visual field expansion during this period of development (de Schonen et al., 1978; Dobson et al., 1998; Harris & MacFarlane, 1974; MacFarlane et al., 1976; Mayer et al., 1988; Maurer & Lewis, 1991; Mohn & van Hof-van Duin, 1986; Lewis & Maurer, 1992; Tronick, 1972). Interestingly, the vast majority of infant research has focused on the first seven months of life (Aslin & Salapatek, 1975; de Schonen et al., 1978; Harris & MacFarlane, 1974; MacFarlane et al., 1976; Mayer et al., 1988; Tronick, 1972) and very limited works covered the remaining months of infancy as well (Delaney, Dobson, Harvey, Mohan, Weidenbacher, & Leber, 2000; Dobson et al., 1998). This is possibly linked with evidence of infants’ visual field reaching the size of adults’ by 6-7 months of age (Mayer et al., 1988; Lewis & Maurer, 1992), although other research has showed a slower development (Dobson et al., 1998; Mohn & van Hof-van Duin, 1986).

At present, firm conclusions about the extent of the developing visual field cannot be easily drawn due to methodological differences across experiments. The Supplementary Table at the end of this chapter provides an overview of seminal works investigating the development of the visual field during infancy, showing how research methods and main results varied across studies. First of all, the variability in stimulus choice used in different developmental studies mean that results across experiments are not easily comparable. Initially, early investigations used real objects with different visual characteristics as peripheral targets (de Schonen et al., 1978; Mohn & van Hof-van Duin, 1986; Tronick, 1972). The use of real objects was then replaced by flashing Light Emitting Diode (LED) lights (Delaney et al., 2000; Dobson et al., 1998; Lewis & Maurer, 1992; Mayer et al., 1988). LEDs are useful but do not allow us to determine the extent to which the infant’s orientation towards the visual periphery is merely a bottom-up response to abrupt luminance changes of the stimulus against the background. In real-world situations, not only abrupt changes are processed in the visual periphery. In fact, peripheral vision is not merely used in situations requiring detection of highly salient visual elements, such as responding to approaching police lights or to other alerting flashing lights appearing in the background, but it also supports a wide variety of tasks in which peripheral information is not always extremely salient, such as scene perception at a glance (e.g., Greene & Oliva, 2009; Larson & Loschky, 2009), visual search in natural scenes (e.g., David, Beitner, & Võ, 2021) or object recognition in natural images (e.g., Thorpe, Gegenfurtner, Fabre-Thorpe, & Bülthoff, 2001). Even among developmental studies adopting similar stimuli, differences in the visual characteristics of those stimuli matter (Delaney et al., 2000; Dobson, Baldwin, Mohan, Delaney, & Harvey, 2003; Delaney, Dobson, Mohan, & Harvey, 2004). For instance, stimulus contrast, luminance and the use of flicker varied across previous studies adopting LEDs and the variation of those characteristics may have an impact in eliciting a response to a peripheral stimulus (See the Supplementary Table for an overview of stimuli and low-level visual features adopted in past studies). In fact, the lateral geniculate nucleus (LGN) of the thalamus is a primary early site of visual processing between the retina and the visual cortex and it relies on parallel processing to analyse distinct sensory features at the same time. Parallel processing in the LGN primarily happens via parvocellular and magnocellular neurons that receive and process complementary spatial, temporal, chromatic, contrast and luminance visual inputs and give rise to different response timings and dynamics (Hubel & Livingstone, 1990; Reid & Shapley, 2002; Schiller & Malpeli, 1978).

Another aspect that should be considered when comparing findings on infant peripheral vision is the procedure used to measure the extent of the visual field. In the last decades, infant studies have relied on static perimetry, kinetic perimetry, or a mixture of both (i.e., hybrid perimetry). Typically, the observer’s attention is focused on the centre of the visual field and a peripheral stimulus either suddenly appears at one of the eccentricities investigated (static perimetry) or moves from the edge of the field towards the centre (kinetic perimetry). Both methods have some limitations. Static perimetry takes longer to map the visual field than kinetic perimetry, and it is thus less suitable for clinical settings and when doing research with moving participants with a limited attention span, such as infants. On the other hand, with kinetic perimetry, detection is credited once the eye movement is initiated. This may result in a misleading impression of a visual field expansion with age, which reflects developmental changes in latency of eye movements that decreases during the first year of life (Aslin & Salapatek, 1975; Maurer & Lewis, 1991). Also, kinetic perimetry may be more influenced by the infants’ willingness to look away from the continuous presence of a central stimulus, whereas with static and hybrid methods the central target can disappear when the peripheral stimulus is presented. These differences in methodology across studies have resulted in variable estimates of the limits of the visual field in infancy (for a comparison of different procedures, see Dobson et al., 1998). To provide an example, Dobson and collaborators (1998) quantified the total visual field throughout development and compared infant with adult values. They showed that by 7 months of age the visual field extent reached 59% of adult values with static and hybrid LED perimetry, whereas it expanded to about 80% of adult values if assessed with kinetic perimetry (Dobson et al., 1998).

The purpose of the present study was to map out the peripheral visual field of 9-month old infants and adults with a robust experiment aligned to the psychophysics tradition used in adult research. We specifically targeted 9-month-old infants as most perimetry studies in infancy did not go beyond 7 months of age (See Supplementary Table) and there is mixed evidence on whether peripheral vision is fully developed at this age (Lewis & Maurer, 1992; Mayer et al., 1988) or not (Dobson et al., 1998; Mohn & van Hof-van Duin, 1986). Additionally, 9-month-olds are the target of many infant studies as this is a key time point in infant motor and socio-cognitive development (e.g., Campos et al., 2000; Cleveland & Striano, 2007; McCrink & Wynn, 2004; Scott, Shannon, & Nelson, 2006). Thus, the current study could inform the design of many infant studies to come. In the current study, all observers were presented with Gabor patches at one of 12 different locations across the visual field (six eccentricities per hemifield, namely 35°, 40°, 45°, 50°, 55° and 60° to the left and right of the midline), and their ability to detect the patches was measured either through orienting behaviour (infants) or through a button press (adults). Gabor patches were chosen as peripheral targets since they drive early visual activity in a controlled fashion and can easily be controlled in terms of low-level features, such as contrast, spatial frequency, orientation, luminance and colour. We wanted to make sure that participants were not responding to a low-level abrupt change across the visual field, as would be the case were we to use flashing lights. This enabled us to investigate sensitivities to peripheral information beyond the most salient and alerting scenarios, but also considering more coherent and ecologically valid situations requiring detection or recognition of information that is cluttered in the visual environment. Our stimulus luminance therefore was matched with the background luminance and our stimulus contrast was not fixed but progressively increased within a Gaussian temporal envelope covering 0-100% contrast levels. In more detail, with the present study we aimed to: (a) investigate the extent and the characteristics of infant peripheral vision as reflected in their orienting behaviour, and (b) compare the infant detection performances with a control group of adults tested with the same experimental stimuli and paradigm used with infants. If the participants' perception across the visual field is similar to a mature visual system, we would expect homogeneous detection rates across eccentricities. Considering the extent of the mature visual field outlined by past research (e.g., To et al., 2011), we hypothesise homogeneous detection rates in the investigated mid-peripheral visual field (from 35° to 60°) for the adult sample. At the same time, if the visual field is adult-like before 9 months of age as suggested by past evidence (Lewis & Maurer, 1992; Mayer et al., 1988), infants are expected to show homogeneous detection performances across eccentricities as adults. Overall, we hypothesise decreased detection performances with our stimuli, which are equiluminant with the background, compared to past studies that presented salient LED lights (which elicited an overall change in luminance levels). A better understanding of visual field sensitivities in peripheral vision in infancy would enable researchers to determine what peripheral visual information can be detected, capture attention and trigger foveation so that it can be further processed in central vision. Understanding the limits of the visual field during infancy can inform future developmental studies particularly in terms of ecological validity: by recognising how far infants can perceive into the periphery, stimuli presentation no longer needs to be limited to the central visual areas and infants can be allowed to freely move their eyes and head to process a wider visual area, thereby reflecting a more naturalistic environment.

2.2 METHODS

2.2.1 Participants

Twenty full term 9-month-old infants were recruited from a large Babylab database of volunteer families living in the surroundings of Lancaster, United Kingdom. Two infants were excluded from the final sample for technical issues (n = 1) or for not providing any valid data due to engagement with own body parts (n = 1). Thus, 18 infants (6 females) aged between 8 months and 15 days and 9 months and 15 days (M_{age} = 278 days; SD = 9.30 days) constituted the final sample of infants. The target sample was initially set to align the present study with previously published work having similar procedures and age of infant participants (Mayer, Fulton, & Cummings, 1988). Additionally, the power to detect the fixed effect of interest (Eccentricity) was calculated from a pilot group of five infant participants with simulation methods, which are suitable for power analysis of generalised linear mixed models. Simulations were run in R using the SIMR package (Green & MacLeod, 2016). Based on 100 Monte Carlo simulations, six levels of the predictor Eccentricity ensured to achieve >80% of estimated power to detect an effect size of 0.05 (power = 88%; 95% CI = 79.98, 93.64).

Parental informed consent was obtained for each participant prior to the beginning of the study. Families received a £10 travel compensation and a story-book to thank them for participating. Additionally, a control group of 20 (14 females) predominantly White adult participants (M_{age} = 28.50 years; SD = 11.52 days) with normal or corrected-to-normal vision participated in the experiment. Most of them were Psychology students or staff. Informed consent was obtained for each participant prior to the beginning of the study. Adult participants received £5 to thank them for participating. The Faculty of Science and Technology Research Ethics Committee of Lancaster University reviewed and approved the protocol of the study (Ethics approval reference no. FST18067). This research was conducted according to the principles expressed in the Declaration of Helsinki.

2.2.2 Stimuli

Participants viewed a series of stimuli, either centrally or peripherally, on a grey background. Central stimuli were white Gaussian blobs and peripheral stimuli were monochromatic vertical Gabor patches with spatial frequency of 0.55 cycles per degree, as in a previous study investigating sensitivity to peripheral targets at the edge of the visual field (To et al., 2011). Examples of the peripheral stimuli are shown in Figure 1A. All stimulus images subtended a 180 x 180-pixel area, subtending a visual angle of 5.88° from a 40 cm viewing distance. Both central and peripheral stimuli were presented within a 900 ms

Gaussian temporal envelope such that the maximal contrast (100%) was attained in the middle of their presentation time (450 ms). In order to ensure that participants' behaviour in response to the peripheral targets was not due to an abrupt luminance change, we ensured that the overall luminance of the stimuli matched with the background luminance of the screen (within 25 cd/m^2). All the stimuli were presented along the horizontal meridian.

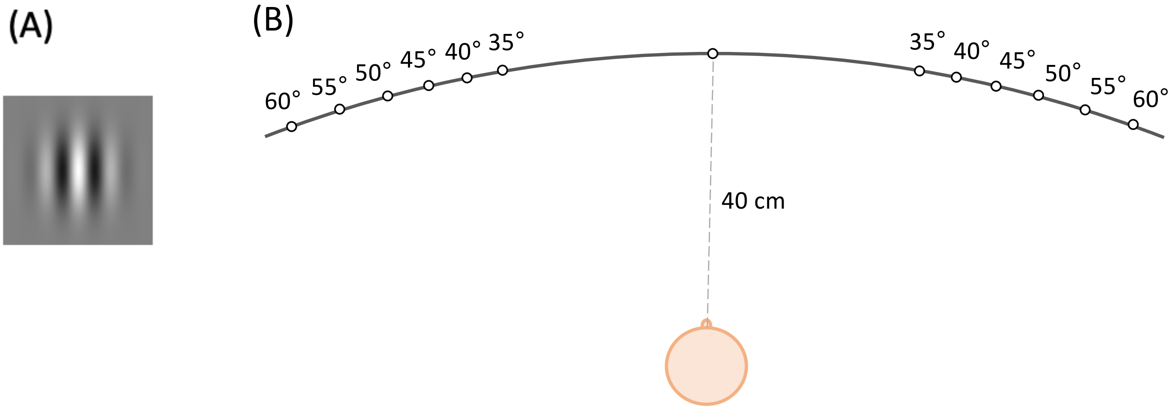


Figure 1. **(A)** The Gabor patch which was presented as the peripheral target. **(B)** The experimental set up with peripheral target locations and participant position.

2.2.3 Apparatus and Procedure

Infants were sat on their caregiver's lap, 40 cm from the centre of a 49-inch curved screen (Samsung LC49HG90DMM, screen resolution 3840 x 1080 pixels, 120.30 cm width and 52.55 cm height without stand) covering 126° Field Of View (FOV). Monitor contrast and brightness were set to 50%. The height of the table and screen was adjusted so that the infant's line of sight corresponded to the centre of all stimuli. Lights were switched off for the duration of the experiment and the area around the computer screen was covered in black felt to minimise light scatter. A hidden video-camera was placed above the screen to track the infant's head and eye movements and an additional video-camera was located behind the participant to record the stimuli presentation. The video-cameras fed into a TV monitor and a digital video recorder behind a separation screen. At the start of each trial, the central Gaussian blob appeared three times in quick succession, fading in and out 3x at 900 ms each (lasting 2.7 s in total). Once the blobs disappeared, the peripheral Gabor patch appeared also three times in quick succession (again, fading in and out 3x at 900 ms each), at one of six eccentricities: 35°, 40°, 45°, 50°, 55°, 60°, either on the left or on the right visual hemifield (See Figure 1B). Each eccentricity corresponds to the visual angle between fixation and the centre of the Gabor patch. The Gabor patch was presented at each eccentricity four times during the experimental session, and the order was semi-randomized. There was a total of 24 trials, with an inter-trial interval of 500 ms. The visual presentation of each stimulus was randomly paired with one of eight auditory tones. These audio clips were taken from the web and included different beep sounds. The study was programmed in MATLAB, using the Psychophysics Toolbox extensions (Brainard, 1997; Kleiner et al., 2007).

For the control group of adults, the set up and the stimulus presentation procedure were the same, except that adults were instructed to maintain their fixation at the centre of the screen throughout the experiment and to press either a left or right key on a computer keyboard to indicate whether the peripheral target appeared to their left or right of fixation.

2.2.4 Data processing and Coding

For infant participants, head and eye gaze orientations in response to the peripheral targets were recorded for offline coding. Video recordings were imported into ELAN software, version 5.9 (Brugman & Russel, 2004; ELAN, 2020; available at https://archive.mpi.nl/tla/elan) for video processing and coding. Each video included the recording of the participant’s face on a side and the recording of the stimulus presentation on the other. Initially, each video was organised in 48 temporal events (24 events corresponding to the central stimulus presentation and 24 events corresponding to the peripheral stimulus presentation). This list of events was saved in ELAN and allowed the coder to retrieve the beginning of each trial without searching this information from the video recording. At this stage, the video was zoomed in so that only the participant’s face was visible to the coder and blind coding could start. The coder double clicked on each event to visualise on a frame-by-frame basis the recording of the participant’s face during the selected time interval and coded the infant’s behaviour. For each trial to be valid, the participant’s head and eyes must be oriented towards the central area of the screen at the offset of the central Gaussian blob presentation. If this condition was met, the observer could code the participant’s behavioural response to the appearance of the peripheral Gabor stimulus, unaware of the target position on each trial. The behaviours were: (a) Fixation or head/eye gaze orientation towards the left hemifield, (b) Fixation or head/eye gaze orientation towards the right hemifield, or (c) No response (including staring at the centre until the end of the trial, looking up, looking down, or looking away from the screen). The coder evaluated the first behavioural response towards one hemifield that could be assessed from a neutral head/eyes position (corresponding to the central stimulus location). This ensured that the eccentricity of the target was as reliable as possible. The infant’s behaviour was assessed from the onset of the peripheral target until the beginning of the next trial. If no orientation towards one side of the screen happened during this time interval, behaviour (c) No response was adopted. These behaviours were later grouped according to the peripheral target location using one of the two following categories: (1) Detection, as either an actual eye gaze fixation towards the target or head/eye gaze orientation towards the hemifield in which the target appeared; (2) No Detection, which could be either head/eye gaze orientation towards the incorrect hemifield or no response. Detection rates were compared across stimulus locations. Successful detection indicated that the peripheral target was perceived and caused an overt behavioural response. To control for any biases in spontaneous eye movements and random orientation towards a specific hemifield, there was an equal number of presentations (at each location) in each hemifield. A second independent researcher (blind to the peripheral target positions) coded a random third of the video recordings and Cohen’s kappa was performed to determine interobserver agreement. Considering coding of our dependent variable, that is, detection of peripheral targets, we obtained near perfect agreement between two coders’ judgments, with 95% observed agreement and $k = 0.89$. In addition, we also determined interobserver agreement considering not only peripheral detection but also trial validity, that is, whether the infant’s head and eyes were oriented towards the centre of the screen before the appearance of a peripheral target. Substantial agreement between judgments was obtained, with 85% observed agreement and *k* = 0.70. In this case, the secondary coder tended to attribute more valid trials than the primary coder, attributing validity even if minor variations in terms of head and eye orientations were behaviourally reported. It is important to stress that, according to the purpose of the study and to obtain a precise measure of the visual field, the infant participant must orient towards the peripheral target from a neutral head and eye position, thus a very careful trial selection is essential.

For adults, key press responses were recorded and classified as either successful or unsuccessful detection: successful when the key press matches the location of the target (e.g., left button when target presented on left), unsuccessful otherwise. Detection rates were compared across eccentricities.

2.2.5 Analysis and Statistics

Generalised linear mixed models (GLMMs) were used to model the data, using the lme4 package (Bates, Maechler, Bolker, & Walker, 2015) implemented in R (version 3.5.2, R Core Team, 2018). A relevant advantage of GLMMS, and of multi-level modelling generally, is that they can incorporate the unbalanced structure of repeats once invalid trials have been removed from our infant data, whereas conventional repeated measures ANOVA requires complete designs and data sets (Judd, Westfall, & Kenny, 2012; Quené & van den Bergh, 2004). Moreover, GLMMs allowed us to consider the multilevel structure of the data sets and thus to control for variation between participants and trials. In this study, detection rate was our dependent variable (binomial link function) and log odds of detection was the model outcome. Participant was included in the model as a random factor to account for the within-subject design. The other model variables were categorical fixed factors: Sex (1 = male; 2 = female) at the individual level, and Eccentricity (35°, 40°, 45°, 50°, 55°, 60°) and Side (1 = left; 2 = right) at the trial level. Confidence intervals (95% CI) were calculated with the Wald method. Models were selected from simple to complex and were compared by Likelihood Ratio Test (LRT) and Akaike Information Criterion (AIC).

2.3 RESULTS

On average, each infant contributed to the analysis with *n* = 12.20 (50.83%) valid trials, thus providing *n* = 219 valid observations in total. Contribution of valid trials as a percentage of all administered trials was similar across eccentricities (52.78% valid trials at 35°, 43.06% at 40°, 52.78% at 45°, 47.22% at 50%, 47.22% at 55° and 61.11% at 60°). The Supplementary Figure at the end of this chapter provides an overview of the percentages of behaviours which made up the Detection and No Detection categories at each eccentricity. We evaluated whether trial-level covariates (Eccentricity and Side) and an individual-level covariate (Sex) improved detection rates of peripheral targets. The null model that only included random effects (AIC = 290.31, LogLik = -143.15) was significantly improved by the addition of Eccentricity as a fixed effect (AIC = 232.91, LogLik = -109.45, $X^2(5) = 67.40$, $p < .001$). The null model was also improved by the inclusion of Eccentricity, Side, and Sex as fixed effects (AIC = 235.63, LogLik = -108.81, $X^2(7) = 68.68$, $p < .001$). However, this model did not improve on the Eccentricity only model which had the lowest AIC and provided the most parsimonious explanation of the infant data. Results revealed heterogeneous performances across eccentricities (see Figure 2).

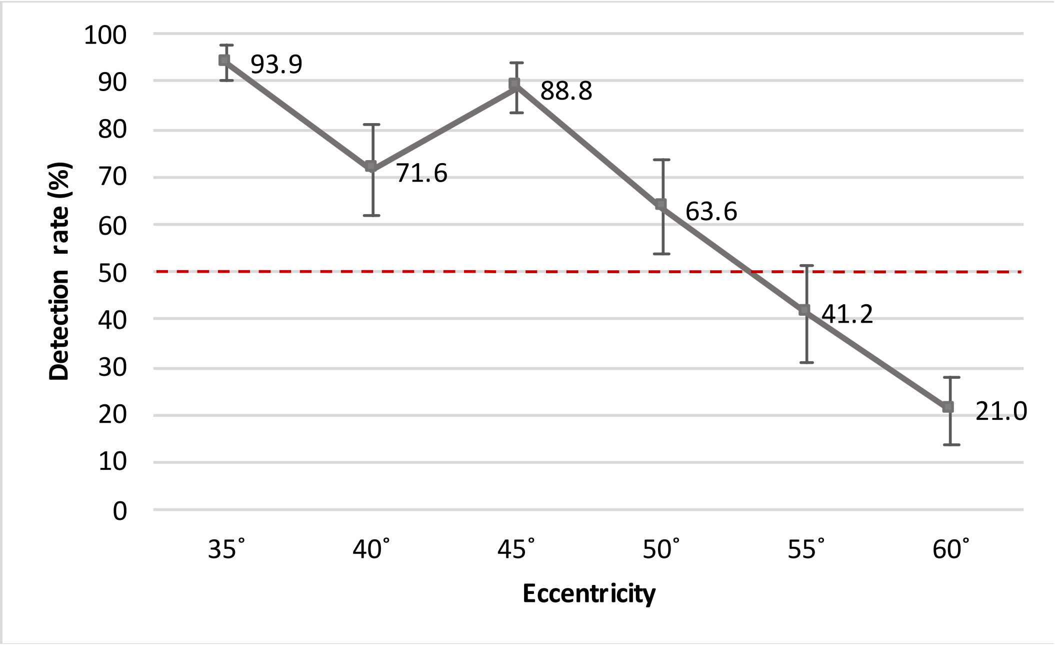


Figure 2. The detection rates of peripheral targets across eccentricities for infants. Error bars represent +/- 1 SE. The dotted line at 50% detection rate represents chance level.

More precisely, infant detection rates dropped at 40° (*M* = 71.60; SE = 9.50) when compared to 35° (*M* = 93.90; SE = 3.80), both in the left and right hemifields. In fact, a generalised linear mixed effects model showed that peripheral targets appearing at 40° were expected to have a 1.82 unit decrease in log odds of Detection than targets appearing at 35° (95% CI = -3.31, -0.32). Performances were still at good levels at 45° (*M* = 88.80; SE = 5.42), to then progressively decrease from 50° onwards, with a 2.18 log unit decrease at 50° (*M* = 63.60, SE = 10.07, 95% CI = -3.66, -0.71), a 3.10 log unit decrease at 55° (*M* = 41.20, SE = 10.20, 95% CI = -4.58, -1.62) and a 4.07 log unit decrease at 60° (*M* = 21.00, SE = 7.06, 95% CI =-5.56, -2.58) when compared to detection rates at 35° (see Table 1). In this model, the Interclass Correlation Coefficient, corresponding to the proportion of variance in the outcome due to individual differences was 15.66%.

Fixed Effects

	Estimate	SE	95% CI	Z	*p*
Intercept	2.74	0.67	1.43, 4.05	4.11	<0.001 ***
Eccentricity (40°)	-1.82	0.76	-3.31, -0.32	-2.38	0.017 *
Eccentricity (45°)	-0.67	0.80	-2.24, 0.90	-0.84	0.402
Eccentricity (50°)	-2.18	0.75	-3.66, -0.71	-2.90	0.004 **
Eccentricity (55°)	-3.10	0.75	-4.58, -1.62	-4.11	<0.001 ***
Eccentricity (60°)	-4.07	0.76	-5.56, -2.58	-5.35	<0.001 ***

Random Effects

	Variance	SD	95% CI
Intercept	0.61	0.78	0.09, 2.02

Table 1. The generalised linear mixed effects model results from infant data. Significance codes: "***" p-value [0, 0.001], "**" p-value (0.001, 0.01] and "*" p-value (0.01, 0.05]. Confidence intervals calculated using the Wald method. Model equation: Detection ~ Eccentricity + (1 | Participant).

Post hoc pairwise comparisons with Tukey's adjustment for multiple comparisons confirmed significant differences between detection rates of peripheral targets appearing at the nearest eccentricity and 50° (95% CI = 0.04, 4.33), 55° (95% CI = 0.95, 5.25) and 60° (95% CI = 1.90, 6.23). Further, detection rates at 60° differed not only from detection rates at 35°, but also from rates at 40° (95% CI = 0.61, 3.90), 45° (95% CI = 1.54, 5.25), and 50° (95% CI = 0.32, 3.45). Also, detection rates at 45° differed from detection rates at 55° (95% CI = 0.58, 4.28).

For adults, each control participant contributed to the analysis with *n* = 24 (100%) valid trials, providing 480 observations in total. Results revealed a clear ceiling effect and did not require further analyses, with 100% accuracy for each of the six eccentricities per hemifield (from 35° to 60° both to the left and to the right of fixation).

2.4 DISCUSSION

This study was designed to measure the limits of infant and adult visual fields using a detection and orientation task. Thus far, prior work has provided mixed evidence about the development of peripheral vision and its extent over the first postnatal year of life and, thus, it has failed to be informative for infant research beyond specialised vision investigations. In the current study, both infants and adults were presented with Gabor patches appearing across a wide visual area covering 126° FOV. The results of the present study strongly suggest that, at 9 months of age, infants' peripheral vision is still developing and the visual information infants can detect varies across eccentricities in their mid-peripheral visual field (from 35° to 60°). Performances were generally above chance up to 50° in the visual field and dropped from 55° onwards. Even within 50°, infants did not show homogeneous detection rates: detection peaked at 35°, dropped around 40°, subsequently increased again at 45° before decreasing steadily beyond 50°, reaching the lowest detection rate at 60°. In contrast, a control group of adult participants performed at ceiling level across all the eccentricities presented up to 60°.

Our infant results appear more conservative than some past investigations that may have overestimated the extent of the infant visual field (See Supplementary Table). For instance, Mayer and collaborators (1988) adopted a LED perimeter and found out that, around 6-7 months of age, the infants' visual field was already almost adult-like, being 93% to that of adults. Similarly, Lewis and Maurer (1992) have suggested that 6-month-olds performed as well as adults in a static perimetry study with flashing lights. In contrast, we obtained similar findings from two out of the three testing methods that Dobson et al. (1998) compared. Our results are in line with both their static and hybrid LED perimetry data, whereas their kinetic perimetry data suggested larger visual field extent compared to the present results. Methodological differences across investigations are therefore relevant and prior findings may have been influenced by highly salient stimuli. Thus, different stimulus characteristics can elicit different detection responses across the visual field. In the present study, we tried to rule out the possibility that participants could respond to abrupt low-level changes (e.g., luminance, colour or contrast changes) in the peripheral visual field rather than resolving the visual stimulus. Even though the vast majority of past studies adopted flashing lights as targets, the human visual experience is not limited to highly salient objects and even less abrupt visual changes can guide exploratory behaviours. Notably, the current investigation fills a void in the literature by presenting a different kind of visual information across the peripheral visual field. Our stimulus avoids any type of sudden onset/offset and abrupt luminance change in relation to the background such as would be produced by flashing stimuli. This enables us to consider peripheral vision as an aspect of information processing independent of changes in luminance and beyond an impoverished by-product of central vision that merely engages with salient or visually arousing stimuli. Clearly, pop-out visual information has a role in engaging attention in the periphery, but real-world scenes are often subtler and do not always involve changes. Peripheral vision is engaged in a wide variety of stimuli and tasks, such as natural scene recognition and visual search. In this study, infants could detect basic stimuli even without abrupt changes in the peripheral visual environment. The interplay of controlled low-level visual features resulted in a more conservative set of results compared to past studies. In fact, abrupt onset, offset or luminance changes associated with stimuli such as LED lights may have increased the involvement of the magnocellular visual subsystem and induced pop-out effects (Theeuwes, 1995). In the present study, we have mapped the visual field sensitivities to a different kind of visual information, controlling some low-level visual features to avoid abrupt luminance changes. Accordingly, the current results suggest that 9-month-old infants can successfully detect basic low-level visual stimuli within 50°. Beyond this limit, it is possible that infants can only respond to significant low-level visual changes and it may well be the case that highly salient stimuli could be needed when detecting a visual target.

Of note, the detection measure that we adopted implies that the peripheral stimulus has been detected and has induced an overt behaviour. Past research has shown that the presence of a competing central stimulus can decrease the probability of orienting towards a peripheral stimulus, with focal stimulus attention inhibiting peripheral orienting behaviour (Aslin & Salapatek, 1975;

Finlay & Ivinskis, 1984; Harris & MacFarlane, 1974; Hicks & Richards, 1998). In such competing situations, heart rate measurements can signal that a peripheral stimulus has been detected even in the absence of a visual orienting response towards it (Finlay & Ivinskis, 1984). In the current paradigm, peripheral targets only appeared following the central stimulus offset, thus the peripheral stimulus was the only visual input on the screen that could potentially engage attention. It could be argued that targets presented at high eccentricities may not cause an overt behaviour or that these stimuli may be less interesting for the infant participant. However, the contributions of behaviours which made up the No Detection category (see Supplementary Figure) indicates that at more extreme eccentricities, that is, 55° and 60°, infants were still orienting towards a hemifield and showing an overt behaviour, but it was more likely that this orienting behaviour was directed towards the incorrect hemifield. In fact, at 55° and 60° around 25% of all the behaviours were orientations towards the incorrect hemifield, whereas this behaviour was marginal at or before 50°. Infants were therefore still engaging and responding during trials with targets appearing at extreme eccentricities, but their orienting behaviour was more random. Further, it seems unlikely that infants would suppress a behavioural response only for some specific target locations.

