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"Infant Gaze-Following in a Neural Entrainment Paradigm: The Involvement of Alpha and Theta Brain Rhythms"

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1 Theoretical Background

The ability to reliably discriminate an interactive partner's gaze direction is critical in order to understand the other person in a complex social environment. Numerous studies support the involvement of gaze-following as a critical component of joint attention in a multitude of cognitive and behavioural processes linked with learning, language acquisition, and social competence during infancy and childhood (Brooks & Meltzoff, 2005; Hoehl et al., 2009; Morales et al., 2005; Mundy, 2018; Mundy et al., 2007; Mundy & Newell, 2007). The maturation of their gaze-following abilities marks a critical milestone in the infant's socio-cognitive development and their ability to learn from social interactions.

Furthermore, there is a growing interest in understanding the role of alpha and theta brain oscillations in social cognition. Recent studies have suggested that these oscillations play a critical role in facilitating social interaction by coordinating attention and supporting the processing of information (Cellier et al., 2021; Klimesch, 1999; Michel et al., 2015). In the context of neural entrainment, this association of alpha and theta brain oscillations with attention and learning raised the question of whether 6-month-old infants would show a difference in gaze-following behaviour depending on whether a gaze-cued object rhythmically flickered in a frequency associated with infant alpha compared with infant theta oscillations.

1.1 Looking Behaviour and Gaze-Following

It is well established that children learn by observing, imitating and interacting with their surroundings. Before children start speaking and can communicate their wants and share their experiences verbally, they are already able to do so, to a more limited extent, non-verbally. This is because infants' ability to share a common reference point with another person in a social interaction develops before language. The human capacity to coordinate one's own attention with that of a social partner is called joined attention (Mundy & Newell, 2007). Existing literature suggests that joint attention involves a complex form of social information processing, for example, other referenced processing, including other people's actions, the direction of gaze, affect, and vocalizations, as well as information processing about the common point of reference such as spatial and sensory information (Mundy, 2018). Therefore, a crucial part and prerequisite of joint attention is gaze-following, the ability to use another person's gaze cue to shift our own attention to a common reference point. The primary purpose of joint attention behaviour and, thus, gaze-

following is believed to be to spontaneously share experiences and interests with interactive partners (Mundy, 2018; Mundy & Newell, 2007).

The ability to follow another person's gaze is the earliest behavioural manifestation of joint attention, which was observed in infants as young as 2 to 4 months and by 6 to 8 months, infants show consistent gaze-following abilities (Gredebäck et al., 2010). At 4 months, infants differentiate between object-directed and object-averted gaze cues (Hoehl et al., 2008). Furthermore, studies found that infants did not only show differences in looking behaviour, such as the duration of looking at an object when watching other peoples' gaze shifts but also in brain activity (Hoehl et al., 2008, 2009). The development of behaviours associated with responding to joint attention, including gaze-following, is characterized by an increase in response efficiency. According to a review paper by Mundy (2018) on joint attention and social-cognitive brain systems, the response latency for following the direction of attention of others decreased from infancy to adolescence.

The maturing of gaze-following abilities marks a critical milestone in the infant's socio-cognitive development and their ability to learn from social interactions. The ability to reliably discriminate an interactive partner's gaze direction is critical in order to understand the other person in a complex social environment (Emery, 2000). Numerous studies support the involvement of joint attention, and especially gaze-following, in a multitude of cognitive and behavioural processes linked with learning, language acquisition and social competence during infancy and childhood (Brooks & Meltzoff, 2005; Hoehl et al., 2009; Morales et al., 2005; Mundy, 2018; Mundy et al., 2007; Mundy & Newell, 2007).

Research on learning during infancy associates gaze-following with the depth of information processing (Hoehl et al., 2009). The ability to follow gaze cues helps infants redirect their attention to socially relevant information in a complex environment, enabling them to process this information more efficiently. One such study (Hoehl et al., 2008) that supports the hypothesis that infants form a stronger memory representation for cued objects presented 4-month-old infants with photographs of female faces which had their eye gaze averted either to the left or to the right. Hoehl and colleagues then displayed pictures of toys on either side of the face, at eye height. By doing this, the team tried to simulate real-life gaze-cue situations with object-directed and averted conditions. In this setup, object-directed gaze cues lead to enhanced positive slow-wave brain activity, which has been associated with memory encoding in infants (Webb et al., 2005). Based on their findings, the authors suggested that infants can process object-directed eye gaze faster than object-averted gaze and encode information that is socially cued this way more deeply. This kind of cued information processing was also shown to facilitate social learning (Hoehl et al., 2009; Michel et al., 2015).

Furthermore, Studies found that observed joint attention behaviours were predictive of individual differences in language development, even after controlling for general cognition (Brooks & Meltzoff, 2005; Morales et al., 2000; Mundy et al., 2007). This could be due to the structuring and attention-regulating role gaze-cueing processes play in social information processing during the early unstructured social learning situations in which language acquisition occurs (Mundy & Newell, 2007). In other words, infants use their interactive partners' gaze cues to attend to the referent object in spontaneous novel-word learning.

As gaze-following develops very early in life, healthy adults are usually able to follow other people's gaze cues consistently. Adults commonly show a faster response time to gaze-cued targets than miscued targets. This phenomenon is also called the gaze-cueing effect (McKay et al., 2021). Research on gaze-cueing in older adults seems to hint at a reduction in gaze-cued attention with progressing age (for a meta-analysis, see McKay et al., 2022). In traditional gaze-cueing paradigms that show the picture of a face whose gaze is manipulated to either look towards or away from the presented stimuli, older adults seem to have difficulties decoding important social cues from the eye region, leading to less gaze-following when compared to their younger counterparts (Slessor et al., 2016). Fernandes and colleagues, who investigated gaze-following behaviour during a more naturalistic free-viewing paradigms with contextualized stimuli, argued that these observed age-related differences in gaze-following abilities might result from the characteristics of the traditional task setup. In their study, older adults were more likely to prioritize the gaze-cued location for early visual inspection compared to younger adults, who spent more time looking at the face in the presented picture. Measured for the whole trial, though, there was no difference in total time younger and older adults fixated on the gaze-cued location (Fernandes et al., 2022). This could mean that aside from eye-gaze, contextual aspects become more important as gaze-following abilities progress from infancy to late adulthood.

Thus, the direction of others' eye gaze is an essential source of information in social settings because it indicates another person's focus of attention. The ability to discriminate other peoples' gaze direction is essential for successful social interactions because it allows us to direct our attention to the point of common reference and helps us understand the intentions of other social actors. Gaze perception abilities are, therefore, assumed to be a crucial part of higher-level social communication and social development. Based on this, it is not surprising that research reports a distinct connection between abnormal gaze perception and psychiatric disorders characterized by social cognition deficits and general social impairment (Tso et al., 2020). Gaining knowledge about the developmental processes of gaze-following during infancy could help better understand the emergence and implications of disorders commonly associated with social-cognitive impairments.

1.2 Brain Oscillations

Due to the association of alpha and theta brain oscillations with cognitive function (Cellier et al., 2021), they receive special attention when it comes to studying developmental processes in infants. As this study investigated infant looking behaviour in the context of a neural entrainment paradigm, the following paragraphs will address the basic aspects of infant alpha and theta brain oscillations.

1.2.1 EEG: A Method to Measure Brain Oscillatory Activity

Electroencephalography (EEG) is one of multiple brain imaging methods that can be used to record brain responses during experimental tasks. EEG works by measuring electrical activity in the brain through a number of electrodes that are placed evenly distributed across the scalp (Leong, 2019). In order to record any signal, the electrical activity needs to be strong enough for the electrodes to pick them up, which only occurs when multiple neurons are active simultaneously. Different to action potentials with their all-or-non response, synaptic activity, as part of normal cerebral activity, occurs continuously.

Subcortical structures like the thalamus and the reticular activating system help generate rhythms by synchronizing neural activity, resulting in distinctive patterns called brain oscillations (Hughes & Crunelli, 2005). The main generators for such neural activity are summations of excitatory and inhibitory postsynaptic potentials of pyramidal cells in the superficial layers of the cortex, which are radially orientated and, therefore, generate polar charges (Jadeja, 2021). This leads to tiny voltage fields or potentials on the scalp that can be picked up by the electrodes. In a typical EEG system, the strength and direction of the current between two electrodes are amplified, and the spatial distribution of the potentials and their variation over time is displayed as a waveform (Jadeja, 2021).

EEG plays a crucial role when it comes to understanding brain oscillations. It has some benefits over other imaging methods, depending on the type of data one is interested in. First of all, EEG equipment is relatively inexpensive and readily available. With smaller and portable devices, it does not require any spacious laboratories and is relatively flexible in its setup. Secondly, it is non-invasive and completely painless, which makes it possible to use in many clinical settings, as well as with very young children and infants. The last and probably most important benefit is the superior temporal resolution that EEG data provides, allowing for almost real-time observations of brain activity (Jadeja, 2021).

On the other hand, some limitations must be considered before deciding to use EEG for data collection. Because of the way EEG works, with each electrode sampling a larger area of the cortex,

one of its main limitations is its spatial resolution, which only allows for general regional activity mapping (Jadeja, 2021). Another limitation would be that EEG can only pick up superficial potentials because potentials generated within deeper structures of the brain are too weak to be picked up by the scalp electrodes. With the cortex being deeply folded, it is estimated that only about one-third of the cortex is accessible for EEG recordings (Worrell et al., 2002).

1.2.2 Functional Brain Rhythms

Current literature defines six distinct brain rhythms that are said to serve differing purposes and are primarily associated with certain states of the brain, such as sleeping or learning. The names of these frequency bands are based on the order of their discovery and not on their frequency range. Adult oscillation frequency bands are commonly defined as following: higher gamma (80-150 Hz), lower gamma (30-80 Hz), beta (15-30 Hz), alpha (8-12 Hz), theta (4-8 Hz) and delta (2-4 Hz) (Cohen, 2014).