In the present work, the central stimulus faded away before peripheral target onset. This way, we avoided that detection could be influenced by the participant’s willingness to look away from the central stimulus. In fact, the presence of a central stimulus in perimetry studies may inhibit orienting towards peripheral targets and the degree of this inhibition varies during development (e.g., Maurer & Lewis, 1991). For this reason, we started investigating a simple situation where there was no competition for attentional resources (i.e., the onset of the peripheral target followed the offset of the central stimulus). However, future studies could investigate if the present detection measure is influenced by the continuous presence of a central stimulus. In real world, visual information is unlikely to fade away and, thus, investigating a competing condition could reflect a more naturalistic situation.

It should also be mentioned that most past infant research on peripheral vision had a focus on the first 7 months of age. Measurements of the limits of the infant visual field are rare for age groups over 7 months, although a considerable amount of infant research in psychology investigates the second half of the first postnatal year of infancy. Also, the few infant studies we could use as a comparison reported percentage of infant visual field compared to adult values as their main measure, which does not provide a clear information in terms of eccentricity. Critically, this is the first study which adopted low-level controlled stimuli aligned with the psychophysics tradition to measure not only adult but also infant visual fields at high eccentricities.

Furthermore, the present study showed unequal infant performances even before 50°, with a dip around 40°, although performances were still above chance level. This outcome cannot be fully explained by methodological aspects of the current paradigm. All participants were presented with the same number of trials per eccentricity. Moreover, the final contribution of valid trials per eccentricity was similar and does not explain the heterogeneous detection performances across the visual field. It is feasible that this outcome is tied to the anatomy of the developing retina and the distribution of photoreceptors in infancy. Even though the peripheral retina is relatively mature at birth compared to the fovea, morphological development of photoreceptors in parafoveal and mid-peripheral regions still occurs in the first five postnatal years (Hendrickson & Drucker, 1992; Hendrickson et al., 2008). Intriguingly, although the peripheral retina is relatively mature at early stages, the development of peripheral vision is not faster than central vision, as a better visual acuity for the central field compared to the peripheral field occurs at all ages in infants tested from 10 to 39 weeks of age (Allen, Tyler, & Norcia, 1996). More studies are needed to examine the unequal detection performances in the mid-peripheral visual field during infancy and to shed light on potential explanations.

In everyday life, peripheral vision plays an important role for the developing infant. It is therefore important to estimate how far infants can see across their visual fields. In the infant age range that we tested, locomotion changes the visual experiences that an infant receives. The human infant becomes progressively able to explore the surrounding space more independently with the amount of visual information actively gathered growing dramatically. Peripheral vision plays a role in balance adjustments and the optical flow happening in the visual periphery seems to be essential for a stable standing position (Horiuchi, Ishihara, & Imanaka, 2017) and for walking (McManus, Amour, & Harris, 2017). Also, being sensitive to moving visual targets across the visual field is critical to detect potential threats and to guide the infant's exploratory behaviour. In this context, knowing the boundaries of the infant's visual field and what sort of visual information can be perceived during infancy is essential to understand more about early visual exploratory behaviour together with other aspects of motor and social development. Thus, these data may be informative not only for vision research, but also to set the scene for more naturalistic infant studies across multiple domains including social information processing, object perception, attention, memory, spatial development, motor development and action planning. Along with several domains of developmental psychology and neuroscience, these results could also provide relevant inputs to computational modelling and epigenetic robotics by helping to build a virtual visual environment from which a simulated infant can learn.

It should also be noted that adult results are consistent with past research, which set the edge of the mature peripheral visual field to over 90-100° (e.g., Johnson, Wall, Frisen, & Wagschal, 2016; To et al., 2011). In the present work, we chose to adopt the same apparatus and visual presentation of controlled stimuli aligned with the psychophysics tradition to test both our infant and adult samples. This enabled us to verify that peripheral stimuli detection is relatively easy with mature vision. Although being simple, this paradigm provided results consistent with past adult literature and enabled us to demonstrate, in contrast with some previous evidence (Mayer et al., 1988; Lewis & Maurer, 1992), that at 9 months of age the visual field is not yet similar to that of adults and it is heterogeneous across eccentricities.

2.5 CONCLUSIONS

This work aimed at investigating sensitivities to low-level visual features at 9 months of age and in a control group of adults across the mid-peripheral visual field. In contrast with adult peripheral vision, which is fully developed, this study shows that peripheral vision is clearly still maturing in 9-month-olds and sets infants' successful detection of low-level visual stimuli up to 50° in eccentricity. Infant performance further suggests unequal sensitivities to low-level visual information across eccentricities in the mid periphery. These findings help us define the spatial boundaries of infant visual attention and understand what sort of visual information can be detected and further processed in a wide visual environment. In turn, this study could also be key to setting the scene for further infant experiments in ecologically valid situation where a wider visual field is explored. Future studies may address whether the visual information carried by the target has an influence on the infant's detection abilities even at the edge of their visual field. In conclusion, this is the first study to systematically explore infant and adult sensitivities to stimulus eccentricity utilising low-level controlled stimuli. The results show that it is possible to measure detection and orienting behaviours across the visual field and that peripheral sensitivities are still developing at 9 months of age.

2.6 SUPPLEMENTARY MATERIAL

Table 2 (Supplementary Table). Past seminal research investigating the development of the visual field extent during infancy.

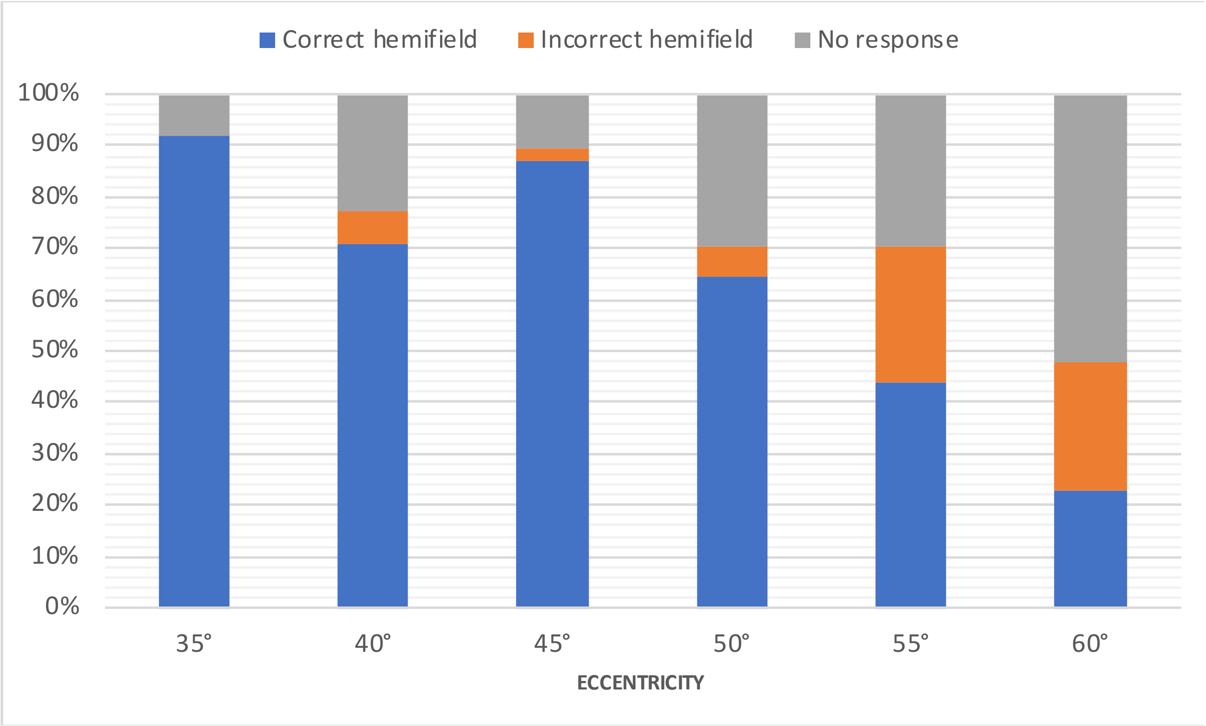
Authors (Year)	Age of subjects	Stimuli	Perimetry	Apparatus	Procedures	Main findings
Tronick (1972)	2 to 10 weeks old infants (longitudinal)	Brightly coloured rectangular solids, 6°x5°x2°	Static perimetry	Semi-circular apparatus with a fixation object at the infant's midline and a movable peripheral object	Peripheral objects moved 10° per trial in a staircase design. The starting point was always 20°. The participant has 15s to make a gaze shift to the target	Effective visual field of 15° at 2 weeks. Expansion of the visual field from around 6 weeks of age if the central stimulus was stationary and the peripheral stimulus was moving, reaching 40° at 10 weeks of age.
Harris & MacFarlane (1974)	1-6 days old and 7 weeks old infants	Light bulbs (4-W) with 1cm/3° diameter. Maximum luminance of 1.6 log fL	Static perimetry	Mattress with a hemicylindrical chamber above. Two bulbs, one at the midline and the other attached to a mobile arm	Peripheral light initially located at 40°, moving 5° closer after 4 negative trials (lasting 5 s). Competing condition (C; i.e. central light remain on) vs. Noncompeting condition (NC; i.e. central light extinguished when peripheral target appeared)	A central light on (C condition) narrows the range of effective vision. Newborns oriented up to 25° in NC trials and 15° in C ones. Older infants showed an effective field expansion above 30° only in the NC condition.

Aslin & Salapatek (1975)	1- and 2-month-olds	Annular stimuli with 2.6cm/4° diameter. Annular luminance of 10fL and background luminance of 2fL	Static perimetry	Supine subjects viewing stimuli on a rear-projection screen reflected into a half-silvered mirror at 45°	Central fixation stimulus followed by either an addition or replacement condition for the peripheral target. Targets could appear along four axes and trials lasted 10s	At both ages, peripheral detection up to 30° along the horizontal and diagonal axes, and up to 10° along the vertical axis. Reduced probability of target detection if the central stimulus remained visible.
MacFarlane, Harris, & Barnes (1976)	Newborns and 1-month-old infants	As in Harris & MacFarlane (1974), plus peripheral light flashing at 60/min	Static perimetry	As in Harris & MacFarlane (1974)	As in Harris & MacFarlane (1974) but allowing non-nutritive sucking	The size of the visual field increased with age but it was narrowed by sucking and by the presence of a central stimulus.
De Schonen, McKenzie, Maury, & Bresson (1978)	2 to 5 months of age	Red and yellow pompoms, 4cm and 12cm in diameter	Static perimetry	Semi-circular white screen. Peripheral objects emerged from behind the movable screen at a distance of either 30cm or 90cm	Four experimental conditions varying object diameter and distance. The central object remained visible and the peripheral one emerged with a fixed eccentricity sequence: 60°, 10°, 50°, 20°, 40° and 30°. Shift of gaze scored in the 5s following peripheral target presentation	Age dependent expansion of the visual field: from 30-40° at 9 weeks to 50-60° at 22 weeks of age. Expansion was related to the object distance, with nearer targets detected further at 2 to 3 months of age but at 4 to 5 months of age.
Mayer, Fulton, & Cummings (1988)	6 to 7 months of age	Yellow LEDs pulsing at 10Hz with a 42 min arc diameter as peripheral targets. Stimulus luminance was 1.2 log cd/m^2 and background luminance was -0.2 cd/m^2. Four red LEDs	Hybrid perimetry	Grey hemisphere with LEDs spaced at 7° intervals on 24 meridia	Monocular and binocular testing. Peripheral stimulus illuminated for 2s and then progressively advanced its position. Each infant tested on eight meridia	Binocular visual field area was 93% that of the adults. Smaller monocular fields, which was 74% of adults' field area, possibly caused by distraction/irritation due to the patch.

		pulsing at 1Hz as central stimulus				
Lewis & Maurer (1992)	Birth to 6 months of age	Lights of 3° and 6° diameter flashing at 3Hz. Light luminance was 167 cd/m^2 on a background of 0.5 cd/m^2	Static perimetry	Black hemicylinder with circular openings at 15° intervals along the horizontal meridia, through which the peripheral lights appeared. Eccentricities from 15° to 120° covered.	Monocular testing. Presentation of either a peripheral target or a blank control trial	Orienting towards stimuli in the temporal field developed more rapidly than in the nasal field. At 6 months, results were similar of those of adults.
Dobson, Brown, Harvey, & Narter (1998)	3.5 to 30 months of age and adults	Yellow LED lights with 3° diameter flickering at 10Hz. Stimulus luminance of 17.2 cd/m^2, background luminance 1.2 cd/m^2	Static and hybrid perimetry	LED perimeter with stimulus apertures at 10.2° intervals, arms extending to 110°	Infants tested monocularly and toddlers binocularly for all perimetries. For static perimetry, peripheral target on for 5s and 12 peripheral locations tested. For hybrid perimetry, sequential illumination of peripheral targets at 2s intervals for 8 locations	Static and hybrid perimetries yielded similar results: 29% of adult values at 3.5 months, 59% of adult values at 7 months and 80% of adult values at 11 months.
		White spheres, 3° or 6° in diameter. Stimulus luminance was 90.4 cd/m^2 and background	Kinetic perimetry	Four-arm double-arch WSKP perimeter, arms extending to 110°	Peripheral stimulus moving towards the centre at 2-3°/s	More adult-like results with kinetic perimetry: 44% of adult values at 3.5 months and 80% of adult values by age 7 months.

		luminance was 2.1 cd/m^2				
Delaney et al. (2000)	3.5 to 30 months of age and adults	LED lights with identical visual features for both perimetry procedures	Hybrid and kinetic	Black double-arc perimeter	In the hybrid procedure, targets were sequentially illuminated from peripheral to central locations. In the kinetic procedure, a peripheral target was manually moved towards the centre	Larger visual field extent for moving than non-moving peripheral targets in infants and toddlers (3.5-, 11-, 17-, and 30-month-olds), not in adults.
Dobson, Baldwin, Mohan, Delaney, & Harvey (2003)	3.5 and 7 months of age, plus adults	White styrofoam spheres; 1.5° and 6° stimulus diameter were compared	Kinetic perimetry	Black double-arc WSKP perimeter	Monocular testing. Peripheral stimulus moving towards the centre at 3.4°/s	Increasing stimulus size produced larger visual field extent in both 3.5- and 7-month olds, but not in adults.
Delaney, Dobson, Mohan, & Harvey (2004)	3.5 and 7 months of age	LED lights and comparison of 6 flicker conditions: no flicker, 1Hz, 3Hz, 10Hz, 20Hz, and 40Hz	Static perimetry	Four-arm double-arc perimeter	Monocular testing	Flicker can increase the visual field extent at both ages. The effect depended on flicker rate: 10Hz and perhaps 3Hz were more effective in enhancing the field extent

Figure 3 (Supplementary Figure). The contributions of behaviours which made up the Detection (Correct hemifield) and No Detection (Incorrect hemifield and No response) categories at each investigated eccentricity.



Prelude to Chapter 3

Does the nature of the peripheral target affect infant detection in the visual periphery?

The first study showed that 9-month-old infants' sensitivities to peripheral information were heterogeneous across a range of eccentricities from 35° to 60°, whereas adult sensitivities were at ceiling. Previous investigations on peripheral vision development mostly used salient flashing lights as peripheral targets (e.g., Dobson et al., 1998; Lewis & Maurer, 1992; MacFarlane et al., 1976; Mayer et al., 1988) and found mixed evidence about when peripheral vision reaches maturation (see, for instance, Dobson et al., 1998 and Mayer et al., 1988). In Study 1, Gabor patches were presented at different peripheral locations while the participant's behaviour was video recorded. These stimuli enabled us to control for several low-level visual features and to map infants' sensitivities in response to less abrupt visual changes across the visual field. We concluded that peripheral vision as measured by orienting behaviour is still undergoing maturation at 9 months of age. Successful detection was possible up to 50°, with unequal sensitivities even before that eccentricity. The findings of Study 1 were relevant to understanding how more cluttered information is detected across the visual field and to set the scene for further infant investigations in a wide visual space.

A question that emerged following this first investigation was whether and how the target content may influence peripheral vision and the boundaries of peripheral processing. Overall, the characteristics of the visual target can influence peripheral detection (Maurer & Lewis, 1991). We know that faces have an advantage over other visual stimuli from the early stages of development (e.g., Johnson & Morton, 1991) and attentional mechanisms differ if faces and other abstract patterns are presented centrally vs. peripherally (Hunnius & Geuze, 2004). Still, most infant studies explored visual presentations within near-peripheral locations. Hence, in Chapter 3 we examined sensitivities to face-like patterns appearing at mid-peripheral locations (50° to 60° eccentricity) in 9-month-old infants. We adopted the same setup and procedures of Study 1 and all the low-level visual features used with Gabor patches (Study 1) were applied to face images to obtain face-like patterns with comparable spatial frequency, luminance, colour, size and contrast. This way, we could exclude that any potential difference in detection rates was due to any low-level visual feature or experimental procedure variation. In Study 2, we focused on those eccentricities in which peripheral detection rates were dropping steadily in Study 1, namely from 50° eccentricity onwards. Having fewer eccentricities under investigation compared to Study 1 enabled us to explore face-like stimuli orientation in addition to eccentricity. Another question that Study 2 investigated was whether target orientation had a role at peripheral locations. While Gabor patches had only one horizontal orientation, both upright and inverted presentations were possible with face-like targets. Evidence suggested that initial orienting mechanisms to peripheral faces are not influenced by orientation; instead, orientation influences processing once the target has been detected (Gliga, Elsabbagh, Andravizou, & Johnson, 2009). Nevertheless, no infant study investigated this beyond near-peripheral locations yet. Consequently, the aim of Study 2 was to investigate the detection of upright and inverted face-like patterns across mid-peripheral eccentricities and to understand whether social and non-social information are processed in similar ways in peripheral vision.

Chapter 3

The detection of face-like stimuli at the edge of the infant visual field

Text as it appears in Capparini, C., To, M.P.S., & Reid, V.M. (2022). The detection of face-like stimuli at the edge of the infant visual field. *Brain Sciences, 12*(4), 493. https://doi.org/10.3390/brainsci12040493

With the exception of the following sentence added on page 72:

> *"However, to date, this is only a qualitative comparison and future work could directly compare the influence of stimulus type statistically."*

And the following sentences added on page 73:

> *"In terms of brain pathways, past research has suggested that face inversion affects both cortical and subcortical structures (e.g., Johnson, 2005). In fact, a bias for face-like stimuli is evident from very early developmental stages when the cortex is still underdeveloped (Johnson & Morton, 1991; Reid et al., 2017). This face preference, initially mediated by the subcortical pathway, may then bias the input received by the developing cortex (Johnson et al., 2015)."*

Abstract

Human infants are highly sensitive to social information in their visual world. In laboratory settings, researchers have mainly studied the development of social information processing using faces presented on standard computer displays, in paradigms exploring face-to-face, direct eye contact social interactions. This is a simplification of a richer visual environment in which social information derives from the wider visual field and detection involves navigating the world with eyes, head and body movements. The present study measured 9-month-old infants' sensitivities to face-like configurations across mid-peripheral visual areas using a detection task. Upright and inverted face-like stimuli appeared at one of three eccentricities (50°, 55° or 60°) in the left and right hemifields. Detection rates at

different eccentricities were measured from video recordings. Results indicated that infant performance was heterogeneous and dropped beyond 55˚, with a marginal advantage for targets appearing in the left hemifield. Infants’ orienting behaviour was not influenced by the orientation of the target stimulus. These findings are key to understanding how face stimuli are perceived outside foveal regions and are informative for the design of infant paradigms involving stimulus presentation across a wider field of view, in more naturalistic visual environments.

3.1 INTRODUCTION

The visual system of the human infant is biased to attend to stimuli that retain typical characteristics of faces. Accordingly, a preference for schematised face-like configurations over inverted ones is widely documented in newborns (e.g., Johnson & Morton, 1991; Valenza, Simion, Macchi Cassia & Umiltà, 1996) and has been reported even before birth (Reid et al., 2017). This predisposition to process and respond to social information can facilitate learning in social contexts and it is a core building block of typical socio-emotional and cognitive development. This early attentional bias towards face-like configurations becomes more specific in favour of human faces with increasing age, with three-month-olds preferring photographic faces over schematised configurations (Turati, Valenza, Leo, & Simion, 2005; Chien, 2011). By four months of age, face processing changes from featural to holistic, a developmental change that is initially orientation-independent and becomes specific to upright faces from seven months of age (Cashon & Cohen, 2004; Cohen & Cashon, 2001). Similarly, preference and recognition for facial features progressively improve through perceptual learning and exposure to faces (Pascalis, de Haan, & Nelson, 2002; Quinn, Yahr, Kuhn, Slater, & Pascalis, 2002). Over the past decades, there has been much debate over the origins of face processing, ranging from different developmental theories to models of the attentional bias for faces and face-like patterns (e.g. Morton & Johnson, 1991; Johnson, Senju, & Tomalski, 2015; Simion, Macchi Cassia, Turati, & Valenza, 2001; Slater et al., 2010; Wilkinson, Paikan, Gredebäck, Rea, & Melta, 2014).

Despite a significant amount of work exploring the development of social information processing, to date, the bulk of research in this field has relied on images presented between central and near-peripheral locations (up to 30° eccentricity), within the limited visual areas that can be investigated using standard computer displays. These parameters incorporate an inherent simplification of the much wider and richer natural environment in which social information spans across the entire visual field. Although central visual areas have higher spatial resolution compared to peripheral vision (Curcio, Sloan, Kalina, & Hendrickson, 1990), the developing human infant can nonetheless process a multitude of information presented at higher eccentricities. When looking at naturalistic scenes, humans are strongly biased towards scenes containing a person compared to those without any person present (Fletcher-Watson, Findlay, Leekam, & Benson, 2008). This bias is present in infants and increases from the ages of 3 to 12 months (Kelly, Duarte, Meary, Bindemann, Pascalis, 2018). In everyday life, orienting towards a face requires more than eye movements. Often, a combination of head and eye movements is needed to detect social information and to navigate the wider surrounding visual environment. Nevertheless, studies of visual information processing have primarily been constrained to standard screens and paradigms where the head remains fixed and engaged with foveal processed space. In reality, faces not only appear in the visual field centrally but can also be presented at different spatial locations, often moving in a dynamic visual world. In this context, foveation alone is often not enough to attend to visual information and motor activity increasingly plays a role in orienting behaviours beyond near-peripheral locations (Freedman, 2008; Stahl, 1999). As such, a successful visual orienting behaviour in naturalistic situations requires the infant to be active and to engage with visual information across a wide visual array. Notably, newborns move their head and eyes to maintain a face in view, more so for intact faces compared to scrambled ones (Goren, Sarty, & Wu, 1975; Johnson, Dziurawiec, Ellis, & Morton, 1991). In an interesting adaptation of these studies, Johnson and collaborators (1991) tested one- to five-month-old infants using a rotating chair that moved away from face stimuli appearing on a screen. In this procedure, infants had to turn their heads to keep the visual targets in view. This paradigm demonstrated that the preferential tracking of actual face stimuli over face-like or scrambled ones declined after one month of age (Johnson et al., 1991). The authors suggested that newborn infants display orienting mechanisms favouring peripheral visual information via a predominance of subcortical structures in the brain, and this behaviour declines between one and two months of age with the maturation of cortical structures (Johnson et al., 1991; Johnson, 2005). Despite such findings, there has been surprisingly little research on face processing at high eccentricities beyond the first postnatal months. Although reflexive orienting to peripheral targets is lessened with age, the motor abilities of the human infant become progressively refined. The ability to sit and stand allows the infants to spontaneously and freely navigate a wider visual space and to actively process a growing amount of information across their visual environment. As such, exploratory and orienting behaviours can be investigated with fewer motor constraints in older infants.

In the present study, we investigated infants' sensitivities to face-like stimuli across the mid-peripheral visual field. Past literature suggested an expansion of the visual field extent over the first postnatal year (e.g., Dobson, Brown, Harvey, & Narter, 1998; Harris & MacFarlane, 1974; Maurer & Lewis, 1991; Mayer, Fulton, & Cummings, 1988). Research in the development of infant peripheral vision has often relied on the presentation of flashing lights. Whilst such stimuli can offer insight into what information infants can process across their visual fields, they are not representative of naturalistic and socially relevant stimuli, such as faces. In this study, we investigated how nine-month-old infants detect and respond to face-like stimuli displayed in their peripheral field. The infant participants were presented with face-like targets across a wide field of view covering 120° (at three eccentricities per hemifield, namely 50°, 55° and 60° to the left and right of the midline) and their orienting behaviour was measured from video recordings in a detection task. At these high eccentricities, eye movements in isolation were not enough to detect a visual target. Motor activity, as a combination of head and eye movements, was required to engage with this task. The face-like stimuli from this study were produced by spatially filtering natural images of intact faces, whilst controlling for luminance, contrast and colour to match with the simple low-level Gabor stimuli used in our prior work (Capparini, To, & Reid, 2022a), which identified the visual limits of 9-month-olds to detect non-social stimuli to be around 50° from the line of sight. In the present study, both upright and inverted face-like stimuli were presented. Unlike Gabor patches, faces have a typical orientation and upright faces are more often encountered in our visual world. To the best of our knowledge, face orientation has never been investigated at the edge of the developing visual field and it is yet unexplored if the developmental changes in holistic face processing happen across the visual field. Hence, this study could also provide insight into the face properties that influence the ability to orient attention across a wide peripheral visual field. Further, unlike processing non-social stimuli, the processing of social stimuli had revealed a left visual field bias associated with right hemispheric dominance for faces (Dundas, Gastgeb, & Strauss, 2012; Yovel, Tambini, Brandman, 2008). This bias seems to develop between seven and eleven months of age (Dundas et al., 2012). Whether this tendency to attend more to faces in the left visual field is present even at the edge of the developing visual field and can be revealed with face-like targets is yet to be determined. If this side bias is specific to central stimulus presentation and/or to more salient face stimuli then no side difference should be expected. Alternatively, a left visual field advantage could emerge over the right visual field. Overall, we aimed to understand whether face-like patterns can elicit different orienting behaviours and capture the infants' attention better when compared to other non-social stimuli.

There is mixed evidence of an advantage for faces at high eccentricities in adult participants. Research with adults has found that the peripheral recognition of faces seems mostly eccentricity-dependent, with a decrease in recognition performances at increased eccentricities that is not predicted by visual acuity and size scaling according to cortical magnification, i.e., the reduced density of photoreceptors processing a visual stimulus at a more peripheral location (Mäkelä, Näsänen, Rovamo, & Melmoth, 2001; Martelli, Majaj, & Pelli, 2005). Further, some neuroimaging evidence supports a face bias in favour of the central visual field, with faces activating visual areas corresponding with the central visual field as opposed to scenes that showed stronger activation in areas representing the peripheral visual field (e.g. Kanwisher, 2001; Levy, Hasson, Avidan, Hendler, & Malach, 2001). Nevertheless, some authors argued that this brain differential activation is not evident if faces and buildings of a scene are rescaled according to cortical magnification (Rousselet, Husk, Bennett, & Sekuler, 2005). Some behavioural evidence has suggested that face or building superiority at peripheral locations depends on the task demands (Jebara, Pins, Despretz, & Boucart, 2009). Even though there may be a central visual field bias for faces, an advantage for peripheral face vs. other object detection has been reported at higher eccentricities (Hershler, Golan, Bentin, & Hochstein, 2010). Similarly, the speed of processing in a categorisation task was better for human faces presented across a wide visual field up to 80° eccentricity compared with animals and vehicles, even in crowded conditions (Boucart et al., 2016). As it stands, an advantage for faces in peripheral vision is still debatable and it may depend on the task.

If there is an advantage for detecting or processing faces at high eccentricities, as some adult studies have suggested, we would expect infants to be successful at detecting peripheral schematic faces at 50° and beyond. Understanding visual field sensitivities in response to face-like configurations would enable us to determine what sort of visual information can capture infants' attention across the visual field and, in turn, be further processed for ongoing learning.

3.2 METHODS

3.2.1 Participants

Twenty-two 9-month-old infants were recruited from a large database of volunteer families living in the surroundings of Lancaster, United Kingdom. Four infants were excluded from the final sample due to fussiness (*n* = 2) and parental interference during the procedure (*n* = 2). Eighteen infants (10 females) with a mean age of 270.83 days (SD = 9.72 days; range = 8 months and 15 days to 9 months and 15 days) constituted the final sample. All infants were born at term (> 37 weeks) with normal birth weight (> 2.5 kg) and had no history of neurological or other medical conditions. Eye infections or vision impairments were among the criteria that excluded participation in this study. Parental informed consent was obtained for each infant prior to the beginning of the study. Participating families received £10 as travel compensation and a storybook to thank them for taking part in this research. The protocol of the study was reviewed and approved by the Faculty of Science and Technology Research Ethics Committee of Lancaster University (Ethics approval reference no. FST19010). This research followed the principles and ethical standards expressed in the Declaration of Helsinki.

3.2.2 Stimuli

Stimuli consisted of either central or peripheral visual images displayed on a uniform grey background. The central stimulus was a white Gaussian blob presented within a 900 ms Gaussian temporal envelope such that 100% contrast was attained after 450 ms. Peripheral stimuli were monochromatic face-like stimuli. These stimuli were obtained from a black and white female face used in Macchi Cassia, Turati, & Simion (2004). Both the upright and inverted face stimuli were adapted for this study. The original background of the face stimuli was removed and stimuli were filtered with a spatial frequency of 0.55 cycles per degree (cpd) using MATLAB (version 2018a; MathWorks, Natick, MA, USA). This specific spatial frequency was chosen as it has been already adopted to present peripheral targets at the edge of the visual field both with adults (To et al., 2011) and infants (Capparini, et al., 2022a). Peripheral targets were presented within a 900 ms Gaussian temporal envelope such that the maximal contrast was attained in the middle of their presentation time at 450 ms. Figure 4 shows the filtered face-like stimuli at maximal contrast. All stimuli subtended a 5.88° visual angle when viewed from a 40 cm distance and occupied a 180 x 180-pixel area. The stimuli were presented along the horizontal meridian. The overall luminance of the stimuli matched with the background luminance of the screen (within 25 cd/m^2). This ensured that participants did not respond to the peripheral targets due to an abrupt luminance change. Overall, the luminance, spatial frequency, colour and contrast of the face-like stimuli matched with the Gabor stimuli presented in a prior study investigating the limits of peripheral information processing by Capparini et al. (2022a). The visual presentation of each stimulus was randomly paired with an auditory tone. A total of eight beep sounds were adopted (the same sounds were used in Capparini et al., 2022a).

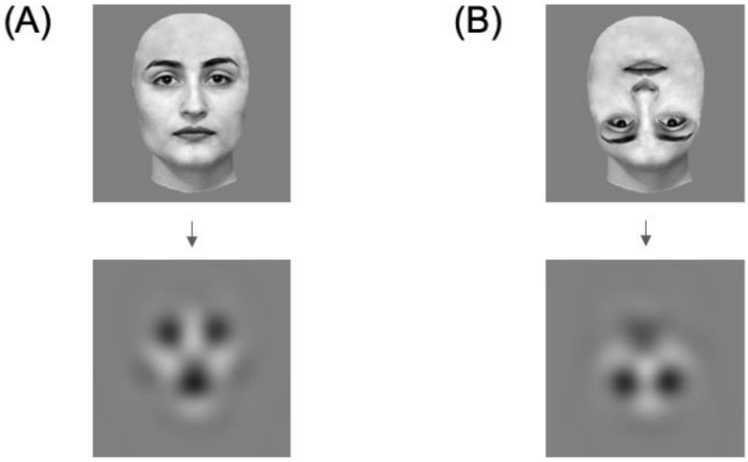


Figure 4. The upright **(A)** and inverted **(B)** face-like stimuli presented as peripheral targets (bottom row). Stimuli were obtained by filtering the upright **(A)** and inverted **(B)** faces (top row) used in Macchi Cassia et al. (2004) at a spatial frequency of 0.55 cpd.

3.2.3 Apparatus and Procedure

Participants sat on their caregiver’s lap at approximately 40 cm from the centre of a 49-inch Samsung LC49HG90DMM curved monitor with a screen resolution of 3840 x 1080 pixels (120.30 cm width and 52.55 cm height without stand). Monitor contrast and brightness were set to 50%. This curved screen covered 126° Field Of View (FOV) in total and was placed on a table whose height was adjusted so that the infant’s line of sight corresponded to the horizontal meridian of the screen. Lights were switched off and the room was only lit by the computer screen. The infant participant’s behaviour was recorded with a hidden video camera above the screen and the experimental procedure was simultaneously recorded with a video camera behind the participant. Black felt covered the area around the monitor and the cameras to minimise light scatter. The two video cameras fed into a TV monitor and a digital video recorder that the experimenter could monitor and that were located behind a room divider. The same room set up, equipment and procedures had been used in Capparini et al. (2022a). Caregivers were instructed to keep their infant in a stable upright position and to maintain the set distance from the screen. They were also instructed to avoid any verbal and non-verbal interference with the testing procedure. The experimental procedure started with the presentation of the central stimulus for 900 ms repeated three times in quick succession, lasting 2.7 s in total. Once this central attention grabber faded away, a peripheral face-like target appeared at one of three eccentricities in the mid-peripheral visual field: 50°, 55°, 60°, either on the left or on the right visual hemifield. Each eccentricity corresponds to the visual angle between the centre of the central stimulus and the centre of the peripheral target. The peripheral target appeared three times in quick succession as the central stimulus (fading in and out 3x at 900 ms each). A total of 24 trials were presented with an inter-trial interval of 500 ms, as in Capparini et al. (2022a). Eccentricity (50°, 55°, 60°), side (left and right) and target orientation (upright and inverted) were semi-randomized across trials. The experimental procedure lasted around 4 minutes. The study was programmed in MATLAB using the Psychophysics Toolbox extension (version 3; Brainard, 1997; Kleiner et al., 2007).

3.2.4 Data processing and Coding

Video recordings were coded offline to measure the orienting behaviour of the infant participant in response to the appearance of a visual target in their mid-peripheral visual field. Video recordings included the multi-camera view of the stimulus presentation and the participant’s face side by side. Videos were processed using ELAN software (version 5.9; Brugman & Russel, 2004; ELAN, 2020; retrieved from https://archive.mpi.nl/tla/elan). For each video, a timeline was created so that each central and peripheral target presentation time (48 intervals per participant) was saved as an annotation that could be easily retrieved and evaluated without searching the stimulus from the video. At this point, each video was zoomed in to allow the coders to see only the infant’s face without being aware of the peripheral target location on each trial. First of all, trial validity was assessed by evaluating the head and eye positions for each central stimulus annotation. For a trial to be valid, the participant must be oriented towards the centre of the screen at the offset of the central stimulus presentation, before the peripheral target appears. If this condition was met, the trial was valid and the coder could proceed to the coding of the behaviour in response to the appearance of the peripheral target. The coder assessed whether the participant (a) oriented towards their left hemifield with eye and/or head movements before the next trial began, (b) oriented towards their right hemifield with eye and/or head movements before the next trial began or (c) had no response or kept staring at the centre for the entire peripheral target presentation, looked up or down or clearly away from the screen. Instances in which the participant could orient towards both hemifields during the peripheral target presentation were rare but, if this was the case, the first clear orientation towards one hemifield was coded. We used the first behavioural response that could be coded from the neutral head and eyes position to ensure that the eccentricity value of the peripheral target was reliable. Once all the valid trials were blindly coded, the behaviours were compared with the target locations and classified either as Detection - if the direction of the orienting behaviour matched the hemifield of appearance of the peripheral target - or as No Detection - if the direction of the orienting behaviour did not match the hemifield of appearance of the peripheral target or if there was no orienting response (behaviour (c)). In this paradigm, detection indicated that the target was perceived and caused an overt behaviour. An equal number of semi-randomised trials at each location and in each hemifield controlled for random orienting behaviours and possible biases in spontaneous eye movements. The coding was accurate to the video frame level, which was 25 frames per second. While the primary blind coder judged all the video recordings, a second independent and blind coder coded a random proportion of the video recordings (8 videos, 44.44%). Cohen's kappa was performed to determine interobserver agreement. Near perfect agreement was obtained between the two coders' judgements, both when they evaluated trial validity and peripheral target detection. Specifically, 93% observed agreement and $k = 0.86$ were obtained judging trial validity, whereas 96% observed agreement and $k = 0.92$ were obtained judging the dependent variable of this study, namely the detection behaviour of the infant participant in response to the peripheral target presentation.

3.2.5 Analysis and Statistics

Detection rates per eccentricity and stimulus orientation were compared across participants. Data were analysed using generalised linear mixed models (GLMMs) with the lme4 package (Bates, Maechler, Bolker, & Walker, 2015) implemented in R (version 3.5.2, R Core Team, 2018). GLMMs have provision to consider the multilevel structure of the data set and, importantly, to incorporate the unbalanced structure of the repeats following the exclusion of invalid trials (for advantages in using GLMMs, see Quené & van den Bergh, 2004). Detection rates were considered as a dependent measure, with log odds of detection as the model outcome. To account for the within-subject design, participant number was included as a random factor. In addition, Sex was included in the model as a categorical fixed factor at the individual level, whereas Eccentricity, Side and Stimulus orientation were included as categorical fixed factors at the trial level. Confidence intervals (95% CI) were calculated using the Wald method. Models were evaluated from the simplest to the more complex and were compared by the Likelihood Ratio Test (LRT) and Akaike Information Criterion (AIC).

3.3 RESULTS

A total of 206 valid observations were obtained, with an average of 11.44 (47.67%) valid trials per participant. Notably, 100% of the investigated orientation behaviours included a combination of eye and head movements that allowed the infant to orient towards the peripheral targets appearing at very high eccentricities. Typically, the saccadic eye movement began slightly before the start of the head movement (55.48% of orientation behaviours) or the eye and head movements were concurrent with each other (43.84% of orientation behaviours). A propensity to move the head before the eyes was extremely rare (0.68% of orientation behaviours). Individual differences played a role in movement timings, with large between-subject variability of eye and head movement tendencies, although this had no relationship with detection outcomes. In fact, the proportion of orientation behaviours in which the eye component preceded the head component ranged from a maximum of 100% to a minimum of 9% of individual orienting behaviours.

We evaluated what factors improved detection rates of peripheral face-like stimuli. The null model only including random effects (AIC = 283.15, LogLik = -139.57) was significantly improved by the inclusion of Eccentricity as a fixed effect (AIC = 258.25, LogLik = -125.13, $X^2(2) = 28.89$, $p < .001$). The inclusion of both Eccentricity and Side as fixed effects further improved the Eccentricity model (AIC = 255.96, LogLik = -122.98, $X^2(1) = 4.29$, $p = .04$). Including Eccentricity, Side and Orientation did not improve the Eccentricity and Side model (AIC = 257.89, LogLik = -122.94, $X^2(1) = 0.07$, $p = .79$). Similarly, including Eccentricity, Side, Orientation and Sex did not improve the Eccentricity and Side model (AIC = 258.01, LogLik = -122.01, $X^2(1) = 0.07$, $p = .79$). Also, an Eccentricity per Side interaction term was added to the model but it did not improve the Eccentricity and Side model (AIC = 257.80, LogLik = -121.90, $X^2(2) = 2.16$, $p = .34$). Thus, we retained the model with lowest AIC which provided the most parsimonious explanation of the data, namely the Eccentricity and Side model (Table 3).

Fixed Effects

	Estimate	**SE**	**95% CI**	**Z**	***p***
Intercept	1.58	0.37	0.85, 2.31	4.24	<0.001 ***
Eccentricity (55°)	-0.59	0.39	-1.35, 0.18	-1.50	0.13
Eccentricity (60°)	-2.01	0.41	-2.81, -1.22	-4.95	<0.001 ***
Side (Right)	-0.66	0.32	-1.29, -0.03	-2.04	0.04 *

Random Effects

	Variance	**SD**	**95% CI**
Intercept	0.20	0.45	0, 1.04

Table 3. The generalised linear mixed effects model (GLMM) results. Significance code "***" p-value [0, 0.001], "*" p-value [0.01, 0.05]. Confidence intervals calculated using the Wald method. Model equation: Detection ~ Eccentricity + Side + (1 | Participant).

Results revealed that detection rates were mostly explained by target eccentricity, with detection rates dropping at high eccentricities, particularly at 60°. Targets appearing at 50° and 55° both led to good detection performances that did not significantly differ from each other, with targets appearing at 55° (*M* = 66.10, SE = 6.47) expected to have a 0.59 unit decrease in log odds of detection compared to 50° (*M* = 77.80, SE = 5.40, 95% CI = -1.35, 0.18). Performances significantly dropped at 60° (*M* = 31.80, SE = 6.38), with a 2.01 unit decrease in log odds of detection compared to targets appearing at 50° (95% CI = -2.81, -1.22). In addition, Side had a partial role in explaining the detection rates results. Overall, better detection rates were obtained for targets appearing on the left side. In fact, targets appearing on the right side (*M* = 51.40, SE = 6.00) were expected to have a 0.66 unit decrease in log odds of detection compared to targets appearing on the left side (*M* = 67.10, SE = 5.75, 95% CI = -1.29, -0.03; Figure 5).

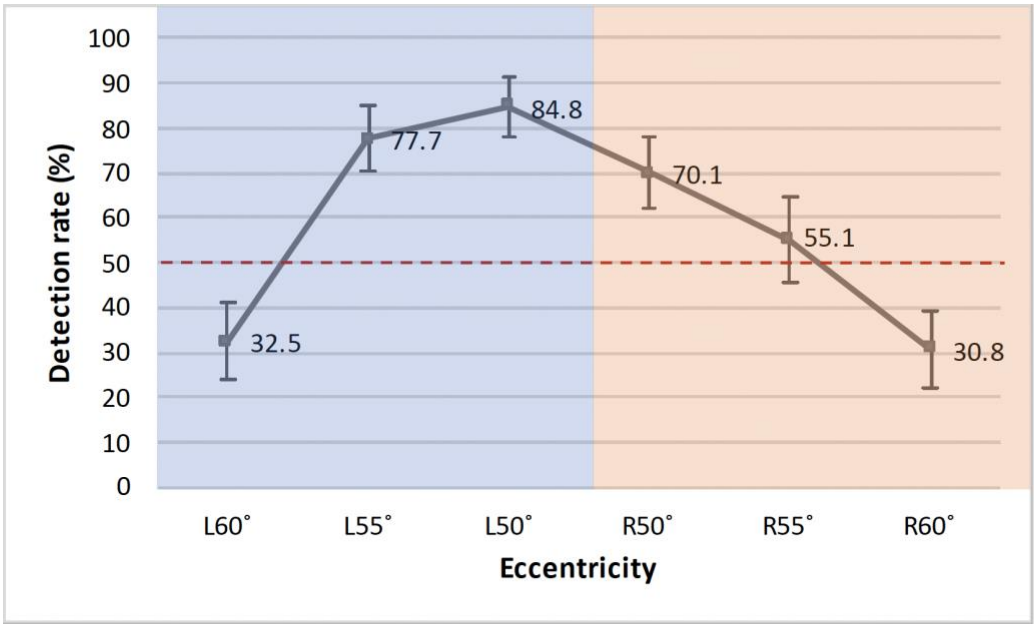


Figure 5. The detection rates of face-like targets across eccentricities in the left (blue) and right (orange) hemifields. Error bars represent +/- 1 SE.

The contribution of valid trials was similar across eccentricities and sides and this factor did not explain these results. In more detail, 71 valid trials were obtained at 50° (31 on the left and 40 on the right side), 68 valid trials were obtained at 55° (34 left and 34 right trials) and 67 valid trials were obtained at

60° (33 left and 34 right trials). A few more valid trials on the right side were localised at 50° where detection performance was at its peak. Thus, this could have favoured detection rates on the right side and does not explain better overall performances on the left side. In this model, the proportion of the outcome variance due to individual differences, as expressed by the Interclass Correlation Coefficient was 5.77%. Post hoc analyses were conducted on the effects that significantly influenced the model. Post hoc pairwise comparisons with Tukey's adjustment for multiple comparisons confirmed no difference between detection rates of peripheral targets appearing at 50° and 55° (95% CI = -0.33, 1.50), whereas significant differences emerged between targets appearing at 50° and 60° (95% CI = 1.06, 2.97) and also between 55° and 60° (95% CI = 0.52, 2.34). Further, detection rates of targets appearing on the left side marginally differed from targets on the right side (95% CI = 0.03, 1.29).

3.4 DISCUSSION

This work aimed to explore face-like stimuli detection at the edge of the developing visual field. The developmental mechanisms behind face detection and processing have thus far been mostly investigated between central and near-peripheral locations, with exploration at high eccentricities absent from the literature. We presented 9-month-old infants with schematic face patterns appearing in the mid-peripheral visual field (50°, 55° and 60°, to the left and right side of a central location) in a detection and orientation task. Our results suggested that detection is heterogeneous across the visual field, with detection rates mostly explained by eccentricity. Specifically, detection progressively decreased with increasing eccentricities, with good detection rates from 50° to 55° and a significant drop at 60°. Overall, detection performances were slightly better for targets appearing in the left hemifield.

In everyday life, we deal with faces entering the visual field at various locations. A combination of head and eye movements is often required to bring faces into foveal view, enabling further processing and social interaction. Nevertheless, most laboratory paradigms have studied the perceptual and cognitive mechanisms behind this social orienting behaviour using standard computer displays where eye movements alone could process the limited visual space under investigation. In the present task, infants always combined head and eye movements to orient towards the peripheral targets appearing at high eccentricities. In line with past adult data (Freedman, 2008; Stahl, 1999), the timing of the eye and head components of the orienting behaviour showed large variability between subjects. Further, the current study showed that 9-month-old infants could detect face-like configurations at high eccentricities, up to about 55° in their visual field. The decreasing detection rates at larger eccentricities may be explained by a developing peripheral vision. Visual acuity in the mid-peripheral visual field does not seem fully mature, as the developed adult visual field extends to around 95-110° eccentricity (To et al., 2011). This is in line with past evidence that reported peripheral vision to develop across the course of the first postnatal year (e.g., Dobson et al., 1998; Maurer & Lewis, 1991). It is of note that the current stimuli were carefully matched with the background luminance and the stimuli faded in and out, gradually reaching maximal contrast. As such, in this paradigm the orientation could not be due to abrupt low-level changes in the visual field such as luminance changes, flashing or flickering of the stimuli. It is possible that more salient images - such as coloured photographs of real faces - can be detected even further in the visual field, but utilizing those in the present study would have confounded low- and high-level visual feature processing with the consequence that we would not be able to make conclusions concerning the drivers behind infant orienting behaviours.

Prior perimetry studies have reported mixed results in terms of the extent and characteristics of the developing visual field. Some studies have implied a developing peripheral vision during the entire first postnatal year (Dobson et al., 1998), whereas other studies have reported adult-like performances around six months of age (Mayer et al., 1988; Lewis & Maurer, 1992). This is likely due to different testing procedures and stimuli adopted across studies, with most studies using highly salient stimuli such as flashing lights and variable procedures. In the present study, we paid particular attention to the low-level visual features of the peripheral targets to ensure that detection was not guided by low-level abrupt changes in the visual field. Further, this study adopted the same testing procedures, paradigm and low-level visual features of the peripheral targets (colour, contrast, spatial frequency and luminance) already used in a prior study presenting Gabor patches as peripheral targets (Capparini, et al., 2022a). Even though both investigations found heterogeneous performances across the developing visual field and decreased detection performances at higher eccentricities, detection was better with schematic faces than with Gabor patches at each investigated mid-peripheral eccentricity. In particular, while detection rates dropped below chance with Gabor patches presented at 55°, the drop was at 60° using face-like targets. This would suggest that, although peripheral vision is still developing, stimulus type can enhance detection and attentional mechanisms even at the edge of the developing visual field. Given that the low-level visual features of the peripheral targets were comparable, the structural configuration of the face patterns likely played a relevant role in detection performance. However, to date, this is only a qualitative comparison and future work could directly compare the influence of stimulus type statistically.

This face advantage beyond foveal presentations is in line with past adult behavioural evidence, such as a more efficient detection of peripheral faces compared with objects or other animals (Boucart et al., 2016). Intriguingly, the authors investigated high eccentricities up to 80°, whereas most studies investigating peripheral processing did not go beyond near-peripheral locations (up to 30° eccentricity). The current data provide evidence of a pop-out attentional response to faces at high eccentricities even during infancy. This advantage may be due to a rapid pre-attentive mechanism for faces that is activated prior to orientation and fixation, as suggested by Herscher et al. (2010) and Fletcher-Watson et al. (2008). At the neural level, this is likely the same subcortical visual pathway that enables rapid detection and reaction to faces and threatening social information, which is evident in the newborn (Johnson, 2005, 2011) and has residual activity in adults (Johnson, 2011; Tomalski, Csibra, & Johnson, 2009; Tomalski, Johnson, & Csibra, 2009). Such a mechanism is critical to quickly detect biologically relevant information and guide the infant’s exploratory behaviour.

Interestingly, infants' detection performances were not influenced by the orientation of the target stimulus. In terms of brain pathways, past research has suggested that face inversion affects both cortical and subcortical structures (e.g., Johnson, 2005). In fact, a bias for face-like stimuli is evident from very early developmental stages when the cortex is still underdeveloped (Johnson & Morton, 1991; Reid et al., 2017). This face preference, initially mediated by the subcortical pathway, may then bias the input received by the developing cortex (Johnson et al., 2015). However, at high eccentricities both upright and inverted face-like stimuli were equally salient and yielded comparable detection rates, independent of their orientation. This finding is in line with past infant research which theorised that initial orienting mechanisms and attention-getting mechanisms are not influenced by face orientation (Gliga, Elsabbagh, Andravizou, & Johnson, 2009). The authors presented 6-month-old infants with circular visual arrays including faces and other objects and found a pop-out effect for faces compared to non-face objects. The first look direction towards faces was not influenced by face orientation, with both upright and inverted faces attracting participants' first looks. In contrast to this, the authors found an orientation effect when measuring attention-holding mechanisms, i.e., those mechanisms involved in maintaining the infant's attention once the visual target has been detected (Gliga et al., 2009). As such, an orientation effect could be evident from measures such as looking duration, number of fixations, or saccadic reaction times (see, for instance, Gliga et al., 2009 for an investigation using the number of fixations in infancy, Valenza, et al., 2015 for a study measuring saccadic latencies in infancy, or Tomalski, Csibra, & Johnson, 2009 for a study using saccadic reaction times with adults). In the present study, looking duration and other measures in the time domain were not easily assessable as both clear fixations towards the target on screen and more general orientations towards the correct hemifield indicated detection. Future studies could address whether attention-holding mechanisms show an advantage for upright face-like patterns compared to inverted patterns even at high eccentricities.

As it stands, we provide evidence that orienting to faces appearing at the edge of the visual field is guided by some general facial structural features; this is consistent with Gliga et al.’s (2009) findings on a face orientation bias at near-peripheral locations. Peripheral vision has a role in rapid orienting towards changes and threats entering the visual field. As such, a rapid orienting response that is not too selective in terms of stimulus orientation may be an optimal solution before faces are further processed. Research with adults has also found no difference in both accuracy and in target-directed saccades to upright and inverted faces presented at peripheral locations in circular arrays (Brown, Huey, & Findlay, 1997). An accuracy difference in favour of upright faces emerged only following some practice with upright faces before the task (Brown et al., 1997). Similarly, Calvo and collaborators (2010) found a happy-face advantage in adults’ peripheral vision which was not affected by stimulus inversion.

The current investigation also showed that detection performances are slightly influenced by the target side, with increased detection rates for filtered faces appearing in the left hemifield compared to the right hemifield. This does not seem to be explained by the contribution of valid trials by side and eccentricity. Interestingly, this side effect was not evident when presenting infants with Gabor patches in the same paradigm (Capparini et al., 2022a). This behavioural advantage for face-like stimuli appearing in the left visual field field is in line with a left visual field bias for face processing developing within the first postnatal year (Dundas et al., 2012; Guo et al., 2009) and could reflect an emerging functional cerebral dominance in the right hemisphere (e.g., Carey & Diamond, 1980; Kanwisher & Yovel, 2006; Levine, Banich, & Koch-Weser, 1988; Yovel et al., 2008). Past research has mostly focused on an early bias to attend towards the left hemiface (Dundas et al., 2012; Guo et al., 2009), which has also been linked with left social positioning biases and cradling behaviours that favor right hemisphere processing (Forrester, Davis, Mareschal, Malatesta & Todd, 2019; Giljov, Karenina, & Malashichev, 2018; Malatesta, Marzoli, & Tommasi, 2020). Interestingly, the present study provided some preliminary indication of lateralisation of face processing at high eccentricities, beyond centrally presented faces and side biases within the face. Although side had a marginal role compared to eccentricity in explaining the detection rates, this bias could emerge from or soon after 9 months of age (Dundas et al., 2012; Davis, Donati, Finnegan, Boardman, Fletcher-Watson, & Forrester, 2022). Future investigations may address whether this effect is more pronounced in older infants and whether there may be a neural correlate of a left visual field superiority for detection of face patterns at the edge of the developing visual field.

3.5 CONCLUSIONS

Sensitivities to face-like stimuli are unequal at the edge of the visual field of 9-month-old infants. Detection progressively decreased at higher eccentricities, with successful detection rates up to about 55° in the mid-peripheral visual field. Infant performance further suggested a marginal influence of the target side, with an advantage for stimuli appearing in the left hemifield. Compared with a past investigation adopting identical procedures and low-level visual features of the non-face peripheral targets, the present findings revealed increased peripheral sensitivities to face-like stimuli. Overall, this work suggests that the spatial boundaries of infant visual attention may be influenced by the stimulus type even at very high eccentricities. These findings may be informative in developing future studies investigating wide natural scenes. In conclusion, this is the first study to identify the limits of infants' peripheral information processing utilising face-like stimuli across a wide visual field of over 120°. The results show that peripheral sensitivities to face-like targets are mostly predicted by eccentricity.

Prelude to Chapter 4

Is it possible to investigate attentional mechanisms at the edge of the peripheral visual field with eye tracking tools?

The first two studies of this thesis investigated 9-month-olds' sensitivities to Gabor patches (Study 1) and face-like stimuli (Study 2) presented across a wide field of view of about 120°. Overall, we found that detection performances (as measured by head and eye orientations to peripheral targets) decreased with increased eccentricity. Also, a qualitative increase in detection performances was found with face-like stimuli than with Gabor patches. Study 2 suggested successful detection of face-like stimuli up to 55° eccentricity, without any influence of target orientation on peripheral detection. Of note, the boundaries of peripheral processing have been previously set at 50° when presenting Gabor patches in Study 1. These findings suggested that faces may retain an advantage even at peripheral locations, despite poorer visual acuity in peripheral vision compared to more central locations. Both studies presented so far took advantage of video recordings that allowed to investigate whether a target was detected or not in a dichotomous fashion.

The successful detection performance in response to face-like targets at mid-peripheral locations opened up the possibility to better explore social information processing at high eccentricities and to focus on the quantitative characteristics of eye and head movements in response to peripheral faces. Namely, we wanted to investigate not only attention capture (as in Study 1 and 2) but also attention-holding mechanisms (such as dwell time) with eye tracking techniques. To achieve this, the spatial constraints of most commercial eye tracking solutions (supporting displays up to 28-30 inches) were limiting the possibility to collect eye tracking data across a wide visual field. In Chapter 4 (Study 3), we aimed to collect infant eye and head tracking data across a horizontal field of view up to 126°. In the past, a similar solution was piloted by Pratesi and collaborators (2015) using multiple displays. In our study, we tested this eye tracking solution in a larger sample of infant participants and we tracked a single wide visual area. Further, we focused on data quality and an offline calibration tool to improve spatial accuracy was presented.

Chapter 4

Offline calibration for infant gaze and head tracking across a wide horizontal visual field

Text as it appears in Capparini, C., To, M.P.S., Dardenne, C., & Reid, V.M. Offline calibration for infant gaze and head tracking across a wide horizontal visual field. In review in *Sensors*.

Abstract

Most well-established eye tracking research paradigms adopt remote systems which typically feature regular flat screens of limited width. Limitations of current eye tracking methods over a wide area include calibration, the significant loss of data due to head movements, and the reduction of data quality over the course of an experimental session. Here we introduced a novel method of tracking gaze and head movements that combines the possibility of investigating a wide field of view and an offline gaze calibration procedure to enhance the accuracy of measurements. A 4-camera Smart Eye Pro system was adapted for infant research to detect head and gaze movements across 126° of the horizontal meridian. To accurately track this visual area, an online system calibration was combined with a new offline gaze calibration procedure. Through a simple interface, 6 samples in which the infant participant looked at the visual target were selected per participant and used for offline calibration. Results revealed that the proposed system successfully tracked infants' head and gaze beyond the average screen size. The implementation of an offline calibration procedure improved validity and spatial accuracy of measures by correcting a systematic top-right error (1.38˚ mean horizontal error and 1.46˚ mean vertical error). This approach could be critical for accurate physiological measures derived from the eye and represents a substantial methodological advance for tracking looking behaviour across both central and peripheral regions. The offline gaze

calibration is particularly useful for developing populations such as infants, and in people who may have difficulties in following instructions.

4.1 INTRODUCTION

Eye tracking represents an accessible and non-invasive tool capable of measuring looking times, recording saccadic behaviours, assessing physiological ocular measures, such as pupil dilation, and shedding light on mental processes (Aslin, 2012; Holmqvist & Andersson, 2017; Wass, 2016). Due to the low level of cooperation required from participants, eye tracking techniques are particularly suitable for non-verbal participants and participants who are unable of following instructions, such as infants. In the last decades, eye trackers have allowed researchers to explore infant development and gain significant insights into early perception and cognition (see Aslin & McMurray, 2004; Gredebäck, Johnson, & Von Hofsten, 2010; Oakes, 2012, for reviews on eye tracking in infancy). Even though eye tracking is a valid tool for addressing a variety of research questions about infant perception and cognition, researchers are constantly faced with technical challenges and constraints. As outlined by Oakes (2012), some of these challenges include head movements (raising the possibility of missing data if participants move the head outside the trackable area and the system must find the eye coordinates again), obtaining a good calibration, experimental design implementation and data processing required to analyse the data. Whereas the two latter aspects are more related to the analytical and technical skills of the researcher before and after data acquisition, the former two are closely linked with the infant population and as such, will be the focus on this paper. Additionally, some challenges are related to the physiology of the infant eye, both in terms of anatomical differences between the structure of the developing eye compared with the adult eye, and in terms of typical features of infants, such as the tendency for wet eyes. Anatomical differences will be also considered in the present work.