The bandwidth of brain rhythms undergoes changes from infancy to adulthood, with infant frequency ranges starting lower and reaching adult levels somewhere around adolescence. In infant research, the exact cut-off points can vary between publications, but usually frequency bands are defined around 30 to 50 Hz for gamma, 9 to 30 Hz for beta (Anderson et al., 2022), 6 to 9 Hz for alpha (Anderson et al., 2022; E. Orekhova et al., 2006), 3 to 6 Hz for theta (Braithwaite et al., 2020) and 1 to 4 Hz for delta oscillations (Pappas et al., 2019). Much of infant research focuses on alpha and theta oscillations as they are believed to play a pivotal role in early development due to their involvement in memory, learning and attentional processes (Cellier et al., 2021; Klimesch, 1999; Michel et al., 2015).

1.2.2.1 Alpha Oscillations

*A*lpha oscillations are the primary brain rhythm of the awake adult brain with a frequency range of 8 to 12 Hz (Klimesch, 1999). Longitudinal studies with infants reported the emergence of a clear pattern of alpha rhythm at around 10 to 12 months of age (Xie et al., 2018). Studies that have investigated developmental changes in alpha oscillations showed an increase in alpha frequency during childhood and adolescence, with the peak frequency increasing from 5.5 to 8, 9 and 10 Hz for 1, 3, 9 and 15-year-olds respectively (Klimesch, 1999; Tröndle et al., 2022).
A common cut-off point for infant studies seems to be 6 to 9 Hz for alpha oscillations, but the exact frequency range can differ between authors.

Both in adults (Jensen & Mazaheri, 2010; Klimesch, 1999) and infants (Tröndle et al., 2022; Xie et al., 2018), alpha de-synchronization is associated with attention and memory performance. Studies with adults found that alpha plays an important role in working memory performance and inhibition of task-irrelevant processes, such as the inhibition of information processing of otherwise

distracting sensory modalities (Cellier et al., 2021; Clayton et al., 2015; Klimesch, 1999). Bell investigated alpha in the context of a looking version of the A-not-B task with 8-month-old infants (Bell, 2001, 2002). During the classic A-not-B task, an attractive toy is repeatedly hidden under the same box (box A) from which the infant needs to retrieve it. After a few repetitions, the toy is placed under a second box (box B), which is just as easily reachable for the infant, and the infant is again encouraged to retrieve the hidden toy. In the looking version of the A-not-B task utilized by Bell, infants were scored on the correctness of their first eye movement towards one of the two boxes rather than the retrieval of the toy. The study showed that alpha power increased from EEG baseline measures to the A-not-B task for the high-performing group, while low performers did not show any change in alpha power (Bell, 2001). Because successful performance in this task heavily relies on infants' working memory, Bell argued that alpha power is also involved in working memory processes in infants.

Moreover, a connection between alpha frequency and general cognitive performance is supported by findings showing that cognitive and memory abilities increase during childhood and adolescence in a similar ways as individual alpha peaks increase during brain maturation (Klimesch, 1999; Tröndle et al., 2022).

In general evidence suggests, that alpha shows a desynchronization during cognitively demanding tasks (Begus & Bonawitz, 2020; E. Orekhova et al., 2006). Based on this, alpha power suppression would mark an increase in attention and memory performance (Klimesch, 1999).

1.2.2.2 Theta Oscillations

In adults, theta oscillations are commonly defined in a frequency range of 4 to 8 Hz (Cellier et al., 2021), whereas the cut-off point in infant studies is often set between 3 and 6 Hz (Braithwaite et al., 2020; Jones et al., 2020), with some variation between studies, depending on the age range of the participants. Theta has been observed to be the dominant frequency band during infancy and early childhood, whereas alpha power is dominant in the adult brain (Cellier et al., 2021; Marshall et al., 2002). Similar to the recorded increase in alpha peak frequency during childhood, theta is reported to increase in its peak frequency from infancy to adulthood. Congruently, findings suggest a general shift from lower to higher frequency oscillations from infancy to adulthood (Clarke et al., 2001).

Theta oscillations are known to play an important role during early cognitive development, as well as adult cognitive performance. A multitude of studies have shown a connection between theta activity and cognitive processes such as sustained attention, memory performance and learning, both in adults (Klimesch, 1999) and infants (Braithwaite et al., 2020; Jones et al., 2020; Xie et al., 2018; see Begus & Bonawitz, (2020) for a review). When it comes to theta's role in memory performance, it is hypothesized that theta synchronization reflects episodic memory

performance, which is pivotal for encoding new information and, thus, learning in general (Klimesch, 1999). This hypothesis is supported by evidence on theta activity increase during the processing of novel information in adults and children (Köster et al., 2017). It was also observed that theta power increases during visual exploration in infants (Wass et al., 2018), which would naturally include aspects of novel information encoding and require some degree of sustained attention. As previously discussed, we would expect to see a synchronization of theta oscillations during sustained attention. Previous studies with infants suggested that this increase in theta synchronization during cognitively demanding tasks could be due to the involvement of an attention network. The development and maturation of this network are thought to allow for voluntary attention control (Mundy & Newell, 2007; Orekhova et al., 1999; Xie et al., 2018). Furthermore, research indicates that visual attention could be an intrinsically rhythmic process. It means that even though our attention seems continuously sustained to one location, it constantly ebbs and flows rhythmically at about 7 Hz. (VanRullen, 2016; Vinogradova et al., 1998). Related to this are findings suggesting that attentional reorientation, that is, the shift of attention between the locations of two presented stimuli, might also happen periodically around theta frequency (Senoussi et al., 2019). In this context, some studies could show behavioural performance differences, such as influence on reaction time, in coherence with theta oscillations (Kienitz et al., 2022).

1.2.2.2.1 Theta Oscillations during Viewing of Non-social Videos

Adult, as well as infant EEG studies differentiate between task-related and baseline or resting state brain activity. This distinction helps to put brain activities recorded during a task in perspective to brain activity as it is when the participant is not engaging in the task. This makes it possible to associate certain brain activities with the tasks by comparing brain activity before and during the time window of task engagement. It also helps compare task-related changes in brain activity between participants, as brain activity can naturally vary between people. Therefore, the individual resting-state measures can serve as a reference frame for a common neural activity baseline between participants.

The set-up for recording baseline measures is strongly influenced by the age of the participants, however. While adult resting-state measures are usually recorded while the participant looks at a simple fixation cue or has their eyes closed, infant baseline EEG is mostly recorded while the infants watch a dynamic non-social video (Anderson et al., 2022). Because dynamic properties take longer to encode, dynamic videos are more successful in holding the infants' attention for a prolonged time (Horst et al., 2005; Robinson & Sloutsky, 2007). This should keep the infants still and calm, which is essential for EEG measures. On the other hand, it is only logical that for infants, watching a complex video comes with specific cognitive demands. While the dynamic properties of

the video help grab the infants' attention, it is questionable if one can compare the infant's "resting state" conditions with the adult's EEG baseline measures.

Studies that have taken a closer look at infant and adult baseline measures have found that measures of resting-state brain activity could potentially influence subsequent task performance (infants: Anderson et al., 2022; adults: De Blasio et al., 2013). Infant baseline theta power was found to be predictive of general measures of cognitive development. For example, in a study investigating the association between dynamic theta power and video viewing time, Braithwaite and colleagues showed that theta power increased during the viewing of a non-social video in 6-month-old infants. Furthermore, they found a positive association between individual differences in theta power change at 6 months and cognitive abilities at 9 months of age (Braithwaite et al., 2020). This study supported and extended previous findings that reported the same relationship between theta power change during the viewing of a dynamic video at 12 months and variation in cognitive skills at the age of 1, 2, 3 and 7 years (Jones et al., 2020). The observed increase in theta power over the time of video viewing suggests the engagement of cognitive processes involved in sustained attention and memory systems that would be needed in order to encode the dynamic events presented to the infants (Braithwaite et al., 2020; Jones et al., 2020).

1.2.2.3 Alpha and Theta Oscillations during Gaze-Following

For adults and infants, looking towards a shared object has been related to a desynchronisation of alpha oscillations (Hoehl et al., 2014; Lachat et al., 2012; Michel et al., 2015). For example, a dual-EEG experiment in a face-to-face paradigm with adults found stronger alpha power attenuation when both participants looked at the same object compared to when the participants each looked at a different object (Lachat et al., 2012). Similar findings have been reported in infant studies. For example, studies with infants as young as 4 months have found a stronger desynchronisation of alpha oscillations during object-directed compared to object-averted conditions (Michel et al., 2015). Hoehl and colleagues (2014) suggested that this alpha desynchronisation may be specific to neural processes involved in triadic social interactions, as they did not find evidence of alpha desynchronisation in experimental conditions with no eye contact prior to the gaze shift. Somewhat contradictory to this suggestion was a recent study from Angelini et al. (2023) that reported an increase in alpha activity during object-directed compared to object-averted conditions, following a direct gaze phase, in a live paradigm with 9-month-old infants. It was suggested that this increase in alpha could be due to the inhibition of interfering information, which aligns with studies showing a relation between the suppression of task-irrelevant information and alpha oscillations (Klimesch, 1999). Based on the literature on gaze-cue following in infants and the evidence pointing to alpha activity as a sensitive measure for attentional mechanisms,

including the suppression of task-irrelevant information, it can be hypothesised that the stronger desynchronisation of alpha is a sign of focused attention towards the gaze-cued object and thus facilitates early social learning in infants (Hoehl et al., 2014; Michel et al., 2015).

The in comparison still rather sparse literature around theta activity during gaze-following in infants seems to point to a stronger synchronisation of theta during object-averted compared to object-directed eye gaze (Angelini et al., 2023; Michel et al., 2015). Michel and colleagues investigated theta activity during object-directed and object-averted gaze conditions in 2, 4, 5 and 9-month-old infants and only found enhanced theta activity during the object-averted condition in the 5-month-old infants (Michel et al., 2015). In a face-to-face live paradigm study, the authors could also show the synchronisation of theta for object-averted gaze in 9-month-old infants (Angelini et al., 2023). The authors of this study hypothesised that the enhanced theta activity during incongruent object-gaze shift conditions reflects cognitive processes in response to an unexpected event in social interactions. Infants develop a basic expectation for human behaviour during social situations, which in the case of a triadic interaction would be that the interactive partner directs their gaze towards an appearing object and not away. Therefore, besides being involved in general attention processes, theta synchronisation could also be a sign of a mechanism of error detection when social expectations are violated (Angelini et al., 2023; Köster et al., 2021).