To some extent, the impact of head movements depends on the trackable area available for eye tracking which, in turn, depends on the device used to measure eye movements (Niehorster, Cornelissen, Holmqvist, Hooge, & Hessels, 2018). Two broad categories of eye-tracking devices are generally available for infant participants: remote and head-mounted (or wearable) systems. The most well-established eye-tracking paradigms in infancy have taken advantage of non-intrusive remote eye-tracking systems (e.g., Johnson, Amso, & Slemmer, 2003; Richmond & Nelson, 2009; Senju & Csibra, 2008). Most commercial solutions support regular flat screens up to 27-inches in size (or up to 30-inches with some limitations). Although small head movements are tolerated by many eye-tracking solutions, the eye’s image is usually lost outside the screen area and has to be reacquired following each tracking loss. According to Tomalski and Malinowska-Korczak (2020), infant participants spend about 10% of a standard eye-tracking session looking away from the monitor, resulting in missed data each time the system has to recover the eye’s image. These spatial constraints restricted by the area of a regular screen mean that gaze orienting behaviours are mostly investigated through the contribution of the eyes, while the head is held in a relatively stable position. In contrast, in everyday situations we orient thanks to both eyes and head movements. Even though such paradigms have enabled valuable insight into infant’s visual behaviour in response to stimuli, more ecologically valid investigations that span across wider visual locations have been limited. To the best of our knowledge, so far, a single study - Pratesi and collaborators (2015) – has adopted a remote eye-tracker to investigate infant gaze behaviour beyond near-peripheral locations (hence, beyond 30°). This was achieved by using five screens (a central screen and two additional screens on each side) across 120° field of view. In addition to remote eye-tracking systems, the development of head-mounted eye-tracking systems has enabled an alternative method that allows free head and body movements and the possibility of investigating a wider three-dimensional space (Franchak, Kretch, Soska, & Adolph, 2011). Some young participants do not, however, respond positively to a wearable system on their heads, and may easily displace or remove the device. Further, these devices can be complicated to set up, resulting in higher overall attrition rates (Corbetta, Guan, & Williams, 2012).

The current study is aimed at testing a remote system that is not invasive for the participant and, at the same time, measures across a wide field of view of 126°. We defined a wide field of view extending beyond the near-peripheral locations (+/-30°) which can be investigated using regular screens supported by most remote eye-tracking solutions. Measuring gaze movements across the visual field opens the possibility of studying the developing visual behaviour in a more naturalistic and unconstrained visual environment. The limitation of a restricted trackable area in which the pupil position can be accurately detected is overcome by using multiple infrared cameras. In the present work, a 4-camera system allows tracking both the contributions of the eye relative to the head and the contributions of the head relative to the spatial environment. This work builds upon the initial investigation across a wide visual field of Pratesi and colleagues (2015), who piloted a similar system on a small group of nine infant participants. The present work extends this approach to a larger sample and to a single and wider screen, while taking advantage of new software specifically adapted to the developing head and eyes. The current multi-camera set up enables researchers to investigate infant perception and cognition beyond standard screen sizes and, potentially, to define a tracking area even without a screen (see, for instance, applications of similar eye-tracking systems in the automotive field in order to track drivers' eye movements across different car spaces; e.g., Trösterer, Meschtscherjakov, Wilfinger, & Tscheligi, 2014). Applications of this system include a range of studies investigating visual behaviour beyond a limited trackable area, in the context of a participant who is less constrained to direct their visual attention to a standard screen space. Visual orientation could be monitored while participants move their heads in an active 'real-world' exploration. At the moment, similar investigations are mostly carried out with head-mounted systems, with the limitations described above.

The second challenge of eye-tracking in infancy research which is addressed in this paper is *calibration*. Every eye-tracking system relies on calibration and quality of the data often depends on this (Gredebäck, Johnson & von Hofsten, 2010). In fact, the data provided by the system (e.g., gaze positions) must be mapped onto the stimulus/display area. Eye-tracking data collected from infants are not always reliable and this can even lead to apparent differences in gaze behaviour when different groups of individuals are compared (Dalrymple, Manner, Harmelink, Teska, & Elison, 2018; Wass, Forssman, & Leppänen, 2014). Among the relevant parameters in evaluating data quality, this paper specifically focuses on (1) spatial accuracy, as this is limited by the quality of the calibration procedure, and (2) robustness (i.e., data loss) as it is linked with the trackable area available. For a focus on precision, a third parameter of data quality, see Wass et al. (2014). Spatial accuracy (offset) refers to the distance between the actual location of the stimulus that a participant is looking relative to the gaze points recorded/extracted by the eye-tracking system (Holmqvist, Nyström, & Mulvey, 2012; Wass, 2016). Traditionally, this is achieved by asking participants to maintain fixation at a number of small visual targets (usually 9 for adults) at predefined locations on the screen. This means calibration is more difficult with young infants who cannot follow such instructions, resulting in a spatial offset of 1-2° (Aslin, 2012). In developmental studies, highly attractive stimuli (e.g., moving or looming colourful images paired with sounds) are typically used and calibration points are significantly reduced to 5 or even 2 in some cases (Aslin & McMurray, 2004). Notably, not all attractive stimuli result in a high accuracy calibration. A recent investigation by Schlegelmilch and Wertz (2019) compared the impact of different calibration targets on infant's attention and found that some targets, such as complex concentric animations or stimuli with the highest contrast at their centre, elicited more accurate gaze than others. In addition, taking the infant's limited attention span into account, calibration should ideally be as brief as possible so that the infant is not too tired and remains cooperative during the following experimental procedure (Aslin & McMurray, 2004). For these reasons, optimal infant gaze calibration is not always achievable before the start of an experiment and, as it stands, there are currently no standard or prescribed calibration guidelines for researchers (see Oakes, 2010, about publishing eye-tracking data in infancy research). For instance, important considerations, such as the criteria that determine whether the calibration is valid and whether it should be adjusted or repeated during the experiment, are not standardised across studies (Oakes, 2012). The efficacy of a calibration procedure in producing accurate gaze measurements has been rarely included in empirical infant research, although it has been previously recommended as a factor of importance for methodological descriptions (Dalrymple et al., 2018; Hessels & Hooge, 2019). Studies using young participants have revealed evidence of systematic calibration errors and low spatial accuracy compared with the manufacturer's estimates (Dalrymple et al., 2018; Frank, Vul, & Saxe, 2012; Morgante, Zolfaghari, & Scott, 2012).

More generally, eye-trackers often show a systematic error even with adult data and after careful calibration (Hornof & Halverson, 2002). To overcome this issue, post-hoc (or implicit) offline calibration has been proposed as a successful approach to replace calibration methods that require explicit collaboration from the participants (Noris, Keller, & Billard, 2010; Wang & Ji, 2018) or as an additional step to improve data quality (Blignaut, Holmqvist, Nyström, & Dewhurst, 2012; Frank et al., 2012; Hornof & Halverson, 2002; Vadillo, Street, Beesley, & Shanks, 2015; Zhang & Hornof, 2014). This procedure normally includes recalibrating individual gaze points at various times during the study, by correcting the error between the recorded gaze data of a participant and the actual location of the visual stimulus. To date, offline calibration methods to correct eye-tracking offset have been rarely adopted in infancy research (Frank et al., 2012). In the present work, we combined an online system calibration with a novel offline implicit gaze calibration to improve the spatial accuracy of the eye-tracking system. The latter was possible as visual targets appeared at stable and predetermined positions during the experiment. Consequently, our simple interface allowed us to improve data quality using this offline calibration technique.

4.2. METHODS

4.2.1 Dataset

Eye-tracking data from an ongoing project which involved 35 (18 females) 9-month-old participants were used for this study. Four infants were excluded either for technical issues which caused complete data loss (*n* = 3) or for the unintended inclusion of parental gaze (*n* = 1). Thirty-one infants (16 females) with a mean age of 275 days (SD = 9.1 days) constituted the final sample. All infants were born full term (> 37 weeks) with normal birth weight (2.5 - 4.5 kg) and were typically developing. Sensory impairments and eye infections were among the criteria that excluded participation in this study. Participants were recruited via email or phone invitation from the Lancaster University’s Babylab database of volunteer families. All parents gave informed written consent prior to the beginning of the study. Families received a £10 travel compensation and a storybook to thank them for participating. The Faculty of Science and Technology Research Ethics Committee of Lancaster University reviewed and approved the protocol of the study (project ethics approval reference no. FST19121, under the programme of studies with approval reference no. FST18067). This work was conducted according to the principles expressed in the Declaration of Helsinki.

4.2.2 Apparatus

Eye-tracking data were recorded with a Smart Eye Pro 4-camera system (Smart Eye AB, Gothenburg, Sweden) running at 60 Hz. This is a corneal-reflection remote system capable of recording gaze at 0.5° accuracy under ideal conditions. A machine learning algorithm initially detects the participant’s facial features. Then, the system uses glints (i.e., the reflections of the infrared flashes on the cornea) to find the centre of the eyes (Pratesi et al., 2015). For this project, Smart Eye provided a modified version of the Smart Eye Pro software, version 8.2, which was specifically adapted to the anatomy of the developing head and eyes. These modifications of the head model have been recently released as an additional child head module that can be enabled in Smart Eye Pro® from version 9.0 onwards. Smart Eye Pro features flexible camera placements that can be adjusted based on the needs of the user. The number of cameras used can vary depending on the span of the visual environment being investigated. In order to cover the entire horizontal Field Of View (FOV) of 126°, four cameras were positioned below the display monitor, a 49-inch Samsung LC49HG90DMM curved screen (120.30 cm width and 52.55 cm height without stand, 3840 x 1080 pixels resolution). The four cameras located across the visual field captured data from both eyes or from a single eye based on the head position, and help to account for large head movements. Three 850 nm wavelength infrared flash producers were placed between the cameras (see Figure 6(A)). Using active infrared illumination to illuminate the participant’s face, the system is described by the manufactured as ambient light independent. As such, the effect of ambient lighting conditions should not necessarily affect data outcomes. This system enabled an accurate identification of gaze direction in a wide visual field, by measuring infants' eye and head components and by using this information to extract their overall orienting behaviours. Visual stimuli were displayed using the Psychophysics Toolbox extensions (version 3; Brainard, 1997; Kleiner et al., 2007) in MATLAB (version 2018a; MathWorks, Natick, MA, USA), which was running on a Dell Latitude 5491 computer managed by the experimenter. The visual stimulus presentation managed by MATLAB and the Smart Eye eye-tracking recordings were connected via User Datagram Protocol (UDP) and were both reading the local time from the computer.

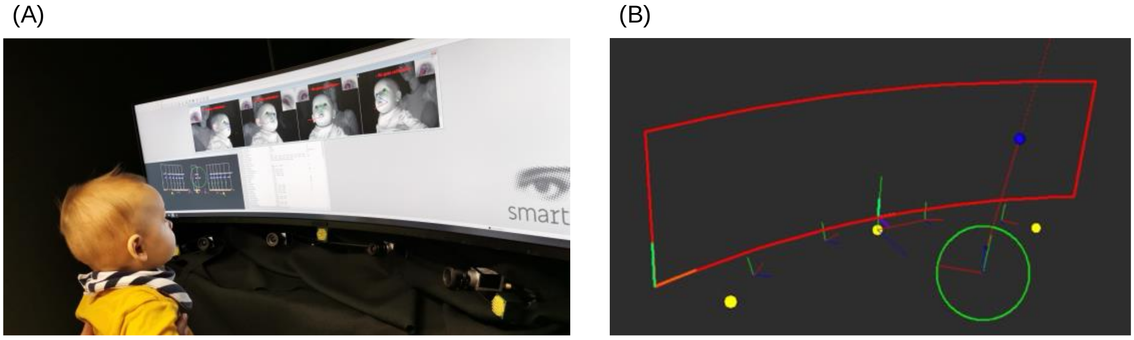


Figure 6. **(A)** Photographic representation of the apparatus adopted in this study. The eye-tracking system, including four cameras and three infrared flashes, was positioned below the display monitor. In this picture, the participant was ready for the system calibration step. **(B)** Image taken from the recording interface displaying the infant's head (green circle) and their gaze position (blue dot) on the curved monitor (red area) during the experimental procedure. The yellow dots represent the three infrared flashes and the four cameras were located in between those.

4.2.3 Experimental procedure

Infant participants sat on their caregivers' lap at 40 cm from the centre of the curved screen. At this distance, the screen covered 126° horizontal FOV and enabled the presentation of visual stimuli up to 60° on each side. Notably, this approximately covers the full visual field available to infants at the tested age (Capparini, To, & Reid, 2022a, 2022b). Most commercial eye-tracking solutions work best at a specific distance (usually between 55-70 cm), whereas the cameras adopted here have an optimal camera-eye distance ranging from 30 to

300 cm, due to adjustable lenses and camera positioning. Caregivers were instructed to maintain their infant in a stable, upright position at a constant distance from the screen. They were also requested to avoid talking and interfering with the infant's looking behaviour during the experimental procedure. Lights were switched off, but the room was lit by the computer screen (screen luminance during the experimental procedure was around 25-26 cd/m^2). This lighting choice limited the possibility of distractions and ensured constant lighting across participants.

Before the experiment started, an eye-tracking system calibration was performed in two phases. First, the positions of the four cameras were examined to ensure that the infant's face was well centred on all cameras (if not, each camera could be rearranged slightly until the participant's face fell within a central headbox provided by the calibration software). The brightness (aperture) and focus settings of each camera were then visually assessed relative to the participant's face and adjusted if required. Optimal aperture and focus settings were reached when the two bars surrounding the participant's face in the Smart Eye Pro's Graphical User Interface (GUI) approached their maximum capacity. In our experimental set up, maintaining the same lighting conditions and the same participant positioning relative to the equipment across participants helped to reduce the adjustments of aperture and focus. In this phase, the caregiver was instructed to maintain the infant's face within the headbox displayed on screen. After that, a small chessboard provided by the manufacturer was placed in front of the participant's eyes (in the centre of the screen) to allow the system to automatically calculate the current position of the four cameras with respect to the entire setup and, in turn, to extrapolate the head and eye positions. From this central position, the chessboard was tilted and rotated until the progress bar of the Smart Eye Pro's GUI was filled for each camera, so that each camera could detect the chessboard. In this phase, the chessboard was required to be visible in each camera view. It is advisable to place it in front of the participant's face, towards which the cameras are already facing, to obtain strong calibration results in that region. This step is required for the software to learn the positions and orientations of the cameras and should be performed each time the camera positions change. In our study, this procedure was performed before each testing session, as advised by the manufacturer. The system calibration was checked using a “Verify Camera Calibration” dialog where the experimenter could verify if calibration values were within parameters (labelled in green by the software interface) for all four cameras. If not, the system calibration was repeated. This system calibration was improved with an offline calibration procedure following the experimental session (see subsection 4.2.5 Offline Calibration). A standard online gaze calibration was not possible given that our large display exceeded the limits of the infant’s visual field. Also, calibrating across the full screen area would have been too time consuming and would have reduced the infant’s cooperation for further data acquisition during the same experimental session.

Following the system calibration, the experiment could start. There was a total of 32 trials per infant. Using a gaze contingent eye-tracking procedure, each trial began with the presentation of a central attention grabber that disappeared as soon as the infant looked at it. The attention grabber was a blob with strongest contrast in its centre, presented within a Gaussian temporal envelope such that 100% contrast was attained in the middle of its total presentation time of 900 ms. The visual presentation was paired with a random synchronous tone. The audio-visual presentation of the central stimulus was interrupted if the participant looked at it or if the participant did not look at the centre of the screen following the sixth repetition of the blob presentation. As soon as the central stimulus faded away, a target stimulus appeared in the left or right edge of the mid-periphery (+/- 60˚) in a randomised order and moved along the horizontal meridian towards the centre of the screen at 5˚/s (covering 12 locations per side ranging from 60˚ to 32.5˚, in 2.5˚ steps). Every 8 trials, the experimenter had to tap a key in order to advance the stimulus presentation. This was useful in case a break was needed or to readjust the participant’s position. Peripheral targets were faces taken from the Radboud Faces Database (see Langner et al., 2010, for an example of the stimuli and for database validation). Each face covered an angular size of 5.88˚ at 40 cm distance (180 x 180 pixels). Visual stimuli were presented on a uniform grey background. In this experimental procedure, the measures of interest were saccadic reaction times to detect the peripheral target and dwell times over the face regions. Saccadic reaction time was defined as the difference between the time in which the gaze reached the peripheral target area and the onset of the peripheral target. Dwell time was defined as the total time that the infant participant spent looking over the region of the detected moving face. The system sampling frequency of 60 Hz provided a good temporal resolution for these outcome measures. As outlined by Andersson, Nyström and Holmqvist (2010), with the adopted sampling frequency, reaction times can have an average sampling error of 8 ms (varying from 0 to 17 ms), whereas fixation durations are expected to have a mean sampling error centred on 0 ms (varying from -17 to 17 ms). Including system calibration, the entire eye-tracking session lasted on average 6-7 minutes. Data acquisition was performed by the same experienced eye-tracking operator for all infant participants.

4.2.4 Data processing and Visualisation

Firstly, a model of the three-dimensional curved screen environment was defined within the Smart Eye Pro software in order to track gaze data relatively to targets appearing on this particular display (Figure 6(B)). Smart Eye Pro computed the gaze intersections with the curved screen model in three dimensions. The information about gaze and screen intersection is saved by the software as *World Intersections*. Raw data were exported from Smart Eye Pro as three-dimensional coordinates relative to the curved screen and were further processed with MATLAB. The imported parameters of interest, as labelled and defined by the Smart Eye Pro software, included: *Frame Information, Head Position, Raw Gaze, Filtered Gaze, World Intersections*. Due to the multi-camera system, raw gaze data were recorded even if the image of the eye was outside the screen area and later mapped onto the screen during the analysis process using the *World Intersections* parameter. This minimised the amount of missing data that was lost when the gaze falls outside of the monitor. Robustness, calculated as the proportion of sample data in which the gaze location information was missing, is reported in the Results section.

Using simple trigonometric relations, the three-dimensional coordinates of the intersection between the screen and the gaze (X, Y, Z) were mapped onto the equivalent in pixels (u, v), so that gaze data and target position information were compatible. Gaze data obtained from Smart Eye and target data obtained from MATLAB were combined and synchronised with the real time clock. The individual gaze points were visualised together with the target locations to allow a visual check of data precision and accuracy. This visual inspection revealed a consistent pattern of systematic error towards the right side of the screen. Since we were interested in saccadic reaction times in response to targets appearing in the left or right peripheral visual hemifields, reducing a systematic side offset and ensuring data accuracy was essential to draw valid conclusions regarding the infants' visual behaviour across the visual field. For this reason, an additional offline calibration step was included (see subsection 4.2.5 Offline Calibration). Following this, central and peripheral Areas Of Interest (AOI) were defined. The AOI were circular regions with a 180-pixel radius surrounding the central stimulus and the peripheral left and right areas where face stimuli appeared. Valid trials were defined as trials in which the participant's gaze was within the central AOI at the offset of the central stimulus and the gaze reached a peripheral location after 100 ms and within 5 s from the onset of the peripheral stimulus. In order for a trial to be considered valid, gaze data could not be located outside the screen before the gaze reached the peripheral target AOI. Outliers were identified in deviating trials in which the latency to detect the peripheral target fell outside the interquartile range of latency across participants.

4.2.5 Offline calibration

An interface was implemented in MATLAB that enabled the experimenter to run an additional offline gaze calibration procedure. This interface allowed to visualise each participant's gaze data together with the visual target on screen on a frame by frame basis. The locations of the visual targets displayed on screen during the experimental procedure were fixed (i.e., one central location and twelve peripheral locations per side) and were constantly marked on the interface. As the experiment progressed, the interface displayed both the stimulus on screen and the infant's gaze data for any given time frame. Initially, the operator visualised the gaze data superimposed on the visual stimuli throughout the entire recording in order to identify the pattern of error from trial to trial. On each trial, a single visual target appeared in the visual periphery and moved at fixed locations towards the centre of the monitor (at a constant velocity) along the horizontal meridian. Thus, the offset could be observed over an extended period of time, with one stimulus on screen at the time. After that, the experimenter could navigate back and forth through the data visualisation with steps of either 1, 10, or 100 frames. Once the experimenter identified a frame in which the gaze had reacted to the target change and gaze data appeared stable and clustered near the target location on the screen for at least 100 ms, they could tap a key to save both the current target position and the gaze coordinates of the participant. A total of 6 samples (3 samples relative to stimuli appearing on the left side and 3 samples relative to stimuli appearing on the right side) were chosen per participant. Only samples in which the visual target was on screen for an extended period of time (at least 1-2 s) were chosen; this occurred after every 8 trials when the target remained on screen until the experimenter made sure the infant participant was well positioned and attentive. A key press by the experimenter continued the presentation. Selection criteria for offline calibration samples included:

(a) Identifying the time segments in which a visual target was stable on screen (in this case, 3 intervals during the experimental procedure: after 8, 16 and 24 trials from the beginning of the test),
(b) Selecting suitable samples in which the gaze had reacted to the target change and gaze points were available, stable and clustered around the chosen target stimulus for at least 100 ms, and
(c) Selecting 3 samples for each side of the screen following the above requirements.

This approach ensured that the 6 selected samples were collected from both sides of the screen/visual field, but were also representative of different experimental stages. Offset was calculated as the difference between current target position and gaze position. The average gaze offset was estimated from 6 individual offsets, described using horizontal and vertical coordinates (x- and y-axes, respectively) and its correction was added to the initial gaze points. Averaging across multiple individual offset coordinates relative to different locations and experimental stages reduced the possibility that the offline calibration procedure would distort the data. In this phase, it is important to visualise the entire recording again, including the gaze data following offline calibration. The new corrected gaze coordinates were overlaid on the interface together with target positions and initial gaze coordinates in order to visually evaluate whether this corrective procedure was successful, i.e., to assess whether the new corrected gaze coordinates appeared closer to the targets throughout the entire experiment compared to the initial gaze coordinates (Figure 7).

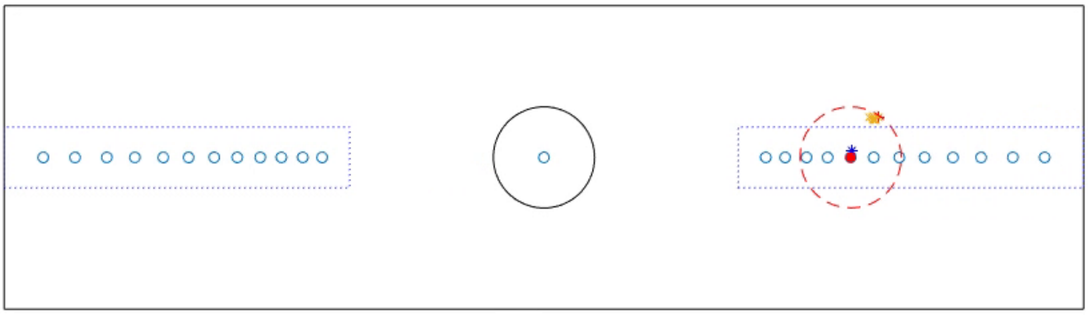


Figure 7. The interface implemented to review the recordings and to collect offline calibration points at different stages of the experiment. This image depicts a frame of a 2D representation of the testing display with the position of the visual target currently on screen (red dot), the initial estimated gaze points (yellow stars), and the new calibrated gaze coordinates (blue star).

4.3 RESULTS

The system allowed tracking infants' head and eyes movements on a wide visual area covering mid-peripheral locations up to 60° per side. Due to head tracking, gaze data were not lost when the participants moved or turned their head. The robustness data revealed that, on average, 23.97% (SD = 11.93%) of the raw data were lost during the entire recording. The system could track data even beyond the screen area and approximately 28.00% of the data (SD = 10.14%) were recorded outside of the screen. Head tracking throughout the entire experiment allowed the monitoring of infants' eye distance from the display. Although this distance was initially set to 40 cm, the variation throughout the recording was high, with median head distance values per trial ranging from 29.20 to 56.50 cm (M = 42.25 cm, SD = 4.73 cm). Importantly, the system could still accommodate this variation and produce meaningful results.

By combining information about target position and gaze position at selected time frames, it was possible to correct a mean offset of -42.22 pixels (SD = 38.88 pixels) on the x-axis and -44.81 pixels (SD = 53.61 pixels) on the y-axis. At 40 cm distance, this corresponds to a -1.38˚ mean offset on the x-axis (SD = 1.27˚) and a -1.46˚ mean offset on the y-axis (SD = 1.75˚). At the individual level, the smallest average correction was -0.17 pixels (-0.01˚) on the x-axis and -0.41 pixels (-0.01˚) on the y-axis, whereas the largest average correction corresponded to 119.40 pixels (3.89˚) on the x-axis and -207.47 pixels (-6.76˚) on the y-axis (see Figure 8). This offline calibration procedure allowed a top-right error that affected the majority of participants (*n* = 27) and that could have contributed towards an incorrect data interpretation.

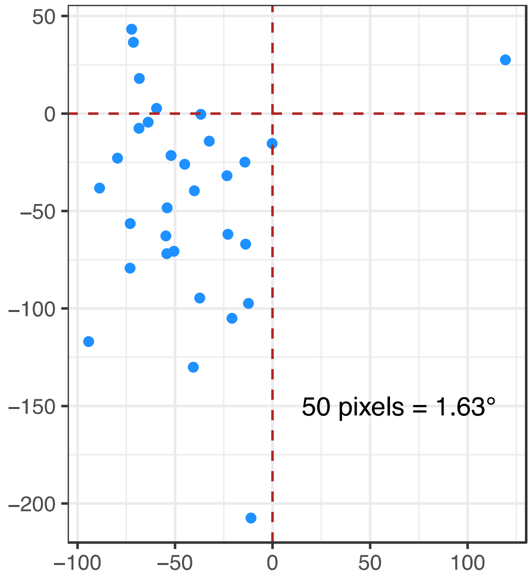


Figure 8. Mean individual gaze offset from the position of the target object, located at the intersection of the red dotted lines.

Saccadic reaction times in response to peripheral targets and dwell times over the face regions were extracted following offset correction. At this stage, trial validity was assessed. Only trials in which the infant was (1) looking at the centre of the screen at the offset of the attention grabber and (2) orienting towards the peripheral target between 100 ms and 5 s from its onset without gazing outside the screen were considered valid. Five infants who ended up with less than 20% valid data were excluded from further analysis. Out of a total 807 trials presented to the infant participants, 444 trials (55.02%) were valid and analysed further. Eighteen trials were also excluded as outliers. Results showed that infant participants detected the peripheral target after an average of 1269 ms (SD = 581 ms). At this time, the moving face target was located at 55˚ eccentricity. Dwell times over the face area were on average 2568 ms per trial (SD = 1505 ms).

4.4 DISCUSSION

The goal in the current investigation was to generate a remote eye-tracking procedure that could successfully address some of the most relevant challenges that researchers face when studying infant participants. First, this method can track and accommodate head movements in a wide testing environment while measuring gaze in response to stimuli presented up to 60˚ per hemifield. In addition, a simple offline calibration procedure was implemented. This not only improved data quality but it was also suitable for non-standard tracking areas and infant participants who cannot follow instructions.

In this study, data loss due to head movements was limited because multiple cameras were used and other cameras could take over when one camera could not acquire data, resulting in a large headbox. Robustness was particularly good for a sample of infant participants. In fact, the current average data loss of 23.97% is comparable with the percentage of data loss reported for adults tested under optimal laboratory conditions, which can reach 20% (Holmqvist & Andersson, 2017, pp. 166-167). The proportion of data loss included blinks and the system failing to record data for technical difficulties or for systematic infant behaviours, such as covering their eyes or orienting towards the caregiver. Data loss in the present work showed an improvement compared to the 40% data loss reported by Pratesi and collaborators (2015), who also used this eye-tracking system with an infant sample. This could be that in the current study the target stimuli presentation was triggered by the infant looking at the central attention getter and, thus, the visual presentation progressed when the infant participant looked at the screen. Not having a gaze-contingent trial presentation could possibly lead to more significant data loss.

The four eye-tracking cameras adopted in the current study kept tracking both eye and head movements within the whole testing environment, over a large visual area of 126˚ (although this can potentially be increased to 360˚ with the use of eight cameras, as reported by the manufacturer). In the present study, the focus was to measure saccadic reaction times and dwell times across a wide horizontal area but more locations, including a bigger vertical area, could be implemented by adjusting the cameras placement. During the entire recording, about 28% gaze data were localised outside of the wide screen but, notably, those data were within the working space of our set up and were still recorded. This value could vary depending on how engaging the infant finds the experimental procedure.

Apart from being able to track eye gaze outside a limited headbox, the tracking system also allowed to monitor the distance between the infants' head from the screen throughout the testing session. Although parents were instructed to keep infants on their lap at a set distance, there was a high degree of variation in infants' head distance during the procedure. Importantly, this method can record and accommodate this expected variation due to the nature of this population and, nonetheless, produce meaningful results. Normally, the head component of an infant orienting behaviour is not considered in standard eye-tracking procedures. The ability to investigate infants' orienting behaviour in a wider visual field, where head positions are less restrained, is essential in the aim to transition from strict laboratory-controlled environments to more naturalistic settings that best represent our everyday experiences. The present work provides some preliminary insights into how fast and how far in the periphery can infants detect information across a wide horizontal visual environment in which both the eye and head component contributions are necessary to successfully detect the target. To the best of our knowledge, a similar Smart Eye eye-tracking system has been used only once in infancy, but with a very small sample size (Pratesi et al., 2015). In the present work, a new software version, specifically designed to recognise the facial proportions and anatomical features typical of infants, was adopted, and its performance was enhanced by implementing an offline calibration procedure.

Here, data quality was also considered and, in particular, spatial accuracy. Offline data inspection revealed a systematic top-right offset in the recorded gaze location compared to the true gaze location (i.e., actual target position). This shift was noticeable in the majority of individual data. The average error that was found in the present work is comparable to past findings in infancy research, which used both an initial gaze calibration and a calibration verification procedure (Morgante et al., 2012; Jones & Klin, 2013). However, there was some variability between each individual's average error. Different researchers have previously raised concerns about the accuracy of infant eye-tracking data (Frank et al., 2012; Morgante et al., 2012; Wass et al., 2014; Hessels, Andersson, Hooge, Nyström, & Kemner, 2015; Dalrymple et al., 2018). The consistent gaze position error that was reported here cannot normally be detected in standard calibration displays. This proposed offline calibration procedure is therefore essential in making sure that a systematic offset is discovered and corrected, and also in overcoming the difficulty of calibrating a non-standard wide tracking environment. Further, standard calibration procedures may not always be exact in developmental studies because infants do not always fixate on the required calibration points for sufficient time, and this can result in at least 1° error in spatial accuracy (Oakes, 2010; Aslin, 2012).