1.2.3 Neural Entrainment of Brain Oscillations

An emerging area of research involving brain rhythms evolved around neural entrainment, which is described as the phase alignment of intrinsic brain oscillations to external periodic stimuli (de Graaf & Duecker, 2022). This alignment can be done with visual or auditory stimuli presented in the frequency one wants to entrain the brain with. What makes this research field so fascinating is the idea that one can enhance task performance by targeting rhythms associated with task-relevant cognitive processes and stimulus perception. Another equally significant opportunity lies in the possibility it provides for investigating the contribution of specific frequency ranges to cognitive processes such as learning and attention.

Because alpha and theta are involved in many such task-relevant processes, they are often at the forefront of these studies. For example, in adults, alpha oscillations have been linked to performance in a visual target detection task. Findings indicated that visual sensitivity for target detection was significantly greater when the target was presented in phase with the entrained sequence (12-Hz), compared with a non-entrainment baseline (Mathewson et al., 2010). Another adult study investigating entrainment found that memory performance was higher for visual stimulation at an individual theta than an individual alpha frequency. As this effect on memory performance was more pronounced for participants with a higher responsiveness to the visual

stimulation, the study concluded that the observed differences in memory performance were due to the entrainment effects of the theta stimulation (Köster et al., 2019b). In an entrainment study with infants, Köster et al. (2019a) implemented rhythmic visual stimulation to induce theta and alpha oscillations while presenting 9-month-old infants with static images of classic violation-of-expectation paradigms. Visual stimulation was established by rhythmically flickering the presented images on the computer screen in 4-Hz and 6-Hz frequencies. Their result showed an increase in visually entrained theta oscillations when infants were presented with images that violated basic expectations.

Even though numerous studies have shown the possibility of entraining the mature and developing brain with specific rhythms (Cantiani et al., 2022; Köster et al., 2019a; Mathewson et al., 2012; Otero et al., 2022), there are still ongoing debates as to the exact nature of the entrainment phenomenon (Banki et al., 2022). Some evidence suggests that entrainment effects are influenced by the phase alignment between the external stimulus and the brain response (Clouter et al., 2017). This notion is supported by studies that could show that visually entrained rhythms close to the participant's naturally occurring frequencies elicited a stronger phase coupling between the external stimulus and the neural response (Notbohm et al., 2016). This relationship between individual endogenous oscillations and stimulus frequency was also found to influence the effect of entrainment on behavioural performance (Gulbinaite et al., 2017).

2 Present Study

Summarizing the existing literature, it is clear that infants' gaze-following abilities greatly influence early socio-cognitive development. Reviewed literature on early social interactions and infant joint attention has shown that accurate gaze-cue responses are positively related to novel information encoding, learning and social competence in infants (Brooks & Meltzoff, 2005; Hoehl et al., 2009; Morales et al., 2005; Mundy, 2018). It is also well-established that alpha and theta oscillations play an important role in early cognitive development due to their joint involvement in processes associated with infant learning and attention (Cellier et al., 2021; Klimesch, 1999; Michel et al., 2015). Furthermore, research has shown that an auditory or visually presented rhythm within the alpha or theta frequency band can influence stimuli perception and task performance (Kienitz et al., 2022; Köster et al., 2019a; Mathewson et al., 2010). This raised the question of whether the rhythm of object presentation during a gaze-cue paradigm could impact infants' looking behaviour. To date, no other study was found that looked at gaze-following abilities in 6-month-old infants in the context of neural entrainment.

Therefore, the aim of this study was to investigate whether 6-month-old infants showed a difference in gaze-following behaviour depending on whether the presented objects in the gaze-cue task are flickering rhythmically in frequencies associated with infant alpha or theta oscillations.
Based on existing literature on gaze-following in infancy, the functionality of alpha and theta oscillations, as well as the phenomenon of neural entrainment, the following hypotheses were investigated:

H1: We expect infants to follow the gaze cue and, therefore, to look more often towards the gaze-cued than the gaze-averted stimulus.
H2: We expect infants not to follow the gaze cue but remain looking at the presented face more often when the peripheral stimuli are flickering in alpha rather than theta or mixed frequencies.
H3: We expect infants to follow the gaze cue more often when the peripheral stimuli are flickering in theta rather than alpha or mixed frequencies.

Furthermore, this study aimed to investigate whether infant theta power changes during the baseline video were predictive of the accuracy of gaze-following behaviour during the subsequent gaze-cue task. This research question was primarily inspired by relatively recent studies, in particular the publication of Braithwaite and colleagues, which highlighted the role of theta, and theta modulation in particular, as an index of cognitive development (Anderson et al., 2022; Braithwaite et al., 2020; De Blasio et al., 2013). Accordingly, the following hypotheses were tested:

H4: We expect infants' theta power to increase over the course of the baseline video.
H5: We expect that the magnitude of theta power change during the baseline video will positively correlate with the proportion of gaze-cue consistent looking behaviour.

Additionally, an increase in baseline theta could reflect a more active theta network, which could facilitate a stronger entrainment to the theta frequencies. Based on previous entrainment studies, we expected that stronger entrainment to the theta frequencies would translate into more accurate gaze-following for the theta condition. Consequently, the following hypothesis was brought forward:

H6: We expect that the association between the baseline theta increase, and the proportion of gaze-cue consistent looking behaviour is stronger for conditions where the gaze-cued stimulus flickers in the theta frequency.

3 Methods

This study was part of a preregistered longitudinal research project of the Wiener Kinderstudien (Vienna Children Studies) at the Department of Developmental and Educational Psychology of the University of Vienna. Supervision was provided by Univ.-Prof. Dr. Stefanie Höhl and Alicja Brzozowska PhD.

3.1 Research Design

The current study employs a within-subject design. Participants were presented with three tasks that were displayed on a computer screen in a fixed order: first, a baseline video; second, a gaze-cue task; and third, a reward prediction task. This study used data from the baseline and the gaze-cue task only.

The baseline video is the same as previously used by Braithwaite et al. (2020) and Jones et al. (2020) and showed a selection of child-friendly, semi-realistic, non-social video clips such as a moving toy train or a bouncing basketball (Figure 1). The baseline video lasted for 2 minutes and 14 seconds. It can be accessed under the following link: https://bit.ly/3N5KGNW.

Figure 1

Exemplary extracts of baseline video

During the gaze-cue task, participants were presented with a fixation cue (randomized duration between 500 ms and 750 ms), followed by the central appearance of the picture of a female face with a direct gaze and two identical, non-social, peripheral stimuli to either side of the face. After 1 second, the display changed to a picture of the same face but with the gaze directed to either

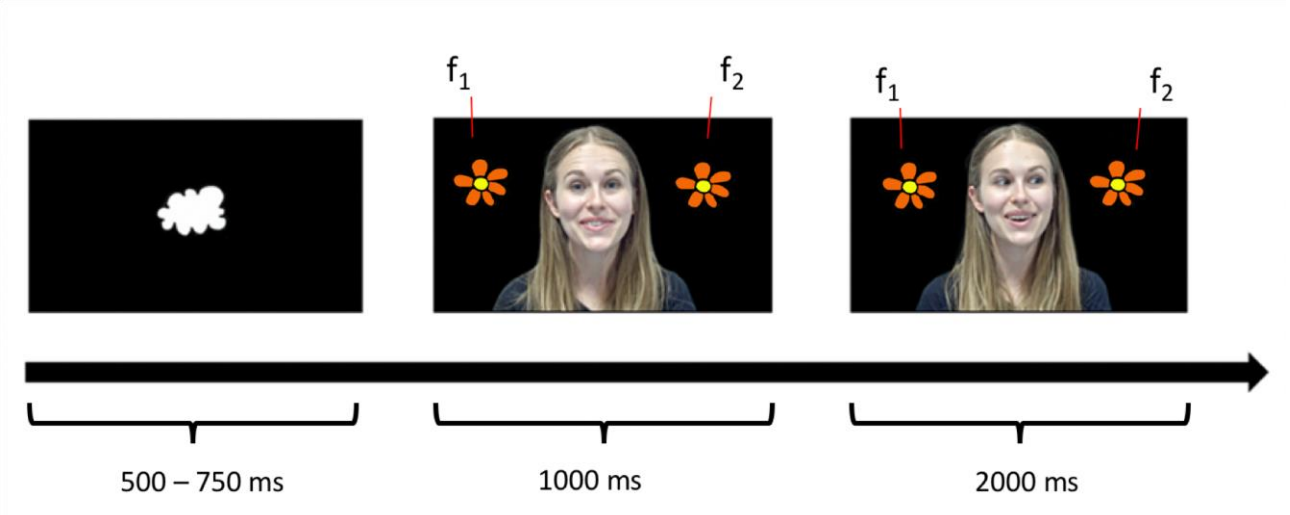
the left or the right flickering stimulus (Figure 2). This picture was visible for 2 seconds. This research design is unique in that it depicted stimuli on both sides of the face instead of only one, as it was commonly done in previous studies investigating gaze-following and joint attention in infants.

The presented stimuli flickered at two different frequencies depending on the trial condition. There were three different types of trial conditions: “alpha”, where both stimuli flickered in frequencies within infants’ alpha EEG band (5.54 Hz & 6.55 Hz); “theta”, where both stimuli flickered in frequencies within infant’s theta EEG band (3.43 Hz & 4.5 Hz), and “mixed”, where one frequency corresponded to the alpha and the other one to the theta EEG band (6.55 Hz & 4.5 Hz respectively). The mixed condition was further subdivided into two conditions, mixed alpha and mixed theta, depending on whether the gaze cue was directed towards the stimulus flickering in the alpha or the theta frequency. The gaze-cue task consisted of 60 trials, thus 20 alpha, 20 theta and 20 mixed trials, with the mixed trials comprising ten mixed alpha and ten mixed theta trials. In mixed alpha trials, the gaze-cued stimulus was flickering at alpha frequency, while the gaze-cued stimulus in mixed theta conditions was flickering at theta frequency. Each trial had a duration between 3500 and 3750 ms.

There were no other limitations to the order of trials other than a maximum of three alpha or theta trials in a row. The direction of the gaze cue (left or right) and the side of a given frequency presentation (i.e., the higher one on the left or on the right) was counterbalanced within participants.

Figure 2

Gaze-cue task experimental set-up



3.2 Participants

This study used data from 140 6-month-old infants collected in the context of the above-mentioned project between September 2022 and January 2023. From the total sample, 126 infants contributed to the analysis addressing hypotheses H1, H2 and H3, while 35 infants contributed to the analysis of hypotheses H4, H5 and H6. These numbers differ because of the differences in exclusion criteria for the looking behaviour and the EEG data analysis, as well as the availability of good quality EEG data from infants that had contributed to the looking behaviour analysis.

3.2.1 Recruitment

Participants were recruited out of a university-associated databank. Parents are free to create an account for the databank anytime if they are interested in taking part in ongoing studies conducted by the University of Vienna. The databank allowed for filtering by age, giving a list possible of participants that could then be contacted. For this study, parents with full-term, typically developing 6-month-old infants were contacted either by phone or by email and asked if they would like to participate in an EEG study with their child. If the parent agreed to participate, a test appointment was scheduled, and an email with all relevant information was sent. The email included the time and date of the appointment, a description of how to get to the building where the testing is taking place, a comprehensive description of the experiment procedure and the participation agreement.

3.2.2 Demographic Data

As this study only recruited infants at 6 months old, the age variance of the data was within 31 days (*M* = 6 months 17 days, *SD* = 8 days, min = 6 months 1 day, max = 7 months 5 days). Participants recruited from the databank all lived in close proximity to Vienna at the time of recruitment.

Of the 140 infants, 54% were female (64 male, 76 female). Due to the nature of recruiting from a university-associated databank, it needs to be considered that this sample might comprise a larger percentage of high-education families than the general population.
The majority of infants were accompanied by their mothers.

3.3 Study Procedure

Caregivers and infants were invited to the laboratory of the Wiener Kinderstudien at the Faculty of Psychology at the University of Vienna. Per session, a time slot of 1 hour was reserved, allowing sufficient time for the infants to get accustomed to the novel environment before the experiment's start and leaving enough time for breaks during the video viewing if necessary to ensure the infant's well-being. There was always a minimum of two experimenters present. Before entering the laboratory, participants were brought to a reception room where the caregivers were informed in more detail about the procedure and purpose of this study and were given room to clarify questions. The experiment could start once the caregiver signed a consent form and the head circumference of the infant was measured.

Once the caregiver and infant entered the laboratory and had some time to familiarise themselves with the room and the two experimenters, a readily prepared EEG cap was placed on the infant's head. For viewing the video, the infant was seated in the caregiver's lab, in a part of the darkened room, separated by a curtain, approximately 80 centimetres away from the computer screen. The caregivers were instructed to limit unnecessary interactions with the infants and to keep them as still as possible during the duration of the testing. Caregivers had been informed that it was possible to pause or abort the testing at any point in time if the infant showed signs of distress. Two synchronized cameras were used to record the session, one above the computer screen filming the infant's face and one behind the participants filming the computer screen. Once the setup had been completed, the video was played. The three parts of the video – baseline, gaze-cue task and reward prediction task – took approximately 12 minutes to watch if no pauses were made.

The EEG resting state was recorded while infants were viewing the baseline video, after which the video proceeded with the gaze-cue task. The prediction task differed from the gaze-cue task only in the added reward stimulus to one side of the screen at the end of each trial. The prediction task was irrelevant to this study as only data from the baseline video and the gaze-cue task were used for analysis.

After the video was finished, the curtain was drawn back, the light switched back on, the EEG cap removed, and the recording stopped.

3.4 Measures

The video and EEG data recordings were done on one computer, and the experimental software was run on a second computer with an HDMI cable connected to the test screen. The video was presented on an Iiyama G-Master GB2560HSU screen with a 144Hz refresh rate. The experiment was run via Psychtoolbox (version 3.0.17, Kleiner et al., 2007) in Matlab (version 2022b, The MathWorks Inc., 2022).

3.4.1 Video Recordings

Two cameras were used to simultaneously record the face of the participant and the computer screen during the experiment. Recordings were done using the VideoSyncPro 2.5.7.5 software (Mangold International GmbH, 2020) that allowed for synchronization of the two videotapes.

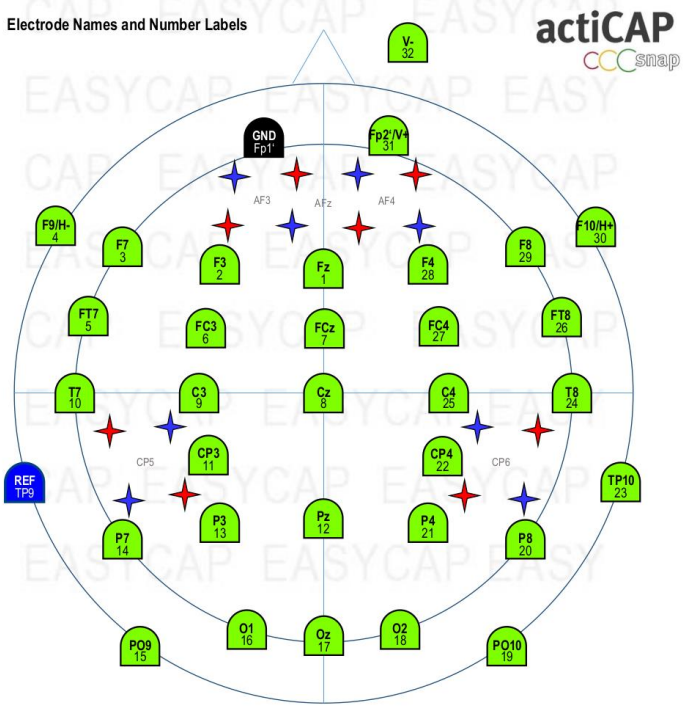
3.4.2 Electroencephalography (EEG) Recording

For the EEG data, the ActiCap EEG system (EasyCap GmbH) with 32 active Ag/AgCl electrodes was used. A reference electrode was positioned behind the left ear (TP9), and a grounding electrode was placed on the forehead of the infant (Fpz) (Figure 3). The 32nd electrode was placed underneath the infant's right eye. An electrode gel was injected in the space between the electrode and the infant's scalp to improve conductivity. The infant EEG caps were available in sizes 42, 44, 46 and 48 (cm head circumference).

The electrodes were connected to a BrainProducts BrainAmp DC amplifier, which was, in turn, connected to the experimental computer. The sampling rate was 500 Hz. Impedances were aimed to be below 10 kΩ whenever possible. The EEG recording was taken with the BrainVision Recorder (version 1.24.001, Brain Products GmbH, 2021), and the stimulus triggers were sent to the streamer from the experimental computer and the photodiode via a trigger box.

Figure 3

Layout of the channel placement for the 32-electrode channel EEG- ActiCap



3.5 Data Analysis

3.5.1 Looking Behaviour Data Processing

3.5.1.1 Video Coding

The video recordings of the infant's faces were used to micro-code infants' looking behaviour during the baseline and the gaze-cue task. The video coding was done with the software "Interact" (Mangold International GmbH, 2020) for all 140 participants.

For the baseline video section, the looking behaviour was coded regarding whether the infant was looking towards or away from the screen. For 25 of the baseline videos, the coding was done by two independent raters. Inter-rater reliability for the baseline video section was very high (k =.92).

The coding of the looking behaviour during the gaze-cue task discriminated whether the infant's gaze was directed (a) towards the centre of the screen, (b) towards the right stimulus, (c) towards the left stimulus, (d) away from the screen, (e) as being distracted by an interaction with the caregiver or (f) as not codable. An extra code was assigned to trials during which infants remained

focused on the central face for the entirety of the trial. Because of the limited availability of independent raters and time restraints, no inter-rater reliability was calculated for the gaze-cue task section.

3.5.1.2 Data Processing

The data was processed using Python in Visual Studio Code (Version 1.81.1, Visual Studio Code, 2021).

After loading the raw data in CSV format, we first specified which stimulus trigger at the beginning of each trial corresponded to which trial condition (alpha, theta, mixed alpha and mixed theta). We furthermore specified which triggers were associated with a right or left gaze cue. After the start and end points of the trials were defined, any trials where an infant had looked away from the screen, was distracted, or looking behaviour was not codable were labelled invalid and excluded from further analysis. The duration each participant spent oriented towards the face in the centre, the left or the right stimulus was calculated for each valid trial. The trial durations were recoded as gaze-cue consistent and gaze-cue inconsistent depending on the stimulus trigger's specification at the trial's beginning. This was done for all trials and all infants.

For each condition, we calculated how many trials each infant had spent looking at the centred face for the entire duration of the trial. To provide a comparable index, the sum of these trials was divided by the total number of valid trials per condition for each infant. This result represented the number of valid trials each infant had spent looking at the centre of the screen only, in proportion.

We calculated the proportion of time infants spent looking at the gaze-cue consistent or inconsistent stimulus based on the publication by Zeng et al. (2023). This gaze-following index represents the time the infant was looking at the gaze-cued or the gaze-averted stimulus as a proportion of the time the infant was looking at the right and left stimulus. Thus, it excluded the time the infant looked at the face. This should make the interpretation of the infant's gaze-following behaviour more straightforward by minimizing the influence of individual differences in infants' interest in the face as an important social cue.

The gaze-cue consistent and gaze-cue inconsistent proportions of time of every trial were averaged over all valid trials and per condition for each infant. This resulted in an overall average proportion of time each infant had spent looking at the gaze-cued stimulus versus the gaze-averted stimulus and an average proportion of time for each condition.