Improving spatial accuracy and estimating each individual's offset are particularly important aspects for data interpretation, especially in some experimental designs. As outlined by Aslin (2012) and Dalrymple et al. (2018), spatial accuracy is extremely relevant if the eye-tracking paradigm relies on whether or not the subject looks at an Area Of Interest (AOI). In fact, poor spatial accuracy can result in gaze points erroneously being recorded as falling outside or inside an AOI, particularly if the AOI is small and/or in close proximity to another. In terms of experimental designs, when different age groups or populations are compared, discrepancies in data quality can potentially produce false differences in the outcome measures, therefore leading to erroneous interpretations (Wass et al., 2014; Hessels & Hooge, 2019).

One additional advantage of implementing an offline calibration procedure is that data are corrected throughout the whole experiment, whereas standard calibration only occurs at the beginning of the session and is very rarely repeated during the experiment. Offline calibration therefore enables more accurate data throughout a testing session and improves the validity of eye-tracking investigations in infancy. This approach could be implemented across eye-tracking systems and is not dependent on one particular hardware system (see Frank et al., 2012, and Morgante et al., 2012, for similar examples with Tobii systems). Overall, an offline calibration procedure should be adapted according to the experimental design and observed data quality. In the present work, we took advantage of the time intervals during which the visual stimuli already included in the experimental procedure were stable on screen. This allowed for six calibration points spanning across different spatial locations and experimental stages. Whether or not all the stable visual stimuli on screen can be used as calibration points depends on data robustness and on whether gaze data are available for a sufficient duration when the target is on screen. When participants are likely not to attend to the stimuli on screen or when data quality is low in terms of robustness, additional calibration targets should be included. Notably, stable visual stimuli may not be required in every experimental procedure but should be incorporated specifically if an offline calibration procedure is planned. In this case, the calibration stimuli should ideally cover the entire tracked area. Overall, even if an offline calibration step is not implemented to correct the offset, we strongly believe it is important to report not only the manufacturer’s accuracy data (albeit usually based on adult data under optimal testing conditions), but also to extract the actual data accuracy and consider the overall effect on data processing and interpretation. Downstream, data accuracy could be used as a potential parameter to exclude individual data (Frank, Vul, & Johnson, 2009), or as a guide for setting the size of the AOI (Dalrymple et al., 2018; Orquin & Holmqvist, 2018).

One limitation of the current investigation is that the visual targets of the experimental procedure only appeared along the horizontal axis. For this reason, offset coordinates were collected at different eccentricities but limited to the horizontal axis. A more accurate offline tracking procedure could include more diverse locations on screen, including along the vertical meridians and locations near the edges of the screen where spatial accuracy typically decreases. This was not possible with the set up and procedure in the present experimental paradigm. In general, the offset that was detected in the current study was linear and consistent within the same participant throughout the procedure. This enabled us to correct it with a simple offline calibration interface. Different offline calibration procedures may be needed if data quality is more heterogeneous in time and space. Further, although the software used in the present investigation considered the anatomy of the developing eyes and head, we did not take into account individual characteristics of our infant sample (for instance, eye colour or infant positioning during the procedure as reported by Hessels at al., 2015) that might have influenced the accuracy of this system and, more generally, data quality. More investigations are needed to identify which factors can affect data quality derived from this eye-tracking system. Still, we highlighted the importance of verifying, and eventually improving, data quality parameters according to the adopted experimental procedure.

4.5 CONCLUSIONS

The current paper presents a useful tool for obtaining gaze and head tracking data in a wide visual area without any physical constraint for the participant. This tool is suitable for infants and can accommodate high variation in head movements, both in terms of rotation and distance from the tracked area. Additionally, the importance of considering individual spatial accuracy was highlighted and a simple interface to improve data quality was proposed. This approach is a promising methodological advance that can directly address some of the larger challenges present in infant eye-tracking.

Prelude to Chapter 5

Can infants perceive threatening facial expressions at the edge of the visual field?

The multi-camera eye tracking tool that we presented in the previous chapter was successful to track infants' eye and head movements across a wide visual field and enabled us to overcome the limited trackable area that most remote eye tracking solutions can support. The infant data that have been used to validate this tool looked at the attentional mechanisms in response to emotional faces appearing at the edge of the visual field. This experimental procedure is described in Chapter 5 (Study 4). We know that peripheral vision has a role in detecting visual changes in the environment and threats often enter the visual field laterally. Also, the results of Study 1 and 2 suggested an advantage of social information at high eccentricities. Hence, in Study 4 we further expanded our understanding of social information processing in peripheral locations by measuring attention to intact faces with either a threatening (angry) or a non-threatening (neutral) facial expression. According to past evidence (e.g., LoBue & DeLoache, 2010), threatening facial expressions are more rapidly detected than non-threatening ones already from infancy. Chapter 5 aimed to explore the latency and dwell time in response to face targets moving across a 126˚ field of view.

Compared to Study 1 and 2 which took advantage of video recordings, the next study precisely measured eye and head tracking data and distinguished between attention-getting (latency) and attention-holding (dwell time) measures. Further, the previous studies were characterised by the presentation of a single peripheral target following the central stimulus offset. In Study 4, we presented both single and double peripheral conditions. Thus, either one face target could appear in one hemifield or two face targets could simultaneously appear in both hemifields. Previous research suggested differential responses to single and double presentations over the first postnatal months (e.g., Atkinson et al., 1992) and we wanted to understand whether one of these presentation conditions was necessary to elicit an attentional bias to threatening faces. Study 4 aimed to disentangle the role of emotional expression and presentation condition on attentional mechanisms in response to faces appearing in a wide visual space.

Chapter 5

Danger all around: Angry emotional faces are rapidly processed in the infant’s extreme visual periphery

Author note: Text in preparation for submission to *Psychological Science*.

Abstract

Infants show an early sensitivity to threatening facial expressions. From 9 months of age, the detection of angry faces is more rapid than for happy faces. In everyday life, incoming threats often initially enter the peripheral visual field. Adult work has found enhanced sensitivities to emotional content at high eccentricities, yet infant research has typically explored these issues in limited visual areas. The present study investigated attention-getting (latency) and attention-holding (dwell time) mechanisms with respect to angry and neutral faces appearing across a 126° horizontal field of view in a group of 9-month-old infants. We also explored whether competition for attentional resources played a role in eliciting any attentional bias by comparing single trials (one face appearing either on the left or right hemifield) and competing trials (two faces simultaneously appearing on both hemifields). Infants showed shorter latency when targets were competing for attention. Competing trials provided evidence for enhanced detection of angry rather than neutral faces and of targets detected in the right compared to the left hemifield. Overall, males had faster latencies than females, suggesting the importance of individual differences when a combination of eye and head movements is required to detect a target. Dwell time measures were not influenced by any individual- or trial-level factor. These data indicate an early bias towards threatening information even at very high eccentricities during infancy. They also underline the importance of a paired stimulus presentation in eliciting this bias.

5.1 INTRODUCTION

The human vision is capable of rapidly perceiving threat-related information across a wide visual array (e.g., Bayle, Henaff, & Krolak-Salmon, 2009; Öhman, Lundqvist, & Esteves, 2001). This is particularly true for emotional facial expressions, especially anger and fear, which may convey information about danger in the environment to a social partner. This rapid detection behaviour has an adaptive function by enabling rapid reaction or adjustment to social requirements. Evidence points towards a subcortical brain pathway to support these capacities (Lang, Bradley, & Cuthbert, 1997; Liddell et al., 2005; Vuilleumier, 2005; Johnson, Senju, & Tomalski, 2015). The peripheral field is often the first visual region to be stimulated by incoming threat and is particularly good at detecting movement and sudden changes (e.g., McKee & Nakayama, 1984; To, Regan, Wood, & Mollon, 2011). Despite the poorer resolution at more peripheral eccentricity, faces can still be processed at high eccentricities compared to other control target objects (Hershler, Golan, Bentin, & Hochstein, 2010). More specifically, adult data has demonstrated an advantage of emotion processing at high eccentricities despite visual acuity being impoverished in peripheral regions (Bayle, Schoendorff, Hénaff, & Krolak-Salmon, 2011; Rigoulot, D’Hondt, Honoré, & Sequeira, 2012). In a task exploring emotion and gender discrimination of faces presented up to 40° eccentricity, Bayle and collaborators (2011) found that emotion recognition (fear and disgust) showed an advantage over gender discrimination at increased eccentricities.

It has been proposed that the more rapid detection of angry faces could be linked with higher processing efficiency and the need for fewer attentional resources to identify angry, potentially more threatening, emotional expressions (Calvo, Avero, & Lundqvist, 2006). This facilitated detection of negative expressions beyond foveal locations implies that their processing may begin pre-attentively (Calvo et al., 2006). Interestingly, other features of facial expressions appear to resist the peripheral visual degradation, such as the presence of a smile accounting for a happy face advantage at high eccentricities (Calvo, Fernández-Martin, & Nummenmaa, 2014; Goren &

Wilson, 2006) or the ability to judge facial attractiveness in peripheral vision (Guo, Liu, & Roebuck, 2011). Overall, both threat-specific and a wider variety of emotionally significant cues may enhance sensory processing across the visual field. These findings may reflect an increased involvement of a rapid magnocellular visual pathway in emotion processing and detection. Magnocellular cells are mostly involved in peripheral processing and have previously been proposed to have a role in processing low spatial frequency information linked with the perception of facial expressions (Bayle et al., 2011).

The dominant theories of threat bias have suggested a specific early-emerging brain circuitry for evaluating threats in the environment (Mathews & Mackintosh, 1998; Öhman & Mineka, 2001). Developmental studies have explored how attentional bias to threat is present during infancy (see Vaish, Grossmann, & Woodward, 2008 for the proposed mechanisms underlying the negativity bias in development and its developmental functions). Accordingly, enhanced attention to negative emotional expressions is evident around 5 months of age (Heck, Hock, White, Jubran, & Bhatt, 2016; LoBue, Buss, Taber-Thomas, & Pérez-Edgar, 2017). This bias is not limited to facial expressions but also involves non-social stimuli, such as snakes (DeLoache & LoBue, 2009; LoBue et al., 2017; LoBue & DeLoache, 2010; Bertels, Bayard, Floccia, & Destrebecqz, 2018). Notably, a bias towards negative emotions was not found in newborn infants (Farroni, Menon, Rigato, & Johnson, 2007), suggesting the emergence of a negativity bias during the first postnatal months. Conversely, newborns and very young infants indicate better discrimination of happy rather than negative emotional expressions and increased looking towards positive emotions (Farroni et al., 2007; LaBarbera, Izard, Vietze, & Parisi, 1976). Some work has proposed a role of individual temperament, anxiety symptoms and maternal personality in developing a negative attentional bias (de Haan, Belsky, Reid, Volein & Johnson, 2004; LoBue & Pérez-Edgar, 2014; Pérez-Edgar et al., 2011), although other research has not found such relationships (Leppänen, Cataldo, Bosquet Enlow, & Nelson, 2018). Additional developmental mechanisms that may play a role in the rapid detection of threatening information in early development are changes in amygdala activation (Moriceau & Sullivan, 2006) and the increase in exposure to negative facial expressions from caregivers when motor skills and active exploration develop and exposure to potential dangers in the environment increase for infants (Campos et al., 2000; Heck et al., 2016).

It may be particularly relevant to minimise danger in visual environments where multiple stimuli compete for attention. As such, a key aspect in the negative attentional bias research relates to whether there is competition for attentional resources or not. Peltola and collaborators (2008) investigated the hypothesis of increased sensory arousal towards negative facial expressions using a gap-overlap paradigm with 7-month-old infants. Infants disengaged their attention less frequently when presented with threatening faces compared to happy faces and their fixations increased during overlap trials (i.e., when there was a competition between a central face and a peripheral target) if the stimulus was a fearful face (Peltola, Leppänen, Palokangas, & Hietanen, 2008). This paradigm involved competing visual information but only one face at a time was presented. It remains unclear whether paired faces elicit an increased attentional allocation compared to the presentation of a single face. Along these lines, it has also been argued that infants may not be able to differentiate the informational value of individually presented emotional expressions but they can do so when faces are simultaneously in view (Nelson & Dolgin, 1985). Similarly, when presented with arrays of faces, adults can detect threatening faces more quickly and accurately than other faces, independent of the size of the face crowd (Öhman, Lundqvist, & Esteves, 2001). Nevertheless, some authors reported results in favour of increased looking towards negative emotional expressions when presenting infants with a single face at the time (de Haan & Nelson, 1998; Leppänen, Moulson, Vogel-Farley, & Nelson, 2007). It is therefore unclear whether a competing presentation is necessary to increase attentional resources towards negative emotions. A comparison of the two conditions in the same experimental paradigm would be needed.

The present study aimed to understand whether an early bias towards angry faces is present at the edge of the developing visual field and whether the competition for attentional resources has a role in the emergence of this bias. This was assessed by presenting 9-month-old infants with neutral and angry faces across a 126˚ field of view. A 4-camera eye-tracking system enabled the recording of eye movements across a wide space while accounting for large head movements. Compared to past investigations in this domain, this study aimed to explore a more ecologically valid situation in which threatening information appears at the edge of the visual field and progressively approaches the centre of the visual field, requiring a combination of head and eye movements to orient towards the visual target. Although in everyday life most orienting behaviours involve a combination of eye, head and body movements, past infant research has mostly focused on eye movements and stimuli presented on standard displays covering a narrow visual area. Emotion processing at high eccentricities has been investigated with adult participants (Bayle et al., 2011; Calvo et al., 2014) but, to the best of our knowledge, this has not been investigated during development in infant participants beyond near-peripheral locations (i.e., beyond +/- 30°).

In this study, both attention-getting (i.e., the latency to detect a peripheral target) and attention-holding mechanisms (i.e., the total dwell time over the moving peripheral target area) were investigated. In accordance with an early-emerging bias for the detection of threatening information in the environment (LoBue & DeLoache, 2010; LoBue et al., 2017), we predicted shorter latencies to detect angry faces compared to neutral ones. Even though emotion detection seems enhanced in an adult's peripheral vision (Bayle et al., 2011; Calvo et al., 2014), this may not be yet the case during infancy when emotional expressions are presented at very high eccentricities. Were this the case, then no latency differences across angry and neutral faces would be expected. In terms of attention-holding mechanisms, past research on the negativity bias during the second half of the first postnatal year have shown mixed results. While longer looking durations at fearful faces have been reported and replicated across multiple studies (e.g., de Haan et al., 2004; Kotsoni, de Haan, & Johnson, 2001; Peltola et al., 2008), looking duration at angry faces has revealed more mixed results. In particular, some authors reported infants looking less at angry than happy faces (Grossmann, Striano, & Friederici, 2007; LaBarbera et al., 1976), whereas work has also shown no differences between angry and other facial expressions (Leppänen et al., 2018; LoBue & DeLoache, 2010; Morales et al., 2017). An adult-like increased sustained attention towards angry faces seems to emerge after 12 months of age (Adams & Kleck, 2005; Leppänen et al., 2018). Therefore, no differences in dwell times across peripheral faces were predicted for our sample of 9-month-old infants.

In addition, unlike the classic visual paired comparison task with two competing stimuli simultaneously appearing in the two hemifields (already used, for instance, in Grossmann et al., 2007; LoBue & DeLoache, 2010; Peltola, Leppänen, Mäki, & Hietanen, 2009), we presented both competing and single trials in the same study. This manipulation was to enable us to better understand whether competing information was necessary to elicit any potential attentional bias. Based on enhanced attention towards emotional stimuli when attentional resources compete (e.g., Vuilleumier, 2005), we hypothesised a detection advantage for competing trials (during which multiple information competes for attention) over single trials.

5.2 METHODS

5.2.1 Participants

Thirty-five typically developing 9-month-old infants were recruited from a large database of volunteer families living in the surroundings of Lancaster, United Kingdom. Five infants were excluded for technical issues which caused complete data lost and four infants were excluded for fussiness that did not allow them to attend the task (25.7% total drop-out rate). Twenty-six infants (13 females) aged between 8 months and 15 days and 9 months and 15 days (*M* = 276 days; SD = 2.75 days) comprised the final sample. Participants were born full-term (> 37 weeks) with normal birth weight (2.5 – 4.5 kg) and had no major complications at birth. All infants were typically developing and had no sensory impairment or eye infections. Caregivers gave informed written consent before the beginning of the study. Families received £10 as travel compensation and a storybook to thank them for participating. This work was conducted according to the principles expressed in the Declaration of Helsinki. The protocol of the study was approved by the Faculty of Science and Technology Research Ethics

Committee of Lancaster University (project approval no. FST19121, under the programme of studies with approval no. FST18067).

5.2.2 Stimuli

A white flashing Gaussian patch was presented as a central attention grabber and four coloured photographs of faces from the Radboud Faces Database (RaDF; see Langner et al., 2010, for database validation information) were presented as peripheral targets. Two Caucasian adult female identities (ID01 and ID61 from RaDF) were used throughout the experiment. Both neutral and angry facial emotional expressions were presented for each identity. According to the RaDF dataset validation, neutral faces had been categorised with an average of 84% agreement (SD = 13%) and angry faces with 81% agreement (SD = 19%; Langner et al., 2010). Angry faces were selected as the threatening emotional expression. When contrasted with fearful faces that have been often used to investigate the negative attentional bias, angry faces signal a direct threat (Kobiella et al., 2008; LoBue & DeLoache, 2010). Also, the angry faces we adopted did not have their mouth open and, to this extent, they were comparable to neutral faces (i.e., the mouth size or the teeth presence could not account for low-level differences across the two emotional expressions). Further, from 7 months of age infants seem to allocate more attentional resources to angry rather than fearful facial expressions (Kobiella et al., 2008). Faces were all forward-facing. All stimuli were presented on a uniform grey background and subtended a visual angle of 5.88° at a 40cm distance (180 x 180-pixel area).

5.2.3 Apparatus

Stimuli were displayed on a 49-inch curved screen (Samsung LC49HG90DMM, screen resolution 3840 x 1080 pixels, 120.30 cm screen width and 52.55 cm screen height). Display monitor contrast and brightness were set to 50%. Stimulus presentation was run in MATLAB (version 2018a; the MathWorks, Natick, MA, USA) using the Psychophysics Toolbox extensions (Brainard, 1997;

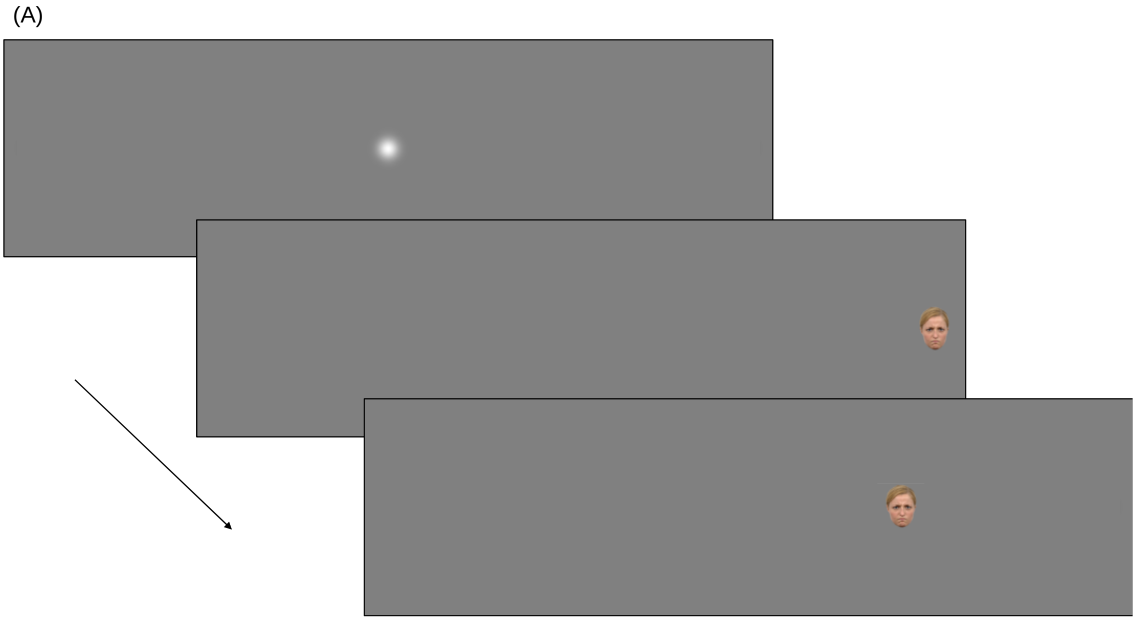
Kleiner et al., 2007) on a Dell Latitude 5491 computer. Eye-tracking data were recorded using a Smart Eye Pro 4-camera corneal-reflection system (Smart Eye AB, Gothenburg, Sweden) running at 60 Hz. A modified version of the Smart Eye Pro 8.2 software that Smart Eye had specifically adapted for the developmental population tested in this project was used (to date, this child head model has been made available from Smart Eye Pro version 9.0 onwards). The machine learning algorithms of this software accounted for the infant's anatomical facial features. In order to track the entire 49-inch display monitor, we used four cameras positioned across the visual field just below the curved display monitor and three 850nm-wavelength infrared flashes positioned in between the cameras. The eye-tracking system enabled the tracking of both the head and eye components of the infant's orienting behaviour. Based on the participant's head position, the cameras could capture data from either a single eye or both eyes. Having four eye-tracking cameras across the visual field enabled us to account for large head movements. Smart Eye eye-tracking recordings and the experimental presentation run with MATLAB were connected via User Datagram Protocol. In addition, two hidden video cameras recorded the testing session. One camera was placed behind the participant facing the curved screen and the other one was located above the curved screen facing the participant. Both video cameras fed into a digital video recorder and a TV monitor behind a room divider, where the experimenter could run and monitor the experimental procedure.

5.2.4 Procedure

Participants sat on their caregiver's lap at a 40 cm distance from the centre of the 49-inch curved screen. At this distance, the display covered a 126° Field Of View (FOV) horizontally. The height of the screen table was adjusted so that the infant's line of sight corresponded to the horizontal meridian where the visual stimuli were displayed. Caregivers were instructed to maintain their infant in a stable upright position at the set distance from the display monitor and to avoid interfering with the infant's looking behaviour during the testing session. Lights were switched off to limit the possibility of distractions and the testing room was only lit by the computer screen. Before each testing session, the experimenter started a two-phase system calibration. First, camera position, brightness (aperture) and focus were visually checked for each of the four eye-tracking cameras and eventually adjusted according to the software indications on the screen. Following this, a chessboard provided by the eye-tracking system manufacturer was tilted and rotated in front of the participant’s face (where it was visible from each camera view). This allowed the system to automatically calculate the current position and orientation of the cameras with respect to the entire setup. This procedure enabled, in turn, the acquisition of eye and head positions. Further, an offline gaze calibration with six calibration points was performed after data collection as explained in Capparini, To, Dardenne, & Reid (submitted).

Once the camera calibration values were within the software’s recommended parameters, the stimulus presentation could start. A total of 32 trials were presented, each consisting of the presentation of a central stimulus followed by peripheral face targets. The trial began with a central patch that disappeared as soon as the infant looked at it in a gaze-contingent eye-tracking procedure. This helped ensure that participants were paying attention to the screen and their gaze was oriented towards the midline at the start of each trial. This central attention grabber was presented within a 900 ms Gaussian temporal envelope such that the maximal contrast (100%) was attained after 450 ms. Each time the central stimulus appeared, its visual presentation was paired with one synchronous tone. Eight tones were used and each one was randomly played with a different trial. The central stimulus continued to fade in and out either until the infant looked at it or until it faded out for the sixth time. The central attention grabber was followed by either a single or a competing trial, in which a face appeared in one hemifield or two faces simultaneously appeared in both the hemifields, respectively.

Out of 32 trials, half the trials presented single faces and the remaining half presented competing faces. In single trials, two emotions (neutral, angry), two sides (left, right) and two identities were repeated twice, for a total of 16 single trials. In competing trials, the same face identity always appeared on both sides, either displaying the same emotion (congruent) or a different emotion per side (incongruent). Thus, two emotions (neutral, angry), two emotional congruency situations (congruent, incongruent) and two face identities were repeated twice, for a total of 16 competing trials. The trial presentation order was semi-randomised. Face targets always appeared in the mid-peripheral visual field and progressively moved towards the centre of the screen along the horizontal meridian, from 60° to 32.5° at 5°/s, covering 12 peripheral locations in 2.5° steps (Figure 9). After every eight trials, the experimenter tapped a key to continue the experimental procedure. This enabled the experimenter to verify if the participant was still well-positioned and collaborative or if a break was needed. The same experienced eye-tracking operator acquired data for all participants. On average, the experimental procedure lasted about 4 to 5 minutes, depending on the participant’s responses to the gaze-contingent central stimulus. The entire eye-tracking session, including the system calibration procedure, lasted 6 to 7 minutes on average.



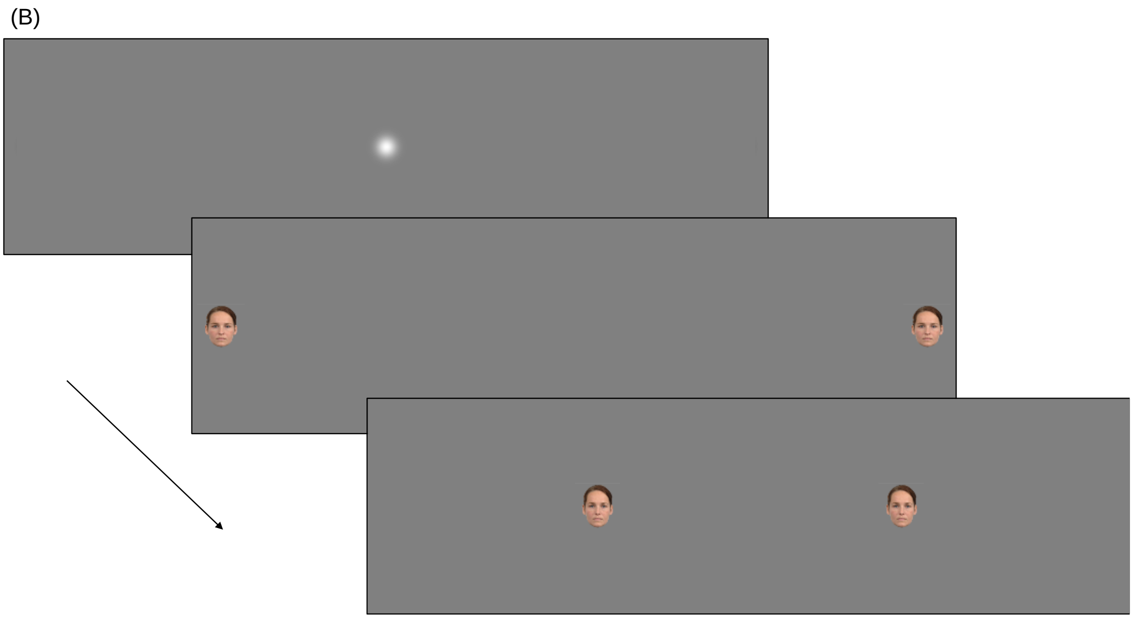


Figure 9. (A) Example of single trial with a central attention grabber which disappeared as soon as the participant looked at it, followed by a peripheral face appearing on one side of the screen (angry face appearing on the right hemifield in this example) and progressively moving towards the centre of the screen. **(B)** Example of competing trial following the same procedure. This time the same face identity is simultaneously appearing in the left and right hemifields (neutral face, congruent emotion in this example).

5.2.5 Data pre-processing and Analysis

Data were exported from Smart Eye Pro and pre-processed and analysed with MATLAB software (version 2018a; The MathWorks, Natick, MA, USA). Data loss was minimised by recording raw data from a wide FOV extending beyond the screen area due to the 4-camera apparatus. Raw data were later mapped onto the curved screen area. Data accuracy was verified for each participant by examining the individual’s point-of-gaze during the stimulus presentation at any given time frame using a customised visualisation interface in MATLAB. At this stage, we identified and corrected a systematic offset with an offline calibration procedure. First, the experimenter identified the pattern of error throughout the stimulus presentation. After that, 6 offline calibration time samples (3 per hemifield) were saved. These were time samples in which the target was on screen for an extended time (at least 1-2 s) and the gaze points were stable and clustered nearby the target. Offline calibration followed the procedure described in Capparini et al. (submitted).

Data extraction focused on attention-getting (saccadic latency) and attention-holding measures (dwell time) to peripheral targets. Circular Areas Of Interest (AOI) with a 180-pixel radius were defined around the central and peripheral visual stimuli. Latency to detect the target was defined as the difference between the onset of the peripheral target appearance and the time when the peripheral AOI was reached. Thus, saccadic latency reflected the first look in the direction of the peripheral target that reached the AOI. Dwell time was calculated as the total time spent looking in the area around the face target moving across the hemifield per trial. In case of competing trials, the total dwell time in the hemifield that the infant looked at first was considered for analysis. A total of 807 trials were obtained across infants (*M* = 31.04 trials per participant). Trials were considered invalid and rejected if (a) the infant was not looking at the central stimulus before the onset of the peripheral target (221 trials, 27.39%), (b) the infant's head and/or body were not centred around the screen midline before the onset of the peripheral target (34 trials, 4.21%), (c) the infant's gaze shifted away from the screen before reaching the peripheral target (31 trials, 3.84%), (d) the infant's gaze did not reach a peripheral AOI while the target was on screen (76 trials, 9.42%) or (e) the gaze reached the peripheral AOI with a latency below 100 ms or above 5 s from the onset of the peripheral target (1 trial, 0.12%). Further, 18 trials were classified as latency outliers and their latency values were discarded. In these trials, the latency fell outside the interquartile range of latency across participants.

Linear mixed models (LMMs) were used for statistical analyses. Analyses were implemented in R (version 3.5.2, R Core Team, 2018) using the lme4 package (Bates et al., 2015). LMMs enabled the incorporation of the unbalanced structure of the data set after invalid trial removal and can account for the multilevel structure of the data. The dependent variables of interest were the latency to detect the peripheral face target and the total dwell time over the moving face region. These outcomes were specified with separate models. To account for the within-subject design, participant was included in the models as a random factor. Participant’s sex (male, female) was included as a categorical fixed effect at the individual level, whereas trial type (single, competing), emotion (angry, neutral) and side (left, right), were included as fixed effects at the trial level. In consideration of experimental differences between competing and single trials, the influence of these effects on the model outcomes was also investigated with separate models for competing and for single trials. For competing trials, the fixed effects were sex (male, female), first emotion detected (angry, neutral), first target side (left, right) and face congruency (same emotional expression on both sides, different emotional expression per side). For single trials, the fixed effects were sex (male, female), emotion (angry, neutral) and side (left, right). In all the investigated models, sum contrasts were used to incorporate categorical effects into LMMs (see Schad, Vasishth, Hohenstein, & Kliegl, 2020, for a tutorial on contrast coding in linear models). Fixed effects were added incrementally and models were compared by likelihood ratio test and Akaike Information Criterion (AIC). Confidence intervals (95%) were calculated with the Wald method. Post hoc analyses were examined for those effects that significantly influenced the model.

5.3 RESULTS

Robustness analysis revealed that on average 22.44% (SD = 10.86%) of raw data were lost throughout the experimental session. To improve spatial accuracy, an average offset of -42.21 pixels (SD = 41.73 pixels) on the x-axis and -34.73 pixels (SD = 41.33 pixels) on the y-axis was corrected using the offline calibration procedure. This approach was already adopted in infant research (e.g., Frank, Vul, & Saxe, 2012) and allowed the minimisation of a systematic top-right error that could have influenced data interpretation. A total of 444 trials were considered valid, including 202 single trials and 242 competing trials.

5.3.1 Saccadic latency

Latency was right-skewed but after square root transformation (previously used, for instance, in Hunnius & Geuze, 2004) latency data were normally distributed. The null model including only the random effect (AIC = 2971.60, LogLik = -1482.80) was significantly improved by incrementally adding the fixed factors. Overall, the model including sex, trial type, emotion and side had the lowest AIC and provided the most parsimonious explanation of the latency data (AIC = 2926.60, LogLik = -1456.30, $X^2(4) = 53.06$, $p < .001$). This model outcome is reported in Table 4.

Fixed Effects					
	Estimate	**SE**	**95% CI**	**t value**	***p***
Intercept	35.07	0.59	33.91, 36.22	59.37	<.001 ***
Sex (F)	4.59	1.18	2.28, 6.90	3.89	<.001 ***
Trial Type (Competing)	-3.99	0.71	-5.39, -2.60	-5.61	<.001 ***
Emotion (Neutral)	1.73	0.71	0.35, 3.12	2.45	.015 *
Side (Right)	-1.65	0.75	-3.12, -0.17	-2.19	.029 *
Random Effects					
	Variance	**SD**	**95% CI**		
Intercept	5.62	2.37	1.72, 11.60		

Table 4. The linear mixed effects model results from the latency model including all trial types. Significance codes: "***" p-value [0, .001] and "*" p-value (.01, .05]. Confidence intervals calculated using the Wald method. Model equation: Latency ~ Sex + Trial Type + Emotion + Side + (1 | Participant).

On average, infants detected a peripheral target after 1230 ms from its appearance at 60°. At detection, the target was located at 55° in the visual field (the peripheral target was located at 55° during the 1000-1500 ms time window from its onset). The latency to detect a peripheral target was influenced by the infant's sex, with females expected to obtain a 4.59 unit increase in the latency to detect a peripheral target compared to males (95% CI = 2.28, 6.90). Latency was shorter for competing trials, with an expected 3.99 unit decrease when compared to single trials (95% CI = -5.39, -2.60). Further, neutral faces were expected to have a 1.73 unit increase in latency compared to angry faces (95% CI = 0.35, 3.12). Also, latency was shorter for targets appearing in the right hemifield, which were expected to have a 1.65 unit decrease in latency compared to targets appearing in the left hemifield (95% CI = -3.12, -0.17). In this model, the proportion of variance in the latency due to individual differences, as expressed by the Interclass Correlation Coefficient (ICC), was 9.76%. Post hoc pairwise comparisons confirmed that males were faster (*M* = 1076 ms, SE = 53 ms) than females (*M* = 1399 ms, SE = 64 ms, 95% CI = -7.02, -2.15) in detecting a peripheral target. Overall, the latency to detect a peripheral target was shorter for competing (*M* = 1096 ms, SE = 44 ms) rather than single trials (*M* = 1376 ms, SE = 53 ms, 95% CI = 2.59, 5.39). In addition, angry target faces (*M* = 1170 ms, SE = 48 ms) were associated with faster latency compared to neutral target faces (*M* = 1289 ms, SE = 49 ms, 95% CI = -3.12, -0.34). Also, detecting a target in the right hemifield (*M* = 1170 ms, SE = 50 ms) led to a faster latency compared to a target in the left hemifield (*M* = 1289 ms, SE = 49 ms, 95% CI = 0.16, 3.14).

A follow-up model explored the factors influencing latency for competing trials. The null model (AIC = 1591.80, LogLik = -792.89) was significantly improved by incrementally adding fixed effects. Among all models, the one with sex, first emotion detected, first target side and face congruency as fixed effects had the lowest AIC and provided the most parsimonious explanation of the latency data (AIC = 1572.90, LogLik = -779.44, $X^2(4) = 26.90$, $p < .001$). This model outcome is reported in Table 5.

Fixed Effects

	Estimate	SE	95% CI	t value	*p*
Intercept	32.82	0.64	31.55, 34.08	50.93	<.001 ***
Sex (F)	4.93	1.30	2.39, 7.47	3.80	<.001 ***
Congruency (Different)	1.30	0.88	-0.42, 3.02	1.48	.141
Emotion (Neutral)	1.95	0.88	0.23, 3.67	2.22	.028 *
Side (Right)	-2.47	0.98	-4.39, -0.55	-2.52	.013 *

Random Effects

	Variance	SD	95% CI
Intercept	5.56	2.36	0.91, 12.61

Table 5. The linear mixed effects model results from the latency model looking at competing trials. Significance codes: “***” p-value [0, .001] and “*” p-value (.01, .05]. Confidence intervals calculated using the Wald method. Model equation: Latency ~ Sex + Congruency + Emotion + Side + (1 | Participant).

On average, the latency to detect a peripheral target during competing trials was 1077 ms, thus the target was located at 55° eccentricity. Again, females were expected to obtain a 4.93 unit increase in the latency to detect a target compared to males (95% CI = 2.39, 7.47). When infants were first oriented to a neutral face a 1.95 unit increase in latency was expected compared to angry faces (95% CI = 0.23, 3.67). Also, when the face they first oriented to was in the right hemifield there was a 2.47 unit decrease in the latency compared to the left hemifield (95% CI = -4.39, -0.55). Whether infants were presented with the same emotion on both sides or with different emotions did not affect the latency to detect a peripheral target. In this model, the ICC was 11.45%. Post hoc pairwise comparisons confirmed that males (*M* = 924 ms, SE = 55 ms) were faster in detecting peripheral targets than females (*M* = 1246 ms, SE = 65 ms, 95% CI = -7.61, -2.25). Angry faces (*M* = 1011 ms, SE = 50 ms) elicited faster latency than neutral ones (*M* = 1142 ms, SE = 53 ms, 95% CI = -3.69, -0.21). Further, targets were detected with faster latency in the right hemifield (*M* = 999 ms, SE = 55 ms) compared to the left one (*M* = 1163 ms, SE = 52 ms, 95% CI = 0.51, 4.43; see Figure 10). In terms of preference among paired stimuli, there was no difference in how frequently the first target the infants looked was an angry face (51% of the time) or a neutral face (49%). Also, infants turned first to the left side 57% of the time and 43% to the left side; the percentages did not differ from chance.

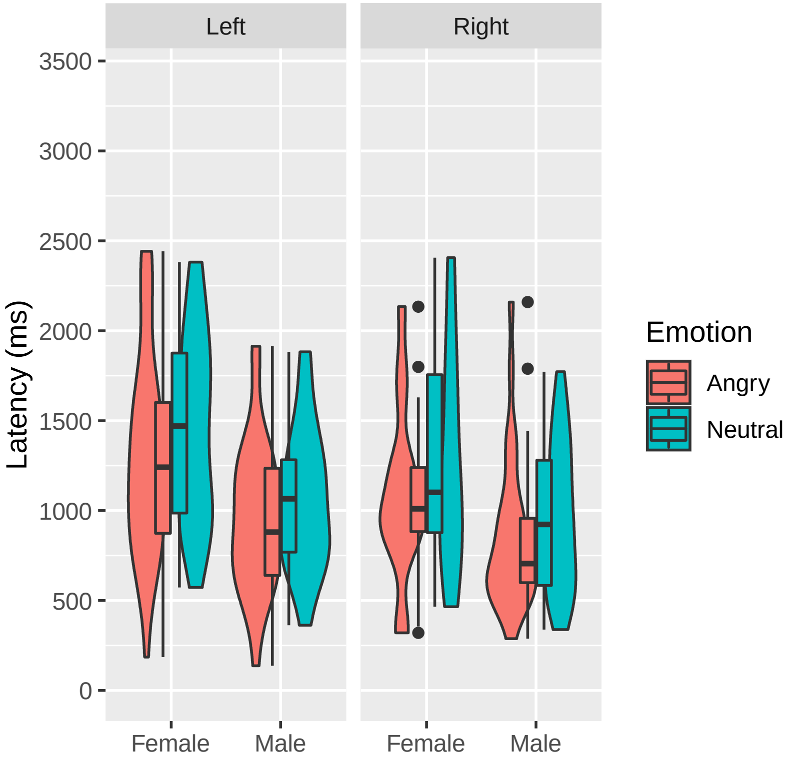


Figure 10. Latency to detect the peripheral target during competing trials. At the individual level, males had shorter latency than females. At the trial level, angry faces were associated with shorter latency than neutral faces and targets detected in the right hemifield had shorter latency than targets detected in the left hemifield.

Lastly, another model investigated what factors influenced latency during single trials. The null model (AIC = 1418.60, LogLik = -706.29) was significantly improved by the inclusion of sex as fixed effect (AIC = 1411.70, LogLik = -701.83, $X^2(1) = 8.93$, $p = .003$). The incremental inclusion of other fixed effects did not improve the model with only sex as a fixed factor. This model outcome is reported in Table 6.

Fixed Effects

	Estimate	SE	95% CI	t value	*p*
Intercept	37.78	0.69	36.43, 39.13	54.85	<.001 ***
Sex (F)	4.39	1.38	1.69, 7.10	3.19	.004 **

Random Effects

	Variance	SD	95% CI
Intercept	2.57	1.60	0, 10.84

Table 6. The linear mixed effects model results from the latency model looking at single trials. Significance codes: “***” p-value [0, .001], “**” p-value (.001, .01]. Confidence intervals calculated using the Wald method. Model equation: Latency ~ Sex + (1 | Participant).

On average, the peripheral target in a single trial was detected after 1427 ms. During this time, the target was located at 55° eccentricity. Females were expected to obtain a 4.39 unit increase in the latency to detect a target during a single trial compared to males (95% CI = 1.69, 7.10). The ICC of this model was 11.45%. Post hoc comparisons confirmed that males (*M* = 1267 ms, SE = 67 ms) were faster in detecting a peripheral target than females (*M* = 1600 ms, SE = 82 ms, 95% CI = -7.28, -1.51; see Figure 11).

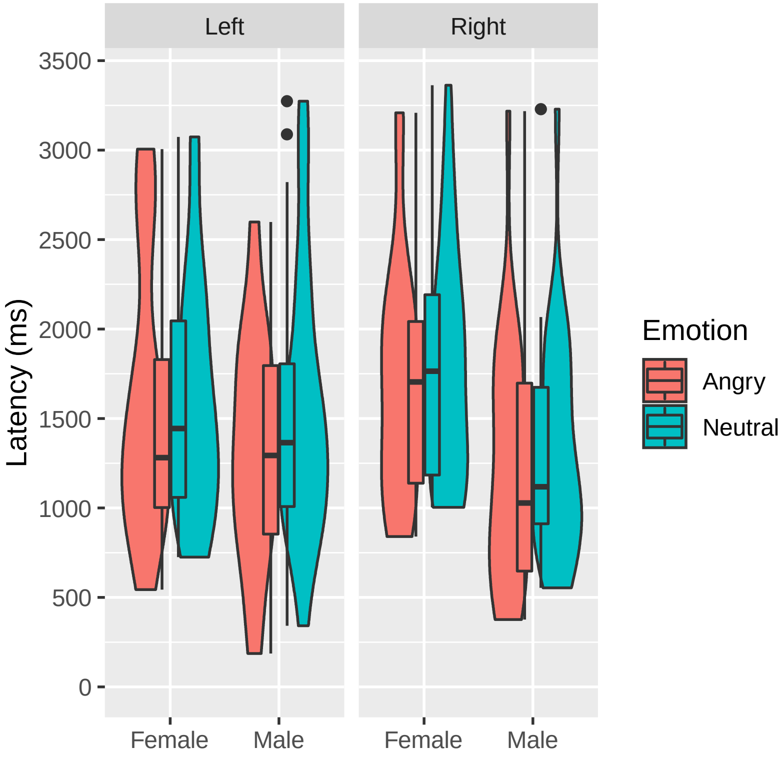


Figure 11. Latency to detect the peripheral target during single trials. Overall, males showed shorter latency than females.

5.3.2 Dwell time

Dwell time data were right-skewed and a square root transformation was applied to improve data distribution, which then better fit for normal distribution. The null model showed that dwell time varied by participant. The intercept, which corresponds to the grand mean, was 47.41 (SE = 1.65, 95% CI = 44.18, 50.64). On average, infants spent 2248 ms following the moving peripheral target face that they first detected. The null model was not improved by incrementally adding the fixed effects and retained the lowest AIC (3623.90) compared to more complex models. Thus, in the present task, dwell time was not predicted by sex, trial type, emotion or side. The ICC of the null model was 24.52%.

5.4 DISCUSSION

This study explored 9-month-old infants' attention-getting and attention-holding mechanisms in response to angry and neutral faces appearing at the edge of the developing visual field. Overall, infants were facilitated when there was a competition for attentional resources. We confirmed evidence of enhanced detection of threatening facial expressions compared to non-threatening ones when two stimuli simultaneously appeared in the peripheral visual field. The current study extends this detection bias to very high eccentricities in the peripheral visual field. Further, during competing trials, latency was shorter if the first target appeared in the right hemifield. Notably, latency data were mostly predicted by the infant's sex, with males faster than females independent of trial characteristics. This study also confirmed that angry faces do not influence 9-month-olds' sustained attention as measured by dwell time.

The current findings relative to a biased detection of angry faces in 9-month-old infants are consistent with past infant research (LoBue & DeLoache, 2010). The authors compared angry vs. happy and fearful vs. happy faces and found more rapid detection of angry faces than happy faces, but no differences between fearful and happy faces (LoBue & DeLoache, 2010). The present study also confirms a detection bias towards angry faces, here compared to neutral faces. It is possible that angry faces are perceived as a direct indicator of human threat and enhance more arousal and attentional resources than other facial expressions (Kobiella et al., 2008). This finding speaks in favour of an early-emerging detection mechanism in response to threatening information (Öhman & Mineka, 2001; Vaish, Grossmann, & Woodward, 2008). In particular, it appears of biological relevance to develop rapid orienting behaviours and allocate more attentional resources towards emotional stimuli that may require the individual to be prepared for action (Bradley, 2009; Lang et al., 1997). At 9 months of age, a bias to negative facial expressions may serve as an adaptive response in social referencing contexts. This would help infants safely navigate the environment and avoid possibly dangerous situations by interpreting an adult's warning expressions (e.g., Cacioppo, Gardner, & Berntson, 1997; Sorce, Emde, Campos, & Klinnert, 1985).

In the past, the detection advantage for negative facial expressions has been also replicated and extended to other threat-relevant stimuli, such as snakes (Bertels et al., 2018; LoBue & DeLoache, 2010). Here we extended this finding to higher eccentricities in the developing visual field. Most developmental studies on the attentional negativity bias used standard computer displays and paradigms predominantly requiring eye movements with a relatively stable head and body. In the present study, we investigated a wide horizontal FOV of 126° in which a combination of eye and head movements was required to successfully detect and orient towards the target. Peripheral targets appeared around the edge of the developing visual field and progressively moved closer to the centre of the screen. This simulates a naturalistic situation in which a threat enters the visual field at the edge of the periphery and travels across visual space. Past adult evidence has suggested that emotional processing may be spared at high eccentricities despite the fact that visual acuity is diminished (Bayle et al., 2011; Calvo et al., 2006, 2014). Our findings suggested that this enhanced perception of emotional content in the peripheral visual field has emerged prior to 9 months of age. Accordingly, Johnson and colleagues (2015) suggested a rapid and early-emerging subcortical pathway that could underpin this process. Of note, the detection bias that we observed for some visual targets in the present study may not be exclusively associated with a more rapid orienting behaviour but also with some moving targets perceived at higher eccentricities compared to others. In the present paradigm, the moving target faces were on average detected at 55° eccentricity. This aligns with evidence reporting 9-month-olds' successful detection of social targets up to 55° eccentricity and of non-social targets up to 50° in the peripheral visual field (Capparini, To, & Reid, 2022a, 2022b).

In contrast to attention-getting mechanisms, attention-holding mechanisms displayed no evidence of a negative emotion bias in the current study. In fact, infants did not show any difference in terms of looking duration between angry and neutral facial expressions. This finding is consistent with past research that showed no differences in sustained attention when angry faces are compared to other expressions in infants aged 9 months (Leppänen et al., 2018; LoBue &

DeLoache, 2010). At the age investigated here, it has been suggested that fearful facial expressions maintain infants’ attention more than other emotional expressions (Kotsoni et al., 2001; Leppänen et al., 2018). Fearful faces may present infants with some attention-grabbing and more novel features, such as wide-open mouth and eyes, that may increase looking duration (Nelson & Dolgin, 1985). In this study, we avoided low-level perceptual confounds in terms of mouth opening, with both the neutral and angry faces featuring closed mouths. Even though we found no differences in dwell times between the investigated emotional expressions, it should also be noted that some past studies have reported infants looking less at angry rather than happy faces in order to withdraw from the threat (Grossmann et al., 2007; LaBarbera et al., 1976; LoBue et al., 2017). According to the vigilance-avoidance theory, the response to a threatening stimulus varies over time and, following a rapid orienting behaviour, there may be an avoidance phase which is related to individual anxiety traits (Mogg, Bradeley, Miles, & Dixon, 2004). It seems plausible that individual differences may play a role in infants’ sustained attention to angry faces, with some individuals turning away from a threat more than others following a rapid detection. In the present study, the proportion of variance in dwell time that was due to individual differences was much higher compared to the one we found with the latency measure. Some individual differences not under investigation in the current study may have a role in explaining attention-holding mechanisms and the capacity to disengage from emotional facial expressions during development.

Of note, the present study shed light on the conditions in which a biased orienting behaviour towards angry faces emerged. We found that infants oriented their attention towards a peripheral target face faster during competing rather than single trials, whereby two faces simultaneously appeared on both hemifields. This would suggest that the more the peripheral visual system is stimulated and when there is a competition of attentional resources, the arousal and orienting response are faster in nature. This is in line with evidence by Atkinson and colleagues (1992) who reported shorter latency in a double-target condition when compared to a single-target condition after 3 months of age, in contrast with 1-month-olds that were slowed down by competing stimuli.

Further, in the present study, angry faces elicited significantly enhanced orienting behaviours than neutral faces only during the paired target presentation. This would suggest an increased sensitivity of some presentation modalities in eliciting differential orienting responses to emotional stimuli. Nelson and Dolgin (1985) proposed that an attentional advantage during paired presentations is linked with the possibility of comparing the informational value of two emotional faces that are seen simultaneously. In this paradigm, faces appeared 120° apart in the peripheral visual field and thus it seems unlikely that their different informational value could be evaluated before orientation. Also, infants oriented equally towards angry and neutral faces during competing trials, suggesting that they may not discriminate facial expressions when two targets appear at the same time. Instead, if some threatening information is detected, infants may speed up their response after the orienting behaviour has started. Overall, it is likely that having two simultaneously approaching targets increased the participants' general arousal towards peripheral locations and their readiness to act compared to seeing only a single target in the visual field. This may also be explained by the so-called *race model* for reaction times by Raab (1962), which suggested quicker reaction times for redundant stimuli. In this model, detection is considered as a race between two or more parallel information that compete to elicit a motor response and reaction time is determined by the faster signal that wins this race between separate detection processes (Raab, 1962). Accordingly, latency is expected to be shorter for redundant rather than single signals.

In the present work, we also found that sex differences had a relevant role in a rapid orienting behaviour towards high eccentricities in the visual field, with an advantage for males rather than females. Although we did not hypothesise this effect, this individual factor was the strongest predictor of the latency measure. This effect was not linked with target emotion, location or trial type. Previous studies investigating attention allocation to threat have not reported any sex differences (Bayet et al., 2017; LoBue & DeLoache, 2010), although most studies did not consider this variable in the analysis. Burris and collaborators (2017) found a greater general vigilance in attention allocation to all kinds of rapidly presented faces in males, while females showed more vigilance only towards some specific emotional expressions. Here we did not find evidence of an interaction between sex and emotion, but there may be a generally increased vigilance in males in this task across the visual field compared to females. Being general, this result could speak in favour of an advantage in this task that investigated attentional mechanisms at the edge of the developing visual field. In particular, we speculate that males could be overall faster in general motor responses requiring wider body, head and eye movements in the wide space under investigation in the present study. Previous work has shown that infant males display an advantage in gross motor activity, whereas females were better in fine motor activities (Piek, Gasson, Barrett, & Case, 2002). Male infants have also shown an increased motor activity level compared to females (Campbell & Eaton, 1999). Interestingly, in an investigation of the factors influencing infants' saccadic reaction times across laboratories, Kenward and collaborators (2017) reported no sex differences in response to targets appearing at 6° but faster reaction times in females rather than males to stimuli appearing at 14°. Here we investigated substantially higher eccentricities, with stimuli appearing at 60° and detected around 55°. Importantly, the human oculomotor range is up to 40° eccentricity, beyond that a combination of eyes and head movements is necessary to successfully orient towards a target (Freedman, 2008). Thus, in the current task head/body movements were required for detection. When a more global motor component is needed to detect stimuli in far peripheral locations, males may display an advantage over females. Conversely, females may show an advantage in near-peripheral locations, as past literature would suggest. Another characteristic of the current paradigm that may have favoured males is that all targets were moving from the periphery towards the centre. These approaching stimuli may have been perceived as more salient or alerting by male infants. Some prior research has reported an early male advantage in following trajectories and tracking the spatiotemporal coordinates of moving objects over time (Alexander & Wilcox, 2012; Levine, Huttenlocher, Taylor, & Langrock, 1999). In the present study, males may have been more interested in moving targets and thus primed to respond to their appearance.

Further, an unexpected right-hemifield advantage emerged in the latency to detect targets during competing trials. It does not seem to be influenced by any systematic error since this side effect was evident during competing trials but not during single trials. Additionally, an offline calibration procedure was implemented and allowed to correct each participant’s spatial accuracy and, in turn, avoid any systematic offset. Thus, results revealed that a target detected on the right hemifield elicits enhanced detection than a target detected in the left hemifield in the case of a paired target presentation (when infants were overall faster). This hemifield effect does not seem to be explained by facial emotion processing itself. Prior research reports a left visual field bias for emotional face processing linked with right hemispheric specialisation (e.g., Dundas, Gastgeb, & Strauss, 2012). What may account for a left visual field bias in this study would be the infants’ tendency to first orient towards the left hemifield (57% of the time, although not significantly different from chance). However, there was a right advantage in terms of speed of responses. The presentation of competing visual information at the edge of the visual field may have a role in explaining these results. It should be noted that the visual field is not binocular at very high eccentricities. In the present paradigm, targets appeared around the edge of the developing visual field, where the visual field is monocular. The right monocular visual field may have a speed advantage and/or be slightly wider compared to the left one before the binocular visual field is reached. Notably, the majority of the population has a right eye dominance (Dellatolas, Curt, Dargent-Paré, & Agostini, 1998; Reiss & Reiss, 1997). Also, whilst a preference for faces seen monocularly with the left eye is evident before 3 months of age, after this age a preference for faces seen through the right monocular field increases over time (Dalrymple, Khan, Duchaine, & Elison, 2021). Another relevant factor is that head movements become necessary to detect a visual target at high eccentricities (beyond 40° eccentricity). Humans prefer turning their heads to the right, a bias which is evident early in development and persists into adulthood (Güntürkün, 2003; Liederman & Kinsbourne, 1980). It is possible that this preference results in a faster head component of the orienting behaviour.

Future studies will be required in order to disentangle whether unexpected differences at the trial level, such as hemifield, and at the individual level, such as participant’s sex, can be explained by the extreme eccentricities investigated in the present task. Another potential aspect to be further investigated is whether the attentional bias we found is specific to angry emotional expressions or whether this also applies to other negative emotions that have been investigated up to near-peripheral locations so far, such as fear. Since adult literature suggested that happy expressions appear to be spared at high eccentricities (e.g., Calvo et al., 2014), it would also be relevant to understand if some specific facial features or low-level aspects can capture attention in the developing visual field, rather the emotional valence itself.

5.5 CONCLUSIONS

The current study demonstrates that 9-month-old infants can detect threatening emotional expressions at high eccentricities when there is a competition of attentional resources. The presentation of angry faces at the edge of the visual field has an influence on infants’ rapid orienting behaviours but not on sustained attention of visual information. These findings provide evidence of an early advantage of emotion detection in a wide visual space and also suggest that individual characteristics may play a role when detection involves a combination of eye and head movements. The existence of an attentional bias at the edge of the visual field has implications for understanding what information attracts infants’ visual attention in everyday complex environments with relevant implications for investigations and theories accounting for the emergence of a threat bias (e.g., Johnson et al., 2015; Leppänen et al., 2018; LoBue et al., 2017).

Prelude to Chapter 6

Is it possible to study infant social attention remotely? Can infants follow the gaze of a virtual partner?

The previous chapters of this thesis shed light on detection and processing mechanisms in response to a range of social and non-social information across a wide visual space. First, the limits of peripheral visual processing have been identified with Gabor patches (Study 1) and with face-like targets (Study 2) in 9-month-old infants. Further, a method to collect eye tracking data across a wide visual field was presented (Study 3) and used to understand attentional mechanisms in response to emotional facial expressions at the edge of the visual field (Study 4). These studies suggested an advantage of some social-communicative information in peripheral vision. All the above-mentioned investigations took place in the laboratory and assessed visual processing over a wide visual field of about 126°. This enabled us to investigate information processing beyond the near-peripheral locations that past research had explored and to test a wide visual space that is more similar to what we experience in daily life.

In this thesis, we aimed to transition infant research to more naturalistic situations and, in addition to investigating a wide visual space, the initial plan was to explore attentional mechanisms during in-person interactions. This option was not possible due to the COVID-19 outbreak. As such, we explored an alternative setting that more and more children have been exposed to, namely video-based online interactions. This allowed testing young participants in their home environments during a live interaction with the experimenter. Hence, Study 5 (Chapter 6) aimed to explore whether it is possible to transition infant research online and whether 11- to 12-month-old infants can follow gaze according to the virtual social partner eye status, as is the case during in-person interactions (e.g., Brooks & Meltzoff, 2002).

Chapter 6

Should I follow your virtual gaze? Infants' gaze following over video call

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Abstract

From 10 months of age, human infants start to understand the function of the eyes in the looking behaviour of others to the point where they preferentially orient towards an object if the social partner has open rather than closed eyes. Thus far, gaze following has been investigated in controlled laboratory paradigms. The current study investigated this early ability using a remote live testing procedure, testing infants in their everyday environment whilst manipulating whether the experimenter can or cannot see some target objects. Thirty-two 11- to 12-month-old infants' looking behaviour was assessed varying the experimenter's eye status condition (Open eyes vs. Closed eyes) in a between-subject design. Results showed that infants follow the gaze of a virtual social partner and they preferentially followed open rather than closed eyes. These data generalise past laboratory findings to a noisier home environment and demonstrate gaze processing capacities of infants to a socially contingent virtual partner.

6.1 INTRODUCTION

Detecting another person’s gaze direction allows humans to learn through others. The ability to look in the same direction that someone has previously looked is a core social interactive skill known as gaze following (Corkum & Moore, 1998; Moore, 2008). Although the developmental origins of gaze following are still debated (in terms of when and how it emerges), we know that this ability develops and becomes progressively more frequent and finely-tuned over the first postnatal year (see Del Bianco, Falck-Ytter, Thorup, & Gredebäck, 2018, for a review). At around 6 months of age, gaze following becomes an accurate and more specific response, which is less influenced by the structure in the environment and the infant’s attentional constraints (D’Entremont, 2000; Gredebäck, Theuring, Hauf, & Kenward, 2008). Nevertheless, up until 9 months of age infants follow the social partner’s head orientation regardless of whether the partner can actually see the target object, thereby demonstrating a lack of differentiation of the perceptual status of the eyes (Brooks & Meltzoff, 2005). Until this age, the motion associated with a head turn is perceptually more salient than the gaze cue itself and, thus, gaze following seems to rely on basic perceptual processes.