3.5.1.3 Case Exclusion

From the 140 tested infants, 12 datasets had to be excluded due to issues with the synchronicity of the video recordings and the trigger exported to the video coding software. This discrepancy did not allow for accurate micro-coding of the infant's looking behaviour. Additionally, two datasets were excluded due to issues with the video coding markers.

Based on the following argumentation, we did not think that testing for side bias was necessary but would have only resulted in a reduced sample size. First, no information on excluding biased cases was found in any relevant literature, and second, we assumed that the index of gaze-following was relatively robust against side bias because of the even distribution of trials with left and right gaze cues. Nevertheless, we tested for side bias in the looking behaviour of the infants to make sure that there was no significant influence of side bias on the analysis outcomes for hypotheses H1, H2 and H3. As expected, the analysis results showed no significant difference between the datasets with and without the exclusion of the 33 infants, which is why we decided not to exclude side-biases cases (see Appendix C).
This left a sample size of $n = 126$ for the looking behaviour analysis.

3.5.2 EEG Data

All EEG pre-processing was conducted in Matlab (version 2022b, The MathWorks Inc., 2022) and EEGLAB (Delorme & Makeig, 2004).

3.5.2.1 EEG Data Pre-Processing

EEG data was pre-processed using the standardized 'HAPPILEE' pipeline (Lopez et al., 2022). Line noise processing was conducted with a multi-taper regression approach to eliminate the 50 Hz electrical noise artefact. Next, a bandpass zero-phase Hamming-windowed sinc FIR filter with cut-off frequencies 1 and 100 Hz was applied to the continuous data. Next, artefact correction was performed with the use of wavelet thresholding. The data was then segmented into 1-second epochs, and channels deemed noisy (signal below/above +/- 150 µV) were interpolated within segments (up to 3 channels; otherwise, a segment was rejected). Indices of quality assessment of the pipeline performance were inspected, and participants for whom the cross-correlation values across all frequencies before and after wavelet thresholding were below 0.1 (indicating a high degree of artefact) were excluded from further analysis (Monachino et al., 2022). Next, data was re-referenced to average reference. Finally, segments where infants were not looking at the screen (based on markers from video coding) were rejected. Infants that contributed less than ten artefact-free segments were excluded from further analysis. Additionally, all channels not belonging to the frontocentral electrode group were removed. Thus, any analysis was only conducted on the

channels Fz, F3, F4, FC3, Fcz and FC4. Channels were selected based on Braithwaite et al. (2020), who used a 62 EEG electrode placement system. As we had a 32-electrode cap, we adjusted for the difference in the number of electrodes by selecting those electrodes that most accurately corresponded with the spatial placement of the frontocentral electrodes used by Braithwaite and colleagues.

Following the processing steps described by Braithwaite et al. (2020), power in the theta frequency range (3 to 6 Hz) was extracted across the frontocentral electrode channels using a Fast Fourier Transform. The theta power for the selected channels was then averaged per artefact-free segment, resulting in an average theta power for each one-second segment.

3.5.2.2 Case Exclusion

From the n = 140 datasets, data from 50 participants was available for the EEG analysis involved in the investigation of hypotheses four, five and six. For the other participants, preprocessing was still in progress.

Out of the 50 files, eight had video synchronization problems or were otherwise corrupt, and another seven remained very noisy even after data cleaning procedures were applied. This resulted in a sample of n = 35 for further EEG data analysis.

3.5.3 Statistical Analysis

Complementary to classic frequentist statistics, statistical tests for the looking behaviour analysis were also run using Bayesian statistics. The Bayesian factors were reported in Appendix D to provide additional insight and support for the application of Bayesian statistics in the field of social science.

3.5.3.1 Looking Behaviour

To account for the violation of normality, paired samples *t*-tests with variables that reached significance in the Shapiro-Wilks test were conducted as Wilcoxon signed-rank tests. For these results, effect sizes were reported as matched rank biserial correlations (r_b), representing the degree of the difference between the two paired samples. All other *t*-tests report effect sizes according to Cohen's *d*. All following statistical tests are conducted with an alpha level of $\alpha = .05$. No correction for multiple analyses was applied, as tests were run independently of each other and not simultaneously.

H1: To investigate if infants showed group-level gaze-following, we compared the group mean of the overall proportion of time the infants spent oriented towards the gaze-cued stimulus against a value of 0.5 as a measure of chance. We expected infants to look more to the gaze-cued than the gaze-averted stimuli.

H2: To investigate if the trial condition had an influence on the number of trials where infants remained looking at the picture of the face for the entire duration of a trial, we tested for significant group-level differences in the average percentage of these trials for the trial conditions alpha, theta, mixed alpha and mixed theta. This was archived using ANOVA, supplemented by one-tailed group mean comparisons between the alpha and other trial conditions. We expected infants not to follow the gaze cue but to remain looking at the presented face more often during alpha than theta or mixed conditions.

H3: To test for differences in gaze-following behaviour between the theta and the other conditions, we compared group means of the proportion of time of the gaze-cue consistent looking behaviour between conditions, as captured by the gaze-following index. This was accomplished with ANOVA and pairwise, one-tailed group mean comparisons. Because we expected infants to follow the gaze-cue more often in the theta than in the alpha or mixed conditions, all paired samples *t*-tests and Wilcoxon signed-rank test were tested under the specification that the theta group mean would be significantly larger than every other trial condition it was compared with.

3.5.3.2 EEG Data

All following analyses were conducted using Matlab (version 2022b, The MathWorks Inc., 2022) and EEGLAB (Delorme & Makeig, 2004).

H4: In order to investigate whether infants showed an increase in theta power over the course of the baseline video viewing, we used Pearson correlation to correlate the average theta power of the frontocentral electrode group from each segment with their corresponding segment number. Segment numbers represent the original placement of the segment before the rejection of noisy segments. The resulting correlation coefficients and *p*-values established the magnitude of theta power change over the baseline for each infant. This analysis of the baseline EEG data closely followed the analysis described in the paper published by Braithwaite and colleagues (2020).

H5: To test for a correlation between the level of theta power change during the baseline period and the infants' gaze-following performance, the correlation coefficients, representing the magnitude of theta power change over the course of the baseline video of each infant, were correlated with the gaze-following index (over all trial conditions) using Pearson correlation. We expected a positive correlation between the magnitude of theta power change and gaze-cue consistent looking behaviour.

H6: As we furthermore expected a stronger association between the baseline theta power increase and the gaze-cue consistent looking behaviour in the theta condition than in the other conditions, we correlated the magnitude of theta power change with the proportions of gaze-cue consistent looking behaviour differentiating between the different conditions. This allowed for comparing the correlation coefficients of the alpha, theta and mixed conditions with the help of MedCalc (version 22.013, MedCalc Statistical Software, 2023).

3.5.3.3 Exploratory Analysis

For exploratory purposes, we also analysed the third hypothesis without the model specifications (theta > alpha, mixed alpha, mixed theta). In other words, we tested for significant differences between the trial conditions without assuming any specific condition to have a higher group mean for the proportion of time the infants spent looking towards the gaze-cued stimulus.

Additionally, we investigated whether the infants displayed a group-level preference for either the higher or the lower frequency stimulus regardless of the gaze cue. To do so, we calculated a new looking behaviour index, which captured the proportion of time infants had oriented towards the stimulus with the higher frequency flickering rate. This analysis tested against the value 0.5 as a measurement of chance.

4 Results

4.1 Descriptive Statistics

A total of 126 datasets were used for further looking behaviour analysis. Over the whole duration of the gaze-cue task, infants were presented with a total of 60 trials. The trial conditions were counterbalanced, resulting in 20 alpha, 20 theta and 20 mixed trials. The mixed condition was subdivided into ten mixed alpha and ten mixed theta trials. On average, infants contributed 45 valid trials, with a minimum of four and a maximum of 60 valid trials (*SD* = 12.809). The average numbers of contributed valid trials were very similar between the alpha (*M* = 18.508, *SD* = 3.543), theta (*M* = 18.135, *SD* = 4.219) and mixed condition (*M* = 18.444, *SD* = 4.285).

A total of 35 datasets were used to investigate hypotheses that required EEG data analysis. On average, infants contributed 109 segments (*SD* = 21). The minimum of contributed segments was 56, and the maximum was 131.

4.2 Looking Behaviour

4.2.1 Hypothesis 1

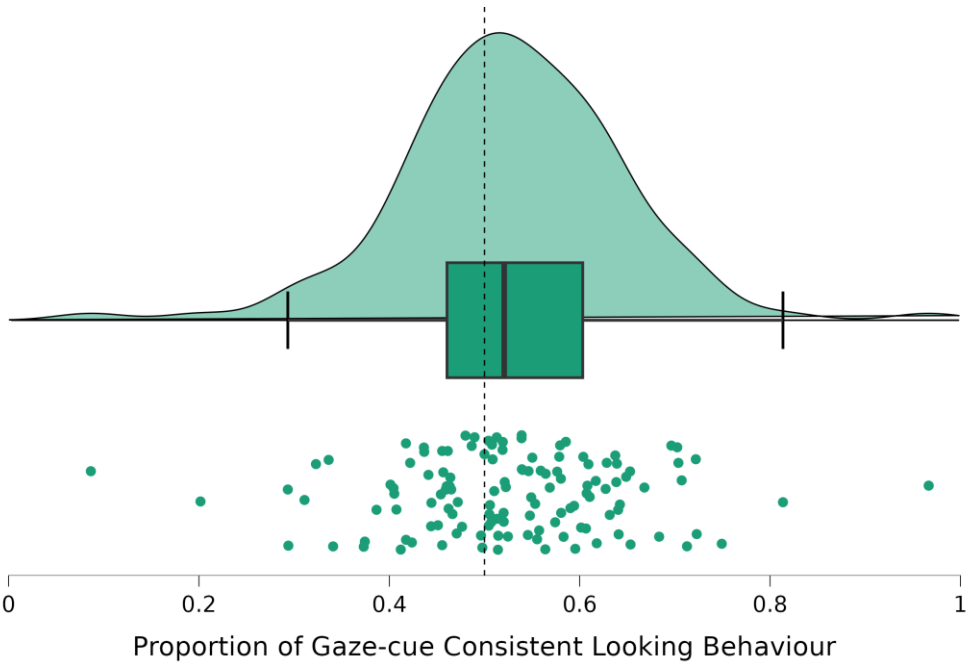
The first hypothesis was that infants at 6 months of age are capable of following another person's gaze-cue and would, therefore, spend more time oriented towards the gaze-cued stimulus than the gaze-averted stimulus. A one-sample Wilcoxon signed-rank test (n = 126) was used to compare the average proportion of time infants spent looking at the gaze-cued against the value of 0.5, with the specification that the gaze-following index would be larger than 0.5.