Interestingly, it is from 10 to 11 months of age that human infants refine which cues are useful to follow others’ attention and start to understand the function of the eyes in the visual attention behaviour of social partners. In fact, infants look more often at a target object when the experimenter turns towards it with open rather than closed eyes (Brooks & Meltzoff, 2002, 2005). In addition, around this age, gaze following becomes less rigid to nearby target locations and associated spatial constraints. Whilst 6-month-olds can only orient towards targets close to midline areas, 9- to 12-months olds can orient to any target across their visual field (Butterworth & Jarrett, 1991; D’Entremont, 2000; Flom, Deák, Phill, & Pick, 2004). From about 10 months of age, infants can gaze follow even in the absence of targets (Corkum & Moore, 1995).

Thus far, gaze following skills have been mostly investigated in strictly controlled laboratory paradigms. The seminal paradigm used by Scaife and Bruner (1975) included an infant sitting face-to-face with an interacting social partner who turned their head from a central location towards a peripheral target object either on their left or right side. Typically, the outcome was the participant’s gaze shift from the adult’s face to the peripheral target object which the adult was looking at. Most researchers have followed this format to carry out manipulations on the spatial relations between the participant and the target objects (e.g., Butterworth & Jarrett, 1991), on the experimenter’s gaze cues (e.g., Brooks & Meltzoff, 2002, 2005) and facial expressions (e.g., Flom & Pick, 2005), or on the target characteristics (e.g., Corkum & Moore, 1998; Deák, Flom & Pick, 2000; D’Entremont, 2000). In parallel to live experiments, a great number of laboratory investigations assessed gaze following using video-based paradigms. Such paradigms followed the investigation of von Hofsten, Dahlström and Fredriksson (2005) and adopted a computerized video presentation of an actor turning towards one of two target objects while recording the infant’s eye movements and gaze following behaviour. Similar video-based investigations and the associated eye-tracking measures had deepened our knowledge on the qualities of the cues that are needed in order to follow gaze (Gredebäck, Astor, & Fawcett, 2018; Senju & Csibra, 2008; Szufnarowska, Rohlfing, Fawcett, & Gredebäck, 2014) and have enabled psychologists to test different theoretical perspectives about the underlying origins of gaze following, including theories focusing on specific socio-cognitive processes, reinforcement learning, and perceptual cueing (Del Bianco, Falck-Ytter, Thorup, & Gredebäck, 2018).

Beyond the laboratory, where both the above-mentioned live and video-based gaze following investigations took place, social interactions happen in less controlled situations. Moreover, as a result of the COVID-19 pandemic, interactions increasingly happen virtually and children’s screen time has increased substantially (Hartshorne et al., 2021). Infants and toddlers younger than two years of age start using screen-based media very early on and their average time using screen-based media is around 49 minutes a day (Ribner & McHarg, 2021; Rideout & Robb, 2020). In this context, it becomes increasingly relevant to understand how social interactions develop via digital media. Evidence suggests that children recognise people on video chats as social partners and video communication is a superior medium for maintaining emotional links when contrasted with telephone communication (Tarasuik, Galligan, & Kaufman, 2013). Nevertheless, it is from the age of four that children understand the representational nature of pictures and videos (Bennette et al., 2021; Flavell, Flavell, Green, & Kormacher, 1990). Before that age, media errors are common. On one hand, children may ignore information from videos and, more in general terms, learning less from a video presentation compared to a face-to-face presentation (the video deficit account, as defined by Anderson & Pempek, 2005; see Strouse & Samson, 2021, for a review). On the other hand, children may treat video or television images as real (the magic window account; Hawkins, 1977), for example expecting images to have the same physical affordances of real objects (Pierroutsakos & Troseth, 2003; Rosengren et al., 2021). Although the video deficit is a well-documented phenomenon before the age of two (e.g., Barr, 2013; Diener, Pierroutsakos, Troseth, & Roberts, 2008; Kremar, Grela, & Lin, 2007; Troseth & DeLoache, 1998), some evidence suggests that children can learn from videos if elements of social contingency are retained (Myers, LeWitt, Gallo, & Maselli, 2017; Nielsen, Simcock, & Jenkins, 2008; Roseberry, Hirsh-Pasek, & Golinkoff, 2014). As such, extracting information through screens can be effective in some scenarios.

In the present study, we asked whether 11- to 12-month-old infants can follow the gaze of a virtual social partner and differentiate between the partner's eye status condition (Open eyes vs. Closed eyes). The study took place remotely via a computer browser that recorded the infants' looking behaviour using their webcam. We used a synchronous online testing procedure with a live interaction between the participant and the experimenter. Thus, the current approach combined some elements of the standard live laboratory paradigms (i.e., the live social-interactive structure) and some elements of the video-based laboratory paradigms (i.e., the computerised presentation). Outside of the head turn phase which was precisely timed, the social partner responded to the infant contingently as in everyday interactions, instead of the predefined timings typical of standard pre-recorded video-based gaze following paradigms. This allowed the experimenter to make sure that eye contact was successfully established, to respond to the infant’s needs contingently, and to adapt the procedure according to the live interaction with the participating family.

To the best of our knowledge, this is the first attempt to investigate gaze following with a live social interaction via video, combining elements of a screen-based presentation with a live interactive setup. This approach allows to investigate infant development beyond the laboratory, in each participant’s everyday home environment. The first goal and main aim of this study was to understand if such research questions can be addressed with online methods, without the participant physically coming to the laboratory. Testing participants online has been particularly useful to continue studying infant development during the COVID-19 pandemic and some recent research has shown promising results (e.g., Nelson & Oakes, 2021; see also Kominsky et al., 2021, for a review about developmental approaches to online methods). Some relevant advantages of online testing include diversifying the traditional laboratory methods of infant research, limiting the barriers for participating families and removing the adaptation to a new environment for the infants.

If the current online method is effective and past results are not tied to a highly controlled and standardised laboratory setup, previous findings should generalise to a virtual environment. As such, infants are expected to show some basic gaze following skills and to follow the social partner’s head orientation. The other goal of this study was to test how past findings generalise to noisier home environments and, specifically, to understand whether infants treat real and virtual gaze cues (open eyes vs. closed eyes) in similar ways when assessed in an online study paradigm. Although international health organisations, such as the World Health Organisation, recommend that screen time is limited in young children, it is the case that virtual interactions are unquestionably part of our everyday life and intertwined with infant development. If the virtual social interactive structure is perceived as a face-to-face interaction, infants are expected to show a different behaviour between the two eye status manipulations and preferentially follow open rather than closed eyes, as prior laboratory-based paradigms have suggested. Alternatively, infants may ignore gaze cue information via video chat and they may not pay attention to the social cues provided by a virtual agent. In particular, during a video call, infants may follow more basic perceptual information conveyed by the head turn without distinguishing between eye status conditions.

6.2 MATERIAL AND METHODS

6.2.1 Participants

Thirty-two typically developing 11- to 12-month-old infants (*M* = 342 days, SD = 18.6 days, range = 319 to 379 days) constituted the final sample and completed both the survey and the video call of this study. The sample included half females (*n* = 16). All participants were born full term (> 37 weeks). Infants were predominantly White and Mixed ethnicity. They were recruited on a voluntary basis from various locations across the UK. We set the target sample size to 32 infants to align with Brooks & Meltzoff (2005). As a further check, according to a G*Power 3.1 analysis (Faul, Erdfelder, Lang, & Buchner, 2007), for an effect size of 1.31 the final sample size ensured to achieve 97% power at .05 alpha level using a Mann-Whitney U-test. Recruitment happened mostly via social media advertisements and partly from Lancaster Babylab’s database of volunteer families. In order to take part in this online study, participating families needed an internet-connected laptop or desktop device with a camera. Nine additional infants were recruited but excluded from the final sample due to sound and/or webcam issues during the video call which did not allow the experimenter to reach the test phase and collect data (*n* = 4), internet delays with parents reporting poor call quality (*n* = 3), or fussiness during the entire online procedure which resulted in more than 50% valid trial loss (*n* = 2). Parental informed consent was obtained for each participant prior to the beginning of the study via Qualtrics Survey. At the end of the study, families received a £5 virtual gift card for books to thank them for participating. The Faculty of Science & Technology Ethics Committee of Lancaster University reviewed and approved the protocol of the study (Ethics approval reference no. FST20017). This research was conducted according to the principles expressed in the Declaration of Helsinki.

6.2.2 Test environment and Stimuli

Infant participants took part in this study remotely from their own home. Before the gaze following interaction, parents were requested to limit distractors in the environment, such as highly attractive objects or people and pets walking around. The experimenter joined the video call from a room with plain walls. In this room, lights were switched off and a ring light was placed in front of the experimenter to ensure uniform lighting conditions during the interaction. A laptop computer (Dell Latitude 5491) with an external webcam including a built-in microphone (Logitech C270, 1280 x 720 pixel) was utilised by the experimenter to host the video call. The gaze-following test took place live via the video conferencing platform Adobe Connect, version 11.2.3 (retrieved from https://www.adobe.com/products/adobeconnect). The experimenter joined the video call via app using an Adobe Connect Meeting Host 25 licence. At the same time, participants could join the video call via a browser using a meeting link, without any need to download the application. They were suggested to avoid Safari as some issues were reported when video conferencing using this browser. This specific video conferencing platform was chosen to limit the set up and layout organisation on the participant’s device and for the experimenter to have full control of the online testing environment, including the participant’s graphic display. The experimenter, who hosted the video call, had complete control of what participants saw on screen, meaning that participants could not change the layout of what was shown on their screen. This way, we ensured that the set-up time before the actual test was only limited to turning the participant’s video and microphone on. Additionally, we also ensured that the call layout was fixed and not varying across participants. Alternative commercial video conferencing solutions required more intensive preparations to standardise the layout of the call. Utilising Adobe Connect enabled the preparation of multiple layouts in advance and the experimenter could quickly switch among layouts. Further, a slide presentation, which included both instructions and stimuli, was preloaded to a central location, making the video call less sensitive to connection speed.

During the gaze following procedure, four unfamiliar objects taken from the Novel Object & Unusual Name (NOUN) Database (Horst & Hout, 2016) were used as peripheral target stimuli (exemplars numbers 2013, 2033, 2055 and 2064). On each trial, two identical mirrored objects were presented peripherally aligned on the horizontal axis. Images of novel objects were 600 DPI resolution.

6.2.3 Design and Procedure

Survey. As soon as parents replied to the study invitation, they received a link to an online survey which was created using Qualtrics (https://www.qualtrics.com). This questionnaire allowed the parents to gather all the information about the following gaze-following test, sign the informed consent, download the documents, and answer a few questions. Firstly, the experimenter introduced the study and provided all the relevant information via a pre-recorded YouTube video. Parents could read and download a PDF version of both information sheet and consent form, and provide their consent to take part in the study. If they provided their consent to take part in the study on behalf of their infant, they were asked a few questions about their environment. In more detail, they were asked about their infant's previous experience with video calls: (a) "Has your baby attended video calls over the last months?" (Multiple choice: Yes, No) and, if yes: (b) "How frequently did your baby attend video calls?" (Multiple choice: Rarely, Once or twice a month, Once a week, Two-three times a week, Daily). The remaining three questions investigated the characteristics of the device that the participants were going to use to join the video call: (c) "Which device will you be using to play the Gaze Following Game?" (Multiple choice: Laptop computer, Desktop computer), (d) "Which best describes the camera on your device?" (Multiple choice: Built-in camera, External camera), and (e) "What is the size of your device monitor in inches?" (Text entry). The survey took approximately 5 minutes of time to be completed.

Video call. Before the video call started, infants were randomly assigned to either the Open-eyes or the Closed-eyes condition. Once the participants joined the call, they were asked to activate their audio and video icons and to enter the full-screen mode. This was the only set up on the participant side and it was achieved in a few seconds by clicking two icons which turned green. Apart from that, the entire layout and what was displayed on the screen was controlled by the experimenter who had two pre-made layouts to choose from.

The experiment included two layouts, one used during the introduction and debriefing sessions and the other one used during the interactive test session itself. The first layout had the participant and experimenter videos side by side on top and a slide presentation at the bottom, whereas the test layout had the slide presentation covering the entire screen area with the experimenter (top position) and participant (bottom position) videos in the centre of the screen floating on top of the slides. Figure 12 shows the video call procedure, displaying the two layouts used during the video call.

Some instructions

- Limit distractors (such as attractive objects or people/pets walking around)
- Sit your baby on your lap
- Adjust the camera to have your baby's face and hands in view

Figure 12. Procedure adopted during the video call. The first call layout, with videos on top and slides at the bottom, was presented during the initial introduction and set up. After that, during the gaze following test, the interactive test layout was adopted. This second layout had videos floating on top of the slides where the target objects appeared. On each trial, the participant's video was covered during the eye contact and head turn phases.

Following the initial setup, parents were reminded of the procedure and were asked to refrain from intervening, talking, or directing their baby's attention (e.g., pointing or gazing towards one target object on screen) during the eye contact and head turn phases (lasting about 7s). Parents were able to engage with their infant during the inter-trial intervals (1-2 minutes) if the infant turned towards them. This limited the possibility that parental lack of response could serve as an ostensive cue that the on-screen information was not relevant or worthy of attention (Demers, Hanson, Kirkorian, Pempek, & Anderson, 2013). At this point, the infant could join the procedure and sit on their parent's lap. Parents were shown an exemplar photo of an ideal infant positioning and were asked to adjust their camera and/or their seat distance in order to have both the baby's face and hands in camera view. At this stage, the experimenter quickly checked if the camera has been mirrored by asking the parent to raise their left hand and then recording could begin. The interactive test layout was selected by the experimenter and automatically changed for the participant as well.

The gaze following paradigm included 4 head-turn trials and followed a similar procedure as the one reported in past laboratory studies with a live experimenter (Brooks & Meltzoff, 2002; 2005). Before the start of each trial, two identical objects appeared to the left- and right-hand sides of the experimenter video. Objects appeared on a light grey background and were aligned on the horizontal axis at approximately eye level relative to the experimenter's face. They appeared peripherally at the edge of the participant's screen area, given that all participants were full-screen. The order of the target objects presentation was randomly chosen before the appointment. Next, the experimenter made eye contact with the infant with a neutral facial expression and tried to ensure that every trial began at the midline by attracting the participant's attention with a squeaky toy. At this point, the participant's video was covered with a patch matching the background so that the participant could only see the experimenter face and the target objects. The experimenter silently turned her head (approximately 45˚) to a predetermined side and shifted her gaze towards the target location with a neutral facial expression. For the closed-eyes condition, the experimenter closed her eyes after making eye contact at midline and silently turned her head to a target with closed eyes. The direction of the experimenter’s head-turn (left or right) followed either an ABBA or ABAB pattern with the first turn direction and pattern counterbalanced across the two eye status conditions. Each trial lasted 6-7 s. The trial started when the adult’s head-turn began and lasted until the adult oriented back towards the midline. The experimenter used a timer with vibration to keep the trial time. After the gaze following trial, the peripheral target objects were removed. The experimenter removed the patch covering the participant’s video and resumed the interaction with a 1- to 2-minute inter-trial interval. During these breaks, the experimenter entertained the baby with two different finger puppets per inter-trial interval and could contingently interact with the participants. All participants were presented with all the trials but in some cases, one trial (n = 5) or two trials (n = 2) were excluded because the infant was distracted or looked away during trial onset. The participant needed to contribute with at least 50% valid trials in order to be included in the analysis.

Following the interactive test, parents were requested to give feedback about the call quality during the session. They were asked to rate both video and sound quality on a 5-point scale (ranging from 1 = very poor to 5 = very good). Additionally, they were asked which browser they were using. Lastly, there was a debriefing with the experimenter with the possibility to ask questions. The total duration of the video call was approximately 15 minutes, including initial instructions to the parent and final debriefing. The gaze following component, which involved the infant, lasted around 4-5 minutes.

6.2.4 Scoring and Data processing

For scoring, video recordings were edited via Adobe Connect to remove the patch which covered the infant video during the live gaze following procedure. Video recordings were then processed via ELAN software, version 5.9 (Brugman & Russel, 2004; ELAN, 2020; retrieved from https://archive.mpi.nl/tla/elan). Each video was zoomed in to allow the coders to only see the infant’s face without being aware of the experimenter’s eye status condition on each trial. The scoring was accurate to the video frame level, which was 19 frames per second. For each trial, the coder assessed if the participant was looking towards the experimenter before the head turn started. If the participant was paying attention to the experimenter before the onset of the head movement, the trial was considered valid and the looking behaviour in response to the following head turn could be coded. This validity check was useful not only to make sure that there was an eye contact phase but also for the coders to get a reference of the infant's face and eyes orientation when looking towards the centre of the screen and disambiguate them from orientations towards one side of the screen. In fact, the participant's webcam position could vary across participants.

Looking score. If a trial was scored as valid, the coder scored the orientation of the participant's first look following the experimenter's head turn. In more detail, the coder scored whether the first look was oriented towards the left or right side compared to the eye contact phase for at least 0.3 s, or if the participant looked away from the screen after the experimenter's head turn. The first look had to start before the experimenter moved back to facing the central camera. Following seminal work in the gaze following literature (e.g., Brooks & Meltzoff, 2002, 2005; Flom et al., 2004; Moore & Corkum, 1998), a difference score was adopted. As such, the scoring was either converted as a "Correct look" (+1) if the first look was directed towards the target the experimenter was looking at, "Incorrect look" (-1) if the first look was directed towards the non-gazed target, or "No look" (0) if the participant did not look at any peripheral target, looked down/away from the screen. In this scoring phase, it was important to take into account if the participant's camera was mirrored or not. The individual looking score was the sum of correct looks, incorrect looks and no looks. Thus, the score could range from -4 to +4 and considered the difference between matches and mismatches. A positive looking score indicates that the participant looked more often towards the direction of the experimenter's turn, a negative looking score indicates that the participant looked more often towards the opposite direction in respect to the experimenter's turn, while a zero score indicates undifferentiated looking behaviour or chance level.

Dichotomous score. In case the infant looked towards more than one direction while the experimenter was turned towards a target, the coder scored the following look direction as well. Thus, a dichotomous score (yes/1 vs. no/0) was created for each trial. It indicated whether the participant had looked at the target location at all while the experimenter head was oriented towards the target, irrespective of the first look direction. Considering that four trials were presented, this dichotomous score could range from 0 to 4, expressing the number of trials during which the infant had followed the experimenter's head turn beyond their first look. For instance, a zero-score meant that the participant never looked towards the correct peripheral target across all trials, while a score of 3 meant that the participant looked towards the correct target direction during three out of four trials, irrespective of the first look direction.

Scoring agreement. A first coder scored all the 32 infants, while a second coder scored a random sample of 8 (25%) infants, uninformed of the research questions and experimental conditions. Using Cohen's kappa, near perfect agreement was obtained, with 94% relative observed agreement and k =0.86.

6.3 RESULTS

6.3.1 Survey

The majority of infant participants (n = 28, 87.50%) had been exposed to video calls in the months prior to their participation in this study. Infants who experienced video calls were mostly exposed at least once per week (24 of 28). In fact, the proportion of infants exposed rarely to video calls was 3.57% (n = 1), those who were exposed once or twice a month were 10.71% (n = 3), 39.29% (n = 11) were exposed once a week, 32.14% (n = 9) two to three times a week, and 14.29% (n = 4) daily.

Regarding the computer device adopted to play the gaze following task, most participants used a laptop computer (n = 29, 90.63%). The remaining participants used a desktop computer (n = 3, 9.37%). The vast majority of the devices had a built-in camera (n = 31, 96.88%) and only one device had an external camera. The median screen size of the computer devices used during the video call was 15’’ (interquartile range [IQR] = 3’’).

6.3.2 Gaze following task

After scoring the trials, there was 7% data loss across participants (9 trials were invalid out of a total of 128 administered trials). Non-valid trials were due to the participant not gazing at the centre of the screen when the experimenter’s head turn started (*n* = 6) or due to fussiness and/or crying during the experimenter’s head turn (*n* = 3). When considering valid trials, the mean frequency of each looking behaviour from which the looking score was derived (i.e., Correct look, Incorrect look and No look) is reported in Table 7.

Behaviour	Open eyes	Closed eyes
Correct look	1.69 (0.96)	0.81 (0.75)
Incorrect look	0.38 (0.72)	1.06 (0.93)
No look	1.75 (1.24)	1.75 (1.24)

Table 7. Mean (and SD) of the frequency of each looking behaviour in response to the experimenter’s head turn per eye status condition. Mean frequency values could range from 0 to 4 given that each infant had 4 trials. The analyses were not based on the frequency values but rather were based on the looking scores.

A one-tailed Mann-Whitney U-test showed a higher looking score for infants assigned to the Open eyes group (Mdn = 1, IQR = 1) compared to the ones assigned to the Closed eyes group (Mdn = 0, IQR = 1, U = 46, *p* < .001; see Figure 13). Median values and non-parametric tests were more appropriate than mean values and parametric tests given the skewed data distribution of the looking score in the two eye status groups (with a right-skewed distribution for the Closed eyes group and a left-skewed distribution for the Open eyes group). Mean values of the looking score are also reported for comparability with prior seminal studies in the gaze following literature, which also reported mean values (e.g., Brooks & Meltzoff, 2002; 2005). The mean looking score was *M* =

1.31 (SD = 1.25) in the Open eyes group and *M* = -0.25 (SD = 1.13) in the Closed eyes group.

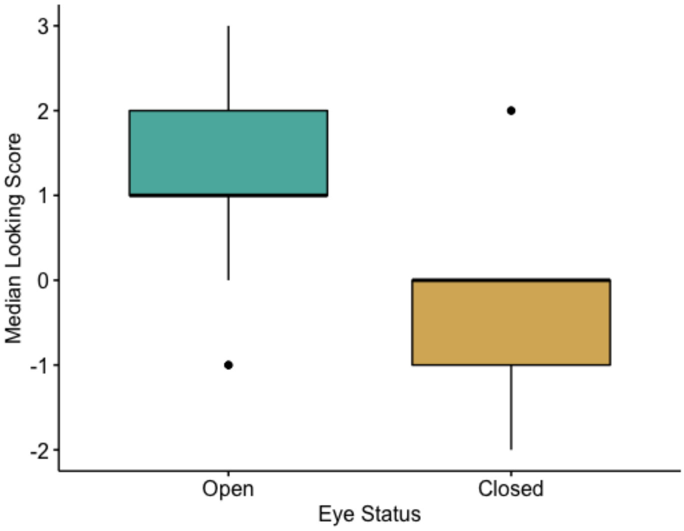

Figure 13. Median looking score for open eyes and closed eyes conditions. The looking score was a difference score that could range from -4 to +4.

Although the looking score is the standard measure in the field, the looking behaviour was also analysed in a dichotomous fashion to understand whether infants looked more times towards the correct side in the open- than closed-eyes condition during the entire trial length, irrespective of what target they looked first. A one-tailed Mann-Whitney U-test showed that infants generally looked more towards the correct side in the Open eyes group (Mdn = 1.5, IQR = 2) compared to the ones assigned to the Closed eyes group (Mdn = 1, IQR = 1.25, U = 79, *p* = .027). As above, we also reported mean values for the dichotomous score in the Open eyes group (*M* = 1.81, SD = 1.11) compared to the Closed eyes group (*M* = 1.06, SD = 1.00).

Further, the ceiling effect at the survey in terms of infants' past exposure to video chat settings (with the vast majority of participants highly exposed to video calls) did not enable us to explore this measure in relation to the gaze following outcomes of interest.

6.4 DISCUSSION

A number of studies have shown that infants start to follow a social partner's gaze on the basis of clear perceptual cues, such as head direction (e.g., Corkum & Moore, 1995; D'Entremont, 2000). Evidence from the laboratory suggested that infants specifically follow eye direction from 10 to 11 months of age (Brooks & Meltzoff, 2005). The present study successfully attempted to investigate this core social-interactive skill outside of the laboratory for the first time, adopting an online method to test 11- to 12-month-old participants in their home environment. First of all, the synchronous testing procedure that we developed was effective for bringing research into the participants' home environment and to test gaze following skills in less controlled settings. A central contribution of this work was the presentation of an alternative way to conduct social attention studies in the home environment. We found that infants successfully follow a virtual partner's gaze. These findings generalise past results not only to a noisier home environment, but also to a virtual social partner contingently interacting with the infant participant. Unlike prior screen-based gaze following studies that have been run in laboratories, here the experimenter was able to respond to the participant in a live-interactive setup and could adapt the procedure according to the infant's responses. Further, infants' gaze following ability did not depend on the experimenter's head orientation, but varied as a function of the perceptual status of the virtual partner's eyes, with infants preferentially following open rather than closed eyes. Thus, from 11 months of age, not only in-person social partners but also virtual social partners are treated as visually-connected social agents.

Our results are generally consistent with past laboratory studies showing that, towards the end of the first postnatal year, infants understand that eye direction is a relevant cue to learn through others (Brooks & Meltzoff, 2002, 2005). The present looking score values were comparable with past in-lab values adopting similar procedures and scoring (see results at age 12 months in Brooks & Meltzoff, 2002 or results at 10 and 11 months in Brooks & Meltzoff, 2005) and showed better gaze following skills if the experimenter turned towards the target with open eyes rather than with closed eyes. This score is the standard in the gaze following literature and considers chance performance using the difference between orientations towards the correct and incorrect hemifields. Disentangling the frequency of each looking behaviour that made up this difference score, infants made on average more first looks towards the correct target compared to the incorrect target in the open eyes condition, whereas they showed a similar amount of correct and incorrect looks in the closed eyes condition. One could possibly argue that the closed eyes condition is less familiar for infants but, interestingly, the frequency of behaviours coded as No looks was identical in the open and closed eyes conditions. This suggests that infants kept looking at the experimenter and did not look towards a peripheral target equally across eye conditions. The relevance of eye direction in guiding the infant’s attention is evident not only from the first look direction, as expressed by the looking score, but also from the number of times infants oriented towards the correct target during the entire trial length, as expressed by the dichotomous score. Overall, infants were orienting more often towards the correct target side during the 6-7 s of head turn if the experimenter turned with open than with closed eyes.

Of note, results also suggested that there is room for developmental improvement in infants’ virtual gaze following and some variation across participants also emerged. One potential source of individual differences that may influence virtual gaze following is the infant’s prior exposure to video calls. In this context, it is reasonable to expect that infants already familiar with video chat may be facilitated in recognising a live interacting virtual partner and may have a better understanding of social cues during video-based interactions compared to infants that have not been exposed to video calls (in line with Troseth et al., 2006). However, other researchers did not find such relationship between experience and experimental outcome (e.g., Myers et al., 2017). As such, it seemed an interesting relation to be further explored. In the current sample, the vast majority had been exposed to video calls and we did not have enough data to compare the gaze following outcomes as a function of experience.

Our data and the measures that we adopted support the hypothesis that eyes assume a relevant role towards the end of the first postnatal year and that those are used as important cues, even beyond face-to-face interactions. The reliance on the eyes in gaze following situations is typically human and may have evolved to support our cooperative behaviour (Tomasello, Hare, Lehmann, & Call, 2007). Humans white sclerae with open eyelids are unique among primates; these characteristics can make the gaze direction visible from a distance to enhance the effectiveness of this communicative signal (Kobayashi & Kohshima, 2001). If in a face-to-face context this information may be evident, in a video call it may be less visible, considering the video-based presentation and the size of the experimenter's face on the screen. Still, in this online study the adult's head motion was not enough to reliably draw the infant's attention to a target object and the social partner needed to turn towards an object with open rather than closed eyes, even from a variable distance and via a virtual medium.

We conclude that objects become more relevant if the adult can see them and is looking at them, in virtual as in in-person contexts. What these two contexts have in common is that the social partner is interacting with the infant contingently and can adapt the procedure according to the infant's needs and behaviour. In fact, our online study was characterised by a live interaction between adult and infant, as it was the case for past in-person laboratory-based investigations. Through a live social interaction, multiple possibilities of learning and cooperation may arise by recognising where the social partner is looking at. In addition, the live presentation can better match real world situations as opposed to pre-recorded videos. Intriguingly, some evidence has suggested the presence of a so-called video deficit phenomenon, i.e., decreased learning from screen-based situations compared to in-person ones, from around 12 months of age (Anderson & Pempek, 2005; Dickerson, Gerhardstein, Zack, & Barr, 2013). Nevertheless, some recent work has failed to replicate this deficit which seemed weak relative to past generations (Sommer, Redshaw, Slaughter, & Wiles, 2021). In particular, this may be the case of video-based studies with a socially contingent interaction, in which a live social partner can support learning (e.g., Myers et al., 2017; Nielsen et al., 2008; Roseberry et al., 2014;

Troseth, Saylor, & Archer, 2006, but see also Troseth, Strouse, Verdine, & Saylor, 2018, for the argument that social contingency is not enough). Currently, infants are increasingly exposed to digital media and this experience may lead them to extract information and learn from both real and virtual agents, when contrasted with prior generations. In our sample, the vast majority of infants had been exposed not only to screens but specifically to video calls, most of them at least once a week. Given that infants were tested while pandemic restrictions were in place across the UK, online interactions represented a key way of keeping in touch with relatives and friends while other forms of gathering were limited. In this context, understanding whether real and virtual social partners are treated in similar ways is highly relevant and contemporary. Future studies may better investigate whether exposure to digital media may have a role in recognising a virtual social partner as a visually connected social agent.