The p-value was significant (p = .001**) [V = 5161.000, r_b = .311] with M = 0.528 (SD = 0.118) for gaze-cue consistent looking behaviour (Figure 4). In comparison, the gaze-cue inconsistent looking behaviour had a mean of 0.472 (SD = 0.118).

This result supported our hypothesis and indicated that 6-month-old infants spent on average, a higher proportion of time oriented towards the gaze-cued than the gaze-averted stimulus.

Figure 4

Proportion of Gaze-Cue Consistent Looking Behaviour tested against the Value of 0.5



4.2.2 Hypothesis 2

For the second hypothesis, we expected infants to remain looking at the centred face more often during trials in the alpha condition compared with trials in theta or mixed conditions. Therefore, an ANOVA (n = 122) was used to compare the number of trials for which infants remained focused on the centre of the screen for the whole duration of the trial between the trial conditions: alpha (M = 0.360, SD = 0.228), theta (M = 0.375, SD = 0.221), mixed alpha (M = 0.395, SD = 0.249) and mixed theta (M = 0.388, SD = 0.272). Because Mauchly's test of sphericity indicated a violation of the model's assumption of sphericity, the Greenhouse-Geisser correction was applied. The ANOVA showed no statistically significant difference between the group means [$F(121,2.79) = 1.417$, $p = .239$, $n^2 = .012$].

These results indicated that infants did not engage in less gaze-following behaviour during alpha trials than during any of the other trial conditions.

4.2.3 Hypothesis 3

To investigate the influence of the theta condition on the gaze-cue consistent looking behaviour of infants, the average proportion of time that infants spent looking at the gaze-cued stimuli was first compared between the trial conditions: alpha, theta, mixed alpha and mixed theta, followed by pair-wise comparison. For the ANOVA, results are presented as reported after the Greenhouse-Geisser correction to account for the violation of sphericity.

We expected the group mean for the theta condition to be larger than for the alpha or mixed conditions.

The ANOVA (n = 113) was significant [$F(112,2.616) = 4.257$, $p = .008$**, $n^2 = .037$], supporting a possible difference in gaze-cue consistent looking behaviour between the trial conditions alpha (M = 0.525, SD = 0.192), theta (M = 0.509, SD = 0.192), mixed alpha (M = 0.586, SD = 0.237) and mixed theta (M = 0.484, SD = 0.256) (Figure 5).

In order to determine if this difference stems from a higher proportion of gaze-cue consistent looking behaviour in the theta condition, the following pair-wise analyses were conducted. For all tests, the alternative hypothesis specified that the mean for the theta trials is greater than the mean of the trial condition it was compared with.

First, we compared the theta with the alpha condition using the Wilcoxon signed-rank test (n = 125). The test did not reach significance [$z = 0.913$, $p = .820$, $r_b = .094$]. The group means were 0.502 (SD = 0.200) and 0.526 (SD = 0.210) for theta and alpha, respectively. Based on the Wilcoxon signed-rank test, the average proportion of time infants spent oriented towards the gaze-cued stimulus was not significantly higher in the theta than in the alpha condition.

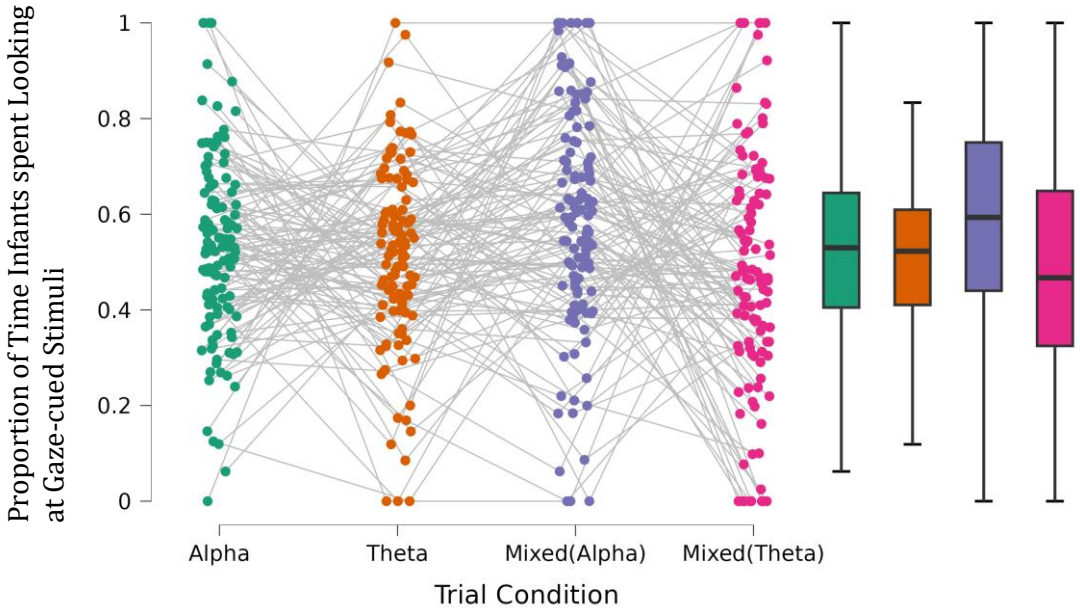
Second, we compared the theta with the mixed alpha condition using a paired samples *t*-test (n = 121). The analysis yielded a non-significant result [$t(119) = -3.249$, $p = .999$, $d = -0.297$] for the comparison of theta ($M = 0.502$, $SD = 0.200$) and mixed alpha ($M = 0.593$, $SD = 0.255$) . Thus, our data did not suggest a significantly higher proportion of gaze-cue consistent looking behaviour in the theta than in the mixed alpha condition.

Third, we compared the theta with the mixed theta condition using a paired samples *t*-test (n = 117). The results were not significant [$t(116) = 0.913$, $p = .182$, $d = 0.084$]. The group means were 0.502 for theta (SD = 0.200) and 0.483 for mixed theta (SD = 0.266).

Contrary to our expectations, these results did not suggest that infants spent significantly more time oriented towards the gaze-cued stimulus in the theta than in the other trial conditions.

Figure 5

Comparison of Gaze-cue Consistent Looking Behaviour over all three Conditions: Alpha, Theta and Mixed



4.2.4 Exploratory Analysis of Looking Behaviour

Based on the significant results of the ANOVA for hypothesis three but the insignificant outcomes for the pairwise comparisons, the following exploratory analysis was done to investigate if there were differences between the trial conditions in terms of the proportion of time infants spent oriented towards the gaze-cued stimulus if no assumptions about the direction of action were specified.

First, we used a Wilcoxon signed-rank test to compare gaze-cue consistent looking behaviour in the alpha and theta conditions (n = 125). We did not find a significant difference between the alpha and the theta condition [z = 0.913, p = .362, r_b = .094] (see Table 1 for mean and standard deviation). Second, we compared the alpha and mixed alpha condition using a paired samples t-test (n = 121). Results indicated a significant difference in the proportion of time infants spent looking at the gaze-cued stimuli during alpha trials and mixed alpha trials [t(119) = -2.130, p = .035*, d = -0.194]. Third, we compared the alpha and mixed theta condition using a paired samples t-test (n = 117). The comparison did not yield a significant result [t(115) = 1.561, p = .121, d = 0.145]. Fourth, we looked at gaze-cue consistent looking behaviour in the theta and mixed alpha condition. The paired samples t-test (n = 121) was significant [t(119) = -3.249, p = .002**, d = -0.297]. Fifth, we compared the theta and mixed theta condition using a paired samples t-test (n = 117). The test results were insignificant [t(116) = 0.913, p = .363, d = 0.084].

Lastly, we investigated the gaze-cue consistent looking behaviour in the mixed alpha and mixed theta condition using a paired samples t-test (n = 117). Results indicated a significant difference between the average proportion of time that infants spent oriented towards the gaze-cued stimulus during the mixed alpha trials and the proportion of time they looked at the gaze-cue consistent stimulus during the mixed theta trials [*$t(113) = 2.493$, $p = .014$*, $d = 0.234$*]. Visualization of these results suggested that infants spent on average, a larger proportion of time oriented towards the gaze-cued stimulus in the mixed alpha than the alpha, theta or mixed theta condition (Figure 6).

To investigate whether infants in our sample might have simply displayed a preference for the stimulus flickering in the higher frequency, we looked at the average time infants had spent oriented towards the higher frequency regardless of the direction of the gaze cue (n = 126). Our analysis indicated that infants indeed spent significantly more time looking at the stimulus flickering at the higher compared to the lower frequency [z = 3.652, *$p < .001$***, r_b = .377] (Figure 7). The mean of the proportion infants had spent looking at the higher frequency stimulus was 0.538 (SD = 0.117), and the mean for the proportion of time infants looked at the stimulus flickering at the lower frequency was 0.462 (SD = 0.117). These results might be a possible explanation for the

higher “gaze-following accuracy” that was found for the mixed alpha condition, where the difference in frequency (alpha: 6.55 Hz, theta: 4.5 Hz) was most pronounced.

Table 1

Mean and Standard Deviation of the Conditions: Alpha, Theta and Mixed

	Condition			
	Alpha	Theta	Mixed Alpha	Mixed Theta
Mean	0.526	0.502	0.593	0.483
Standard Deviation	0.210	0.200	0.255	0.266

Figure 6

Pairwise Comparison of the Mixed Alpha Condition with the Alpha, Theta and Mixed Theta Conditions

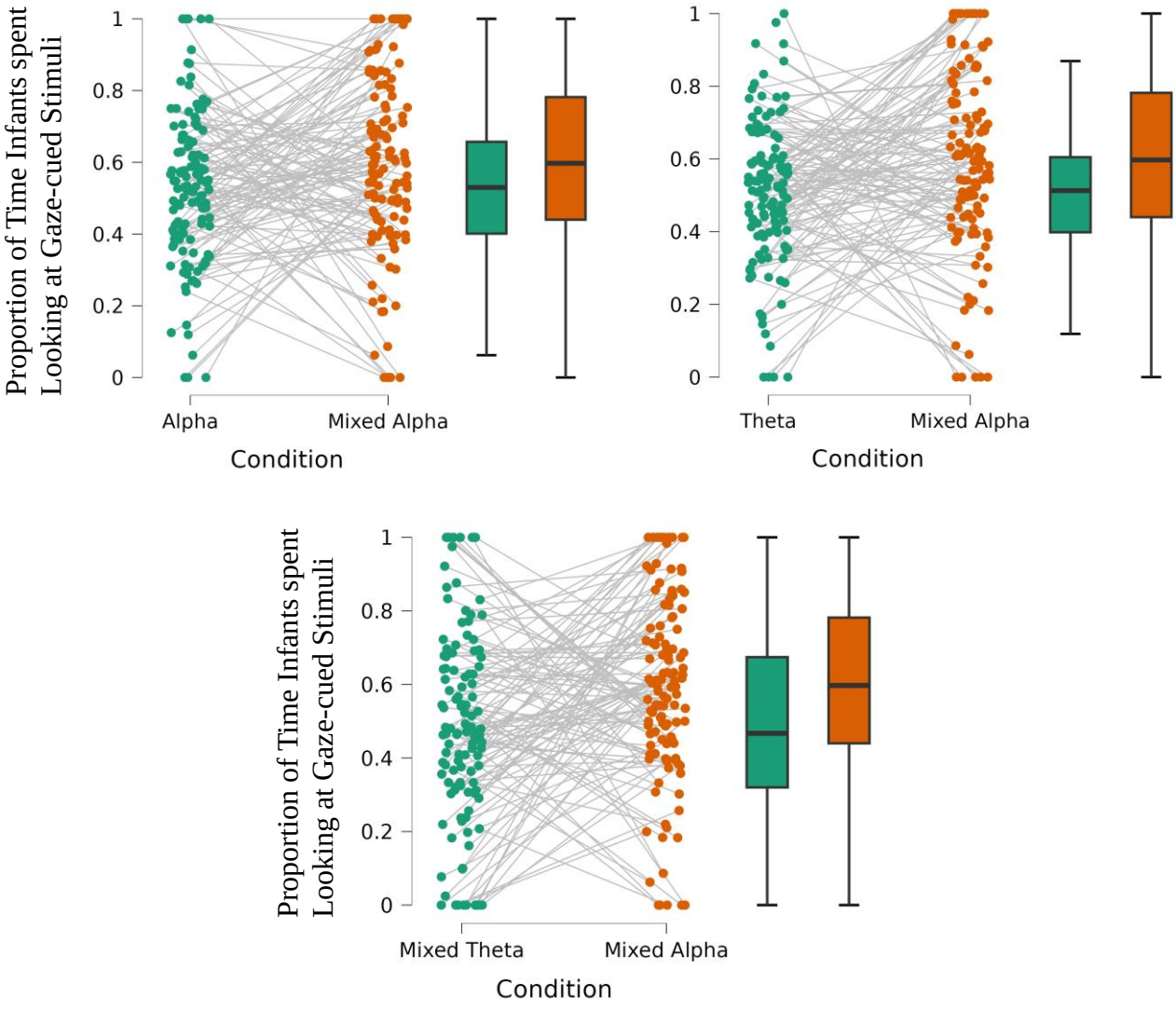
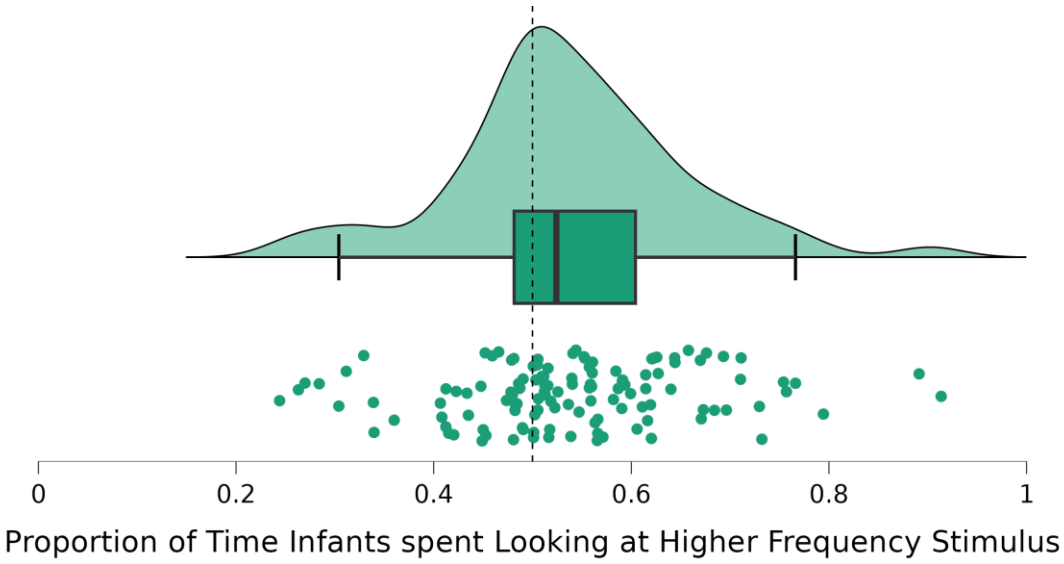


Figure 7

Average Time Infants looked at the Stimulus Flickering at the Higher Frequency tested against a Value of 0.5



4.3 EEG Data

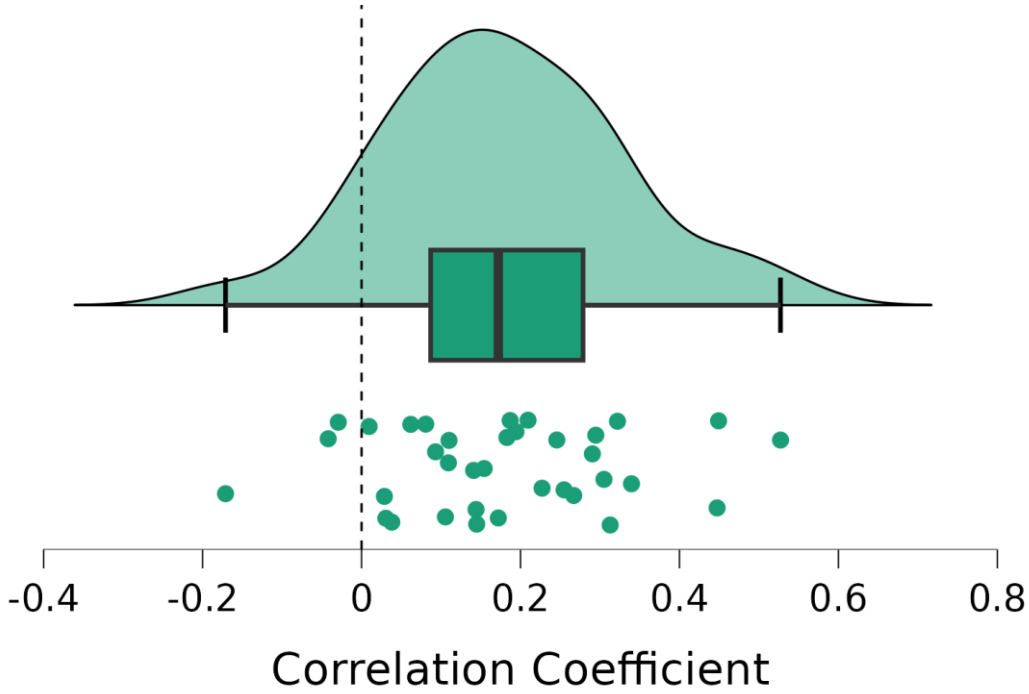
The sample size for all EEG data analyses was $n = 35$.

4.3.1 Hypothesis 4

We expected theta power to increase over the duration of the baseline video in our sample. After calculating the Pearson correlation between segment numbers and average theta power per segment for each infant, a one-sample *t*-test was performed. Correlation coefficients differed significantly from zero [$t(34) = 7.091$, $p < .001$***, $d = 1.199$] and the group mean was positive ($M = 0.178$, $SD = 0.149$). This indicated a group-level increase in frontocentral theta power over the course of the baseline video (Figure 8). The result thus supported and partially replicated the findings of Braithwaite and colleagues (2020).