In addition to extending past findings to a virtual social partner, the present study has also provided evidence of generalisation from past controlled laboratory settings to more heterogeneous home environments. Testing participants online has not only enabled developmental research in a noisier and less controlled context, it also has the advantage of being more comfortable for the infant, who does not have to travel and adapt to a new environment in the laboratory. In addition, this approach allowed us to eliminate geographical barriers and to reach participants from multiple sites across the UK. This is a promising step towards a more diversified sample of participants, although requiring an internet connection may limit the demographics of those who may be involved (Lourenco & Tasimi, 2020). Transitioning to online research also brought some challenges. In particular, those associated with relying on the participant's own device and internet connection, which may lead to heterogeneous data quality, or dealing with uncontrollable distractors from the home environment. As a limit of the present study, we did not plan to use duration measures as connection differences across trials and across infants could have led to slightly imprecise timings, although all our recordings had the same frame rate. Also, although we tried to carefully adapt the same procedures and measures used in prior laboratory studies, there may be some differences between laboratory and remote performance that were undetected here. Overall, we believe that online testing may represent a new frontier via which to flexibly assess development outside the laboratory and it can be an additional method via which to diversify and replicate developmental findings.

6.5 CONCLUSIONS

This online study showed that 11- to 12-month-old infants are developing the ability to recognise social cues provided by a virtual partner in a live-interactive online setup. In fact, infants' gaze following skills varied as a function of the perceptual status of the virtual partner's eyes and gaze following was only possible when the adult's eyes were open. The present data support evidence claiming that infants can genuinely *gaze* follow from about 10 to 11 months of age and extend past results to virtual social interactions. As virtual interactions have a prominent role in our everyday life, these findings have significant implications for understanding how infants treat a virtual agent and how they orient their attention in a rapidly changing social world.

Chapter 7

Discussion

7.1 SUMMARY OF FINDINGS

The work presented in this thesis aimed to map sensitivities to visual information in peripheral locations and to understand how different forms of visual information are processed across the developing visual field. Thus far, developmental research has mostly studied information processing in response to peripheral targets appearing within the relatively narrow field of view that standard computer displays enable to investigate. At the same time, clinical and perceptual measures of the peripheral extent have identified the limits of the visual field across a wide field of view but have not investigated the relation between different types of stimuli and eccentricity. To address this, the investigations presented in the current thesis covered low- to high-level visual information, such as Gabor patches (Chapter 2), face-like stimuli (Chapter 3) and faces expressing emotions (Chapter 4 and 5) presented across the peripheral visual field, and live interacting faces gazing peripheral locations (Chapter 6). All visual presentations were displayed across a wide space that required a combination of eye, head and body movement to successfully detect and further process a target. Overall, findings revealed successful peripheral detection skills at mid-peripheral eccentricities around 9 months of age, with declining performances at increased eccentricity. The stimulus characteristics had an influence on peripheral information processing, especially some social-communicative aspects of the target. The following sections summarise the findings of each experimental chapter in more detail.

7.1.1 Identifying the peripheral visual extent with different types of targets

The first study (Chapter 2) measured how far in their visual field 9-month-old infants and a control group of adults can detect peripheral information. We aimed to develop an infant study aligned with psychophysics experiments so that the target presentation was not associated with abrupt visual changes against the background. Previous studies investigating the peripheral visual extent in infancy have mostly adopted highly salient light targets (e.g., Courage & Adams, 1995; Harris & Macfarlane, 1974; Lewis & Maurer, 1992; Mayer et al., 1988) and the available measures of the developing visual field rely on a limited range of extremely salient situations. In this study, Gabor patches matching the background luminance were presented at 12 locations between 35° to 60° eccentricity to the left and right of the midline on a wide curved display. Abrupt changes across the visual field were also limited by progressively increasing the contrast of the target patch from 0 to 100% contrast levels within a Gaussian temporal envelope. Head and eye movements response to the target appearance were video recorded in infants and button press responses were recorded in adults.

Data revealed that 9-month-old infants' peripheral information detection skills were not fully mature at the investigated eccentricities when compared to adult performances which were at ceiling, in line with evidence that set the extent of the mature visual field up to 100° (e.g., To et al., 2011). Infant performances were not uniform and dropped with increased eccentricity. Performances were above chance level for targets appearing up to 50° eccentricity but fell from 55° eccentricity onwards. Even at closer eccentricities, sensitivities to peripheral information were unequal with a drop around 40°. This suggests that at 9 months of age, peripheral vision, as reflected by the infant's orienting behaviour, is not matured. This agrees with experiments by Dobson et al. (1998), as opposed to studies by Lewis and Maurer (1992) and Mayer et al. (1988) that suggested an already matured peripheral vision at the investigated age. Beyond 50° eccentricity, it remains possible that only highly salient information can be detected.

As already suggested in Maurer and Lewis (1991), stimulus characteristics and methodological differences seem to play a relevant role in peripheral information detection. This was suggested by comparing studies using different testing methodologies and low-level visual features. In consideration of the importance of target characteristics in eliciting a response in the visual periphery, the second study (Chapter 3) investigated socially-relevant information, namely face-like targets. Past research claimed an advantage of face processing due to rapid automatic brain detection mechanisms (see Johnson et al., 2015 for a review) and faces seem to have an advantage compared to other objects when stimuli are arranged in circular arrays covering near-peripheral locations (Gliga et al., 2009; Simpson et al., 2019). As far as we know, no past perimetry work used face-like stimuli to measure sensitivities to peripheral information beyond near-peripheral eccentricities. Importantly, in Study 2 we used the same set up and low-level visual features of the stimuli (i.e., colour, spatial frequency, contrast, luminance, size) that had been used in Study 1. This enabled us to investigate whether the nature of the target had a role on peripheral sensitivities while set up, procedures and low-level visual features of the stimuli were constant. In particular, we wanted to understand whether socially relevant information may have an advantage at high eccentricities or if peripheral degradation does not allow to distinguish between visual configurations. In this second study, another group of 9-month-old infants was tested by video recording their behaviour in response to the appearance of a peripheral target. This time, peripheral locations were reduced to six (50°, 55° and 60° to the left and right of the midline), to focus on what Study 1 suggested as the edge of the infant visual field. Testing less eccentricities enabled us to investigate two target orientations (upright and inverted face-like stimuli).

Results showed heterogeneous detection rates which decreased at higher eccentricities. In particular, performances dropped at 60° eccentricity. Further, there was a marginal advantage in detecting face-like targets appearing on the left hemifield compared to the right hemifield. Target orientation had no effect at the edge of the infant visual field. Overall, the results of Study 2 qualitatively suggested increased peripheral sensitivities with face-like stimuli compared to the Gabor patches presented in Study 1 at all the investigated eccentricities. At present, there is no evidence that the stimuli are processed differently as the comparison among the two studies is only qualitative. Although eccentricity is the factor that better explained detection rates in both Study 1 and Study 2, face-like target also elicited a slight lateralisation effect that was not evident with Gabor patches.

7.1.2 Attention-holding and attention getting mechanisms across the visual field

The first two experimental chapters of this thesis looked at head and eye movements in response to a peripheral target presentation with the aim to map the extent of the visual field. In these studies, the orienting behaviour under investigation was overt and detection was very easily observable via video recordings. In fact, a combination of eye and head movements was required to successfully detect targets across a wide field of view of over 120°. Study 3 (Chapter 4) investigated not only the limits of peripheral processing but also distinguish between attention-getting (latency) and attention-holding (dwell time) mechanisms, in response to targets appearing at the edge of the developing visual field. Eye-tracking enabled us to obtain a quantitative and precise measure in the time domain. The methods work presented in Chapter 4 was designed to overcome one major limitation of most commercial eye-tracking systems, that is recording data within a 30-inch screen. In this set up, we successfully obtained eye tracking data across a 49-inch curved screen. As a further advantage, the detection algorithms were specifically adapted to cater for the developing eye and head. Results had a focus on data quality and an offline calibration procedure was implemented to improve the spatial accuracy of the recordings.

The eye tracking system introduced in Chapter 4 was then adopted in the infant study presented in Chapter 5. In this study, we investigated both attention-getting and attention-holding mechanisms in response to emotional facial expressions appearing at 60° eccentricity and moving towards the midline. Nine-month-old infants were presented with peripheral faces with either an angry or neural expression to understand if a direct threat has an advantage at high eccentricities as suggested by adult research (Bayle et al., 2011) and by infant research (LoBue & DeLoache, 2010), although data only within near-peripheral locations are available during infancy. This study also investigated the effect of competing peripheral information. In fact, the single and competing conditions seemed to rely on different brain processing mechanisms (Atkinson & Nardini, 2008).

Results revealed shorter latency for competing rather than single trials. Hence, infants were faster in orienting towards peripheral visual information when two faces simultaneously appeared in both the left and right hemifields, rather than trials in which a single face appeared either on the left or right hemifield. During these more arousing paired visual presentations, angry faces were detected faster than neutral ones. These data support a bias in detecting threatening information from angry faces and extends this bias to the edge of the developing visual field. Results also revealed two non-predicted effects. Namely, males were overall faster than females across both competing and single trials. This suggested that individual differences may play a role when orienting requires a more global motor behaviour, including eye, head and body movements. Also, during competing trials a side advantage emerged, with targets detected on the right hemifield associated with faster latency than targets detected on the left hemifield. This effect would need to be investigated in more detail to understand whether it is linked with the target stimuli, the competing presentation or the high eccentricities. In contrast to the latency results, dwell times on the moving face area did not differ across experimental conditions, suggesting that sustained attention is not influenced as rapid detection at high eccentricities. Further to the timings of attentional responses, these results provide information about where peripheral information was detected in space. On average, at the time faces were detected they were located at 55° eccentricity. Interestingly, this is in line with evidence we reported in Chapter 3 of successful detection of face-like stimuli up to 55° eccentricity, whereas non-face targets used in Chapter 2 were detected up to 50° eccentricity.

7.1.3 Peripheral information processing in online settings

In the final experiment described in this thesis (Chapter 6), we transitioned to an online study to investigate infant's ability to follow the gaze of a virtual social partner towards a peripheral target on screen. Eleven- to twelve-month-old infants were tested via video call using a moderated testing procedure. We manipulated whether the experimenter could or could not see the target objects (Open eyes vs. Closed eyes conditions) in a between-subject design. Past laboratory-based paradigms revealed that from 10 months of age infants follow the gaze of a live experimenter that turns towards an object more often if the experimenter has open rather than closed eyes (Brooks & Meltzoff, 2002, 2005). In consideration of the increased virtual interactions children have been exposed over the past years, this last study investigated whether infants can recognise someone interacting via video chat as a social agent. The synchronous testing procedure allowed to test a new condition in which the social partner can interact live with the infant (as per live laboratory settings) but the procedure is taking place on a screen (as per video-based laboratory settings).

Results showed evidence of a successful transition to online studies, with a tool that provides several advantages for moderated infant research and the first attempt to investigate gaze following online with a live social partner that can adapt the procedures according to the infant's behaviour. Further, results showed that 11- to 12-month-old infants can follow a social partner's eye gaze towards a peripheral target and they preferentially do so when the virtual gazer had open rather than closed eyes. Hence, not only do these results replicate past laboratory findings by Brooks and Meltzoff (2002, 2005) but they further generalise past findings to a noisier testing environment (the participant's home) and to a virtual partner that interacts in a contingent way with the infant participant. In addition, this work revealed that the vast majority of the infant participants have been exposed to video calls prior to their enrolment in this study. This opens the possibility that infants' exposure to video calls may have facilitated virtual interactions and, in turn, gaze following skills.

7.2 THEORETICAL AND METHODOLOGICAL IMPLICATIONS

The research presented in this thesis provides evidence about infant’s visual information processing skills across a wide visual field. Firstly, it established the boundaries of detection in 9-month-old infants in response to social and non-social visual content. Further, it demonstrated differential attention-getting and attention-holding processes for facial expressions across the visual field. These findings are relevant to set the scene for a variety of laboratory investigations across a wider space and to understand how visual attention and perception can ground further development in different domains. In addition to expanding our knowledge on visual perception and social cognition in laboratory settings, they also demonstrated the feasibility of testing in more naturalistic home environments and expanded our knowledge of social communicative skills in virtual settings. Implications are discussed in terms of theory and methodology in the following sections.

7.2.1 Differential visual processing for social and non-social information across the visual field

The studies conducted within this thesis indicated that at 9 months of age, peripheral vision is still developing. Importantly, in these studies the limits of peripheral visual processing have been investigated beyond the highly salient scenarios investigated so far and our results can have implications in understanding how more cluttered visual changes across the visual field can guide exploratory behaviours during development. Identifying the limits of visual processing is relevant for understanding what information can be perceived from our rich visual environment for further processing and for building a spatial layout of the visual scene. Vision also grounds the development of motor and action control during the first year of infancy and peripheral vision is essential for the functional representation of space (e.g., Atkinson, 2000). For instance, the information about the position of a visual target in space is integrated with the reaching system or for moving a limb in space. Our studies have demonstrated that the boundaries of visual processing depend on the nature of the target, with face-like targets (Chapter 3) detected further out in the visual field than Gabor patches (Chapter 2). While past evidence already suggested that the characteristics of both central and peripheral stimuli affects orienting attention (Hunnius & Geuze, 2004; Valenza et al., 2015), here we investigated the effect of the characteristics of a peripheral stimulus in a wider space that better resembles the daily visual environment.

The current data provide evidence of an advantage of some social-communicative cues at high eccentricities: First, a prominent difference in the limits of the visual field when detecting face configurations (Chapter 3) vs. Gabor patches (Chapter 2), and second, shorter response times for detecting threatening facial expressions vs. non-threatening ones (Chapter 5). Even though face configurations showed increased detection rates compared to basic patches at the edge of the developing visual field, orientation of face-like targets was not relevant at such extreme locations, at least in terms of attention-getting mechanisms (Chapter 3). Accordingly, face-like stimuli may not be holistically perceived at peripheral locations. Alternatively, other measures, such as reaction times or attention-holding measures like dwell times, may be better suited to show a differential processing of upright and inverted stimuli.

A further aspect that emerged from the studies presented in this thesis relates to the lateralisation of visual detection functions at the edge of the visual field. While detection of Gabor patches did not show side differences (Chapter 2), face-like targets were detected more successfully on the left hemifield (Chapter 3). Infants were also found to be faster in orienting towards faces expressing emotions on the right hemifield during competing trials (Chapter 5). The measures are different across studies, either a dichotomic measure of detection (Chapters 2 and 3) or a quantitative measure of reaction times (Chapters 4 and 5). Also, the right advantage emerged only during competing trials, suggesting differential mechanisms for competing and single trials. Other potential explanations of the side biases could be linked with the low-level visual features associated with the peripheral targets (i.e., face-like stimuli obtained from faces filtered at a specific spatial frequency versus intact faces expressing emotional expressions). Spatial frequency may be a candidate difference. For instance, there is evidence of a right visual field superiority with high spatial frequencies

(Efron & Yund, 1999). Overall, while some studies suggested a left bias for face processing (associated with a right hemisphere advantage; e.g., Dundas et al., 2012; Yovel et al., 2008), other studies have shown a right bias (associated with a left hemisphere advantage) for motor behaviours in space (e.g., Atkinson, 2000; Bishop, 1990). Further studies are needed to disentangle the role of target characteristics, competing information and measures of visual detection on side biases at the edge of the visual field.

Another theoretical implication suggested by this research is the differential processing of competing and single social information. Overall, there was an advantage in terms of reaction times when stimuli simultaneously appeared at the edge of the visual field in comparison with situations with a single target appearing at the time. Also, a distinction between threatening and non-threatening information and a side bias were only evident during this arousing competing condition. While past research already suggested differential brain processing mechanisms for single and competing information (e.g., Atkinson & Nardini, 2008), the present data across a wide visual field may have implications for understanding detection of visual information in situations in which our visual system is more stimulated. As such, our detection skills may have developed an advantage for information that is cluttered or simultaneously presented. This opens the possibility of investigating scene recognition in peripheral locations and more complex scenarios.

Overall, we demonstrated the possibility of testing aspects of visual perception and social cognition across a wider visual environment, providing evidence of the information processing mechanisms outside of the most investigated central and near-peripheral locations. The current findings not only shed light on visual processing development, but may be also informative for atypical developmental conditions. Past evidence has shown that some neurological conditions are associated with reduced lateral visual fields and a difficulty to shift attention towards a peripheral target, especially in competition conditions (Atkinson 1989; Mercuri et al., 1995, 1997). Characterising the boundaries of typical visual processing is therefore important for the grounding of further investigations on atypical development.

7.2.2 Methodological tools for investigations in a wide visual space

The studies presented in this thesis can be useful to set the scene for a variety of investigations in a wide space beyond standard screen presentations. Knowing the extent of the visual field and how the characteristics of the stimuli affect visual processing can inform the design of a variety of infant paradigms. Examples include not only investigations on visual orienting behaviour in response to peripheral stimuli as investigated in this thesis, but also studies in the domain of action and motor development in space or in the domain of social-cognitive development when information is outside foveated locations.

In terms of the extent of the visual field, the perimetry work we presented in Chapters 2 and 3 using carefully controlled visual stimuli has implications for understanding visual information processing across the visual field in situations where stimuli are cluttered in the environment. This provides a tool for investigating high eccentricities without presenting alerting and extremely salient visual information. Further, we introduced a multi-camera remote eye tracking system that can record eye and head movements in a wide space (Chapter 4). This has implications for building paradigms in which attention can be investigated across a wide field of view with the head and body that are less constrained in their movements. In fact, the visual behaviour that can be measured using the majority of remote eye tracking solutions is mostly made up of the eye component. The implementation of such eye tracking systems for developing populations enables the investigation of more naturalistic situations in which the eye, head and body move more freely in space. While here we tracked a curved three-dimensional monitor, an area not including a real screen can be tracked as well with a number of different current technologies. Hence, this would enable the investigation of visual behaviour in response to real objects at more diverse locations across the visual field. The eye tracking work we presented also focused on data quality and introduced an offline calibration procedure to improve spatial accuracy. Data quality parameters are rarely reported in infant eye tracking studies and this may have implications for comparing results across groups of participants and for interpreting data (Dalrymple et al., 2018; Wass et al., 2014). In fact, some effects may be due to data quality differences instead of actual differences associated with experimental manipulations. Including a data quality check and the exploration of techniques for improving data accuracy are an important endeavour for developmental eye tracking studies.

Another methodological tool that we presented within this thesis is a moderated online testing procedure to test gaze following in infancy. This method enabled us to test the infant’s behaviour in response to a social partner that interacts via video. Screen-based paradigms used in laboratories are often characterised by the presentation of either images or videos of an actor that are pre-recorded. As such, the procedure cannot be adapted to the infant’s behaviour and the agent that appears on video does not have a way to interact in a live manner. Testing infant participants online via video chat enables a paradigm comprising a mix of video-based and contingent interaction that can open up multiple possibilities of investigating social-communicative behaviours via social media. Further, as far as we know, we used for the first time a video chat software (i.e., Adobe Connect) with infants that provides the opportunity to have full control over what the participant can see on screen. This has implications for developing online research tools that are more controlled and reliable across participants.

7.3 LIMITATIONS AND FUTURE DIRECTIONS

The current thesis has presented a series of studies mapping infants’ sensitivities to different kinds of peripheral visual information. While this work grounds infant research across a wide and more naturalistic visual space and can set the scene for many infant investigations to come, further aspects of visual development could be explored in more detail and many more questions are worthy of exploration. Limitations and further research questions arising from the current thesis are discussed in the following sections.

7.3.1 Limitations of the studies

When considering the limited work investigating perception and attention beyond near-peripheral locations, a general limitation of the studies presented in this thesis is that there is space to investigate our research questions in more detail and with a focus on the developmental trajectory of infant visual capacities. Our studies investigated infants aged 9 months (Chapters 2 to 5) and 11-12 months (Chapter 6). We selected 9-month-old infants as a key time point in consideration of the limited perimetry works at this age and mixed evidence on whether peripheral vision is fully mature or not at this developmental time point (e.g., Dobson et al., 1998; Mayer et al., 1988). Further, peripheral vision is important for moving in space, action control, building spatial representations and orienting to relevant information. At the investigated age, infants increasingly explore their surroundings: we therefore believed that this age was of interest to understand the spatial limits of vision while they explore the environment which requires a wider field of view. Given that we concluded that at 9 months of age peripheral vision as reflected in their orienting behaviour is not fully developed, it would be interesting to understand the full pathway, including the endpoint, of this perceptual capacity.

In general, the first two studies (Chapter 2 and 3) adopted very controlled stimuli and we avoided any abrupt change of the low-level visual features associated with the visual presentation. It would be relevant to map infants' sensitivities to peripheral information at different time points with this set of stimuli. Also, in terms of stimuli, it would be worth investigating how social and non-social stimuli influence sensitivities to peripheral information during different developmental stages. Even though facial-like orientation did not seem influential for detection of face-like targets at mid-peripheral locations, it could be that it is either relevant at a different developmental stage or that another measure is more suitable to detect a difference. More generally, in Chapter 2 and 3 we chose some specific set of low-level visual features to avoid abrupt changes across the visual field but we did not directly measure if more salient stimuli would elicit different peripheral sensitivities.

Limitations are also related to the methodologies we adopted. The first two experimental chapters of this thesis (Chapter 2 and 3) measured the extent of the developing visual field with a set of stimuli whose low-level visual features where carefully controlled to avoid participants responding to abrupt visual changes. We measured detection as head/eye orientations towards the peripheral target and, thus, an overt behaviour. This leaves the possibility that participants can sense a visual change but do not respond overtly. In this case, the visual extent may be underestimated. At the same time, infants could orient randomly to the target during some trials so this may compensate for a lack of response. Also, our data revealed that infants still responded at more extreme eccentricities but with more errors than closer eccentricities. Another option to better investigate no responses would be to include blank trials that do not include the presentation of the peripheral target following the central stimulus presentation (used, for instance, in Lewis & Maurer, 1992). This was not possible in the present study as the duration of the experiment would have been too long for infants. In fact, a limitation of static perimetry is that multiple presentations at the same location are needed. This can be problematic with infants that have limited attention span and that typically induce a number of invalid trials as a function of an erratic behavioural repertoire. As such, the number of trials we presented was limited so that the entire procedure was concluded in a few minutes. The presence of invalid trials and an unbalanced data structure was compensated for via the use of GLMMs for data analyses. A further study could introduce blank trials and reduce the number of eccentricities under investigation. Overall, we had to choose some locations in space to be investigated and we focused on those beyond near-peripheral eccentricities that have been less investigated so far within the literature. While some attentional biases have emerged across the visual field, it should be understood whether they are specific to the extreme peripheral locations under investigation or whether they also affect peripheral processing even at near-peripheral eccentricities.

In the studies based on video recordings presented in Chapters 2 and 3, participants were not forced to respond. This could have been solved with a gaze contingent eye-tracking procedure. Initially, we attempted to use an eye tracker for these studies but we found the infrared light to be distracting in comparison to the stimuli that were not particularly salient. One limit that we found when implementing this eye tracking system across the visual field was the distraction caused by the infrared light, not suitable for paradigms in which the visual stimuli are not very salient. The eye tracking procedure was then adopted with the more salient real faces used in Chapters 4 and 5. A potential limitation implementing this eye tracking system that could cover a wide area is that we limited calibration along the horizontal axis. In fact, the experimental paradigm we used only included these locations, but it would be interesting to extend this across the entire screen area. The evaluation of the system presented in Chapter 4 could have been ideally independent of the experimental procedure presented in Chapter 5. Ideally, calibration points could have been distributed across the entire screen and specifically designed for the calibration procedure instead of using those already presented for the experiment.

In Chapter 5, the eye-tracking procedure we introduced was applied to an experimental paradigm testing attention getting and attention holding mechanisms in response to emotional facial expressions. The measures of interest were both latency (to investigate attention-getting properties of the target stimuli) and dwell time (to investigate attention-holding properties). Results revealed an effect of threatening information on latency but not on dwell times. While this could speak in favour of evidence reporting that indirect threats such as fearful faces affect attention-holding mechanisms but not direct threats such as angry faces used in our study (e.g., Kobiella et al., 2008), an alternative explanation is that the measure we adopted in Chapter 5 did not capture differences across conditions. In particular, infants could have been bored of a long peripheral presentation lasting around 6 s. The paradigm included faces moving towards the midline for an extended period of time as it was not known at which eccentricity infants would respond. A shorter presentation involving targeted eccentricities would benefit the field.

Finally, a limitation of the online study we presented in Chapter 6 is that we could not run an in-person comparison while this study was executed during the pandemic. Instead, we tried to carefully match the procedure used by Brooks and Meltzoff (2002) and used that as a comparison. In an ideal situation, we would have compared our results to our own data collected in the laboratory. Also, although we mentioned the potential role of social contingency in understanding the social partner’s eye status, this has not been manipulated and thus remains an aspect to be further investigated. More general limitations we experienced testing online were connection or hardware issues from the side of the participant. Also, even if online research has the potential to reach a larger and more geographically diverse sample, we did not experience faster recruitment of a larger sample compared to past in-lab studies. This may be due to the fact that, even if participants did not have to travel, they had to schedule an appointment for this synchronous testing procedure. As such, this may be an advantage of unmoderated infant research designs from an operational/procedural data acquisition point of view.

7.3.2 Future directions

Several lines of research and more in-depth studies on the topics of peripheral visual information processing can arise from the work presented in this thesis. As already mentioned in the limitations, a future direction in the study of the infant’s visual extent with controlled stimuli is mapping sensitivities to different kinds of peripheral information at different developmental stages and to find out when orienting behaviour across the periphery reaches full maturation. Further, in consideration of the fact that different stimuli can elicit responses at different eccentricities, more low-level visual characteristics of the targets should be better explored. Among those, the size of stimuli in relation to the eccentricity and distance from the screen may be particularly interesting. As considered in Chapter 1, stimuli could be adapted in size according to a cortical magnification factor, with bigger stimuli at more peripheral locations. We decided to keep target size constant across locations both to align the present studies with most developmental perimetry work, but also in consideration of the fact that in real world situations stimuli are not enlarged in the visual periphery. Nevertheless, it is worth exploring whether detection is possible even at more extreme locations when stimulus size is adjusted according to cortical magnification / retinotopic mapping. Given that peripheral vision contributes to building a representation of space for the developing child, the relation between target size, distance and eccentricity remain as areas of particular interest.

In terms of investigated spatial locations, in Chapters 2 to 5 we focused on eccentricities beyond the near-perimetry as these have been already investigated in infancy via standard screens and also in consideration of the limited number of trials we could present to infants. Future studies could include a direct comparison of visual processing in near-peripheral locations. In terms of eccentricities, an interesting aspect that was not investigated in depth is the detection dip at 40° that we found in our first experimental study (Chapter 2). When we moved to social stimuli (Chapter 3 onwards) we included other manipulations and limited the investigations to high eccentricities in which performances were steadily decreasing. Thus, future studies should better investigate if this dip is reliable across studies and whether it is present with other targets as well.

Further, Chapters 2 to 5 investigated spatial locations that required a combination of head and eye movements to successfully orient towards the target. Given that a combined motor response was needed, motor development may have a role in the orienting tasks we presented and further studies could explore if there is a relation between orienting behaviour at high eccentricities and motor development. Further, vision grounds action control and it is relevant for movement organisation (e.g., Atkinson, 2000). In Chapter 5, results showed faster reaction times in males rather than females. We speculated a role of motor development that would require further data on individual differences. Comparing presentations at closer eccentricities that do not require large body movements may be useful to understand whether a motor component has a role in sex differences. In addition, research has suggested that threat detection is linked with interacting individual factors (e.g., Burris et al., 2019). Accordingly, future work could further explore individual differences to shed light on whether saccadic behaviour in response to emotional stimuli at high eccentricity is related to temperament and/or maternal personality.

The lateral differences across the visual field that we found in Chapters 3 and 5 are an interesting aspect of how our visual system processes peripheral information. For now, we showed a left bias for single face-like targets as measured by detection rates (Chapter 3) and a right bias for competing face-like targets expressing emotions in terms of reaction times (Chapter 5). Future studies should better disentangle the effect of competing information, stimulus type and attention measures on visual field biases.

Overall, a future research line to be explored is the role of other sensory modalities in rapid orienting responses. In most studies presented within this thesis, sounds were paired to visual presentations to attract infant attention and to create a more engaging presentation. The role of sounds has not been specifically manipulated in this thesis but past research suggested a role of other sensory modalities, such as audition and touch, in detecting alerting information (e.g., Nardini, 2015). Hence, the current work could ground investigations across different sensory modalities.

Lastly, the final experimental study presented in this thesis (Chapter 6) investigated gaze following with an online paradigm. While in this paradigm we found comparable results as in past laboratory paradigms and we suggested that such paradigms have in common a social contingent interaction between the gazer and the participant, a future direction is to directly manipulate the social contingency of the gazer in another online study. Thus, we could have the same procedure we presented in Chapter 6 but with a pre-recorded social partner that gazes towards the target. If social contingency matters, we would expect decreased gaze following in this situation. Also, in our online study we collected data on the infants' previous exposure to video calls and we aimed to test whether video exposure had a role in virtual gaze following behaviour. This was not possible to investigate as the vast majority of infants we tested had been exposed to video chats and was not possible to investigate how experience shaped virtual interaction. Future research should try to compare the behaviour in response to a virtual social partner in infants frequently exposed to video calls and in those not, or rarely, exposed to video interactions.

7.4 CONCLUSIONS

The research presented in this thesis was aimed at investigating infant information processing in a wide visual space, ranging from studies on visual perception in laboratory settings to social cognition in home environments. Results showed that peripheral information processing as reflected by infant’s orienting behaviour is still developing at 9 months of age and engagement behaviours progressively decline at more peripheral locations. Further, different stimuli elicited different orienting behaviours at high eccentricities, with increased detection rates for face-like stimuli compared to patches with comparable low-level visual features. Attention-getting and attention-holding mechanisms were differentially influenced by emotional face stimuli appearing at the edge of the visual field. In particular, threatening faces influenced rapid orienting behaviours but not sustained attention. Orienting to peripheral information was also studied in online settings. We showed that infants can follow gaze and successfully orient to a peripheral target as a function of the perceptual status of the virtual partner’s eyes. The overall finding of this thesis is that peripheral information processing during infancy depends on the characteristics of the stimuli and is biased towards some social-communicative cues, even outside foveated locations.

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