Figure 8

Correlation between Average Theta Power of each Segment and Segment Number as Measurement of the Magnitude of Theta Power Change throughout the Baseline Video

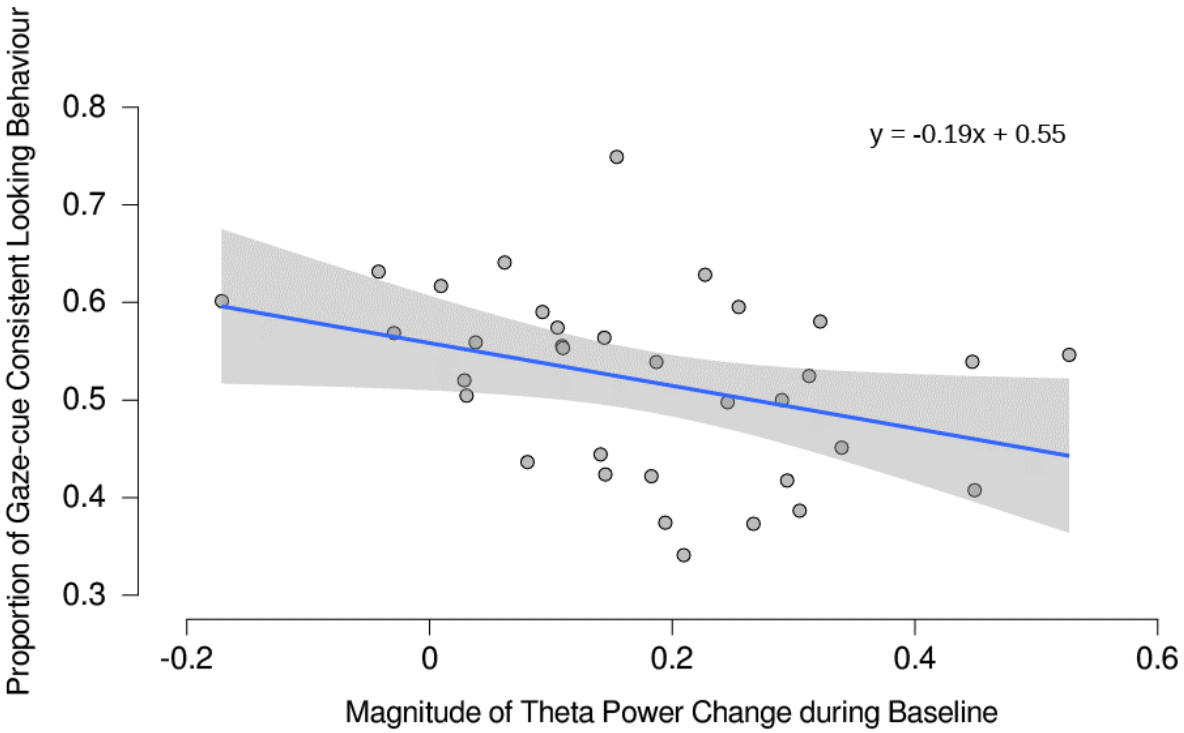


4.3.2 Hypothesis 5

Correlating the theta power change during baseline with the gaze-cue consistent looking behaviour resulted in a negative and non-significant *r*-value [r = -.335, p = .053, r^2 = .112, (95% CI upper: -0.002, lower: -0.601)]. This result did not support our hypothesis regarding a positive correlation between the magnitude of baseline theta power change and gaze-following abilities (Figure 9).

Figure 9

Correlation between the Proportion of Time Infants looked at the Gaze-cued Stimulus and the Magnitude of Theta Power Change



4.3.3 Hypothesis 6

In order to compare the association between the baseline theta power increase and the proportion of gaze-cue consistent looking behaviour between the conditions, we ran Pearson correlations for each trial condition. We expected to find a stronger association between the baseline theta power increase and the gaze-cue consistent looking behaviour in the theta condition than in the other trial conditions.

All correlations but the alpha condition were negative and non-significant. The alpha condition's *r*-value was .010 [p = .956, r^2 = .001, (95% CI upper: 0.342, lower: -0.325). The *r*-value of theta was -.172 [p = .331, r^2 = .030, (95% CI upper: 0.171, lower: -0.478)], for mixed alpha it was r = -.116 [p = 0.522, r^2 = .013, (95% CI upper: 0.226, lower: -0.432)] and mixed theta had r = -.143 [p = .427, r^2 = .020, (95% CI upper: 0.200, lower: -0.455)]. Comparing the correlation coefficients showed that differences between correlation coefficients for alpha and theta (p = .462), theta and mixed alpha (p = .819), as well as theta and mixed theta (p = .905), were not statistically significant.

Thus, the correlation coefficients did not indicate a stronger positive association between the theta power change during the baseline video and the infant's gaze-following abilities during the subsequent gaze-cue task in the theta condition compared with the alpha and mixed condition.

5 Discussion

As alpha and theta brain oscillations are associated with attention regulation and learning during infancy (Begus & Bonawitz, 2020; Cellier et al., 2021; Klimesch, 1999), it makes them especially interesting to study in the context of gaze-following because successful gaze-following plays an important role in directing infants' attention and is a prerequisite for early social learning (Emery, 2000). Infants' success in encoding and reacting to another person's gaze direction by shifting their attention to the relevant reference point has far-reaching implications for their socio-cognitive development and language acquisition (Brooks & Meltzoff, 2005; Hoehl et al., 2009). Based on the neural entrainment hypothesis, which supposes that internal brain oscillations can be entrained with external rhythms through the periodic presentation of the stimuli (Banki et al., 2022), this study thus aimed to investigate infants' gaze-following behaviour when presented with gaze-cued stimuli flickering at rates associated with infant alpha and theta frequency bands. We furthermore built on a finding that associated infant theta power increase during the viewing of a baseline video with the infants' cognitive abilities (Braithwaite et al., 2020) by exploring any possible connection between EEG theta power changes during a baseline video and the infants' gaze-following abilities in the subsequent gaze-cue task. To do this, we analysed the gaze-following behaviour of 6-month-old full-term neurotypical developing infants during a gaze-cue task in a neural entrainment paradigm.

Considering that gaze-following abilities start to develop very early in infancy, with the first signs emerging around 2 to 4 months of age (Gredebäck et al., 2010), we expected to find significant group-level gaze-following abilities at 6 months of age. Our findings were in line with our hypothesis, namely that 6-month-old infants would show more gaze-cue consistent than inconsistent looking behaviour. This finding further strengthens existing evidence that gaze-following abilities develop during the first half year of life. Furthermore, our data showed that infants not only followed the gaze cue but also spent more time looking at the gaze-cued than the non-cued stimulus. This finding shows that infants allocate more attention towards the gaze-cued stimulus in an environment where multiple objects are visible at the same time. In line with the proposed role of gaze-following for guiding infants' attention in complex social interactions, the

ability to sustain one's attention towards a socially relevant stimulus could, therefore, be crucial for infants' successful learning in social settings.

These findings are especially interesting considering that our experimental design differed from some of the previously applied gaze-following paradigms in two ways. First, many other EEG studies utilised a setup in which only one object was presented either to the left or to the right side of the centred face for each trial. Thus, they basically differentiated between object-directed and object-averted gaze conditions. On the other hand, our study design presented the infant with objects on both sides of the face for all trials. This means that the face was always directing its gaze towards a stimulus, independent of the condition. It could be argued that this study design created a more realistic setting as real-live social interactions are highly complex and, more often than not, consist of more than one potentially relevant object in the infant's peripheral field of vision. Therefore, our study might have captured this complexity of everyday attention dynamics better than previous studies that implemented a more traditional gaze-cue paradigm. Second, to our knowledge, no study has been conducted so far that looked at infant gaze-following in the context of an entrainment study. Unlike classic EEG studies, our study design allows us to clearly sort the infants' EEG responses to the trial conditions through frequency-tagging. This is possible because the simultaneously presented stimuli flickered in different frequencies, eliciting distinguishable steady-state responses in the infants' brains. Based on the recorded steady-state potentials, the neurological activity can be attributed to the corresponding stimulus, and thus, the visual processing of each stimulus can be assessed separately (Müller et al., 2003). In light of these considerations, our findings add a unique perspective to the growing body of literature concerned with infant looking behaviour.

Having established that the infants in our sample showed sufficient gaze-following abilities, hypotheses two and three inquired into the effect of the frequency in which the gaze-cued stimuli were presented. We expected to see variation in infants' looking behaviour depending on the frequency of stimulus presentation. This expectation was based on the theoretical proposition that neural entrainment can occur in the developing brain as previous research has shown that the presentation of rhythmic sensory stimuli, such as audio and visual stimuli in the frequency ranges of certain brain frequency bands, can have an effect on brain oscillations and behaviour performance (Köster et al., 2019a; Mathewson et al., 2010; Otero et al., 2022). More precisely, we expected less gaze-following during trials with flickering rates corresponding to infant alpha frequency and more gaze-cue consistent gaze-following during trials with frequencies in the theta frequency band. We expected this because alpha oscillations have been associated with inhibiting the processing of less relevant stimuli, while theta has been linked to learning and the development of voluntary attention networks (Cellier et al., 2021; Klimesch, 1999; Michel et al., 2015).

As we assumed that the centred face, as a critical social cue, holds the most relevant information for infants, the flickering in alpha frequency would generally inhibit the processing of the less relevant peripheral stimuli. Thus, our second hypothesis predicted that infants would remain looking at the centred face and not look at the flickering stimuli when the flickering was in alpha frequencies. However, our data did not support this hypothesis. There was no difference between the conditions regarding the average number of trials infants spent exclusively looking at the centred face. A possible explanation for this finding could be that the initial inhibition of the peripheral stimuli resulted in a delayed gaze-following response rather than an exclusive orientation towards the centre. This prolonged orientation latency might be based on a more detailed encoding of the social cues presented in the centred face when the processing of peripheral stimuli is inhibited. If this was true, orientation latency should be longer for trials where both peripheral stimuli are flickering in alpha frequency compared with trials where flicker in theta or when one stimulus flickers in alpha and the other in theta frequency. As the current study did not investigate orientation latencies, follow-up studies could allow for testing this alternative explanation.

The third hypothesis posited that the infant's gaze-following would be more accurate when the peripheral stimuli both flicker in theta rather than alpha or mixed frequencies. We expected this because of theta's involvement in information processing and learning (Begus & Bonawitz, 2020) and the possibility of visually entraining endogenous theta (Köster et al., 2019a) during the theta condition, where both peripheral stimuli flickered in the theta frequency range, which means that the rhythmic flickering of the stimuli in the theta frequency range could facilitate the processing of informative stimuli, which in turn could result in a more consistently accurate gaze-following behaviour. While our findings showed that infants' looking behaviour varied depending on the condition, we did not find a significantly higher proportion of gaze-cue consistent looking behaviour when the peripheral stimuli were flickering in theta compared with alpha or mixed frequencies. The exploratory analysis suggested that this difference in gaze-following behaviour mainly stemmed from a higher gaze-following accuracy in the mixed alpha condition, where the gaze-cued stimulus was flickering in alpha and the gaze-averted stimulus in theta frequency, compared with trials where both stimuli were flickering in alpha or theta frequency as well as when the gaze-cued stimulus was flickering in theta and the gaze-averted stimulus in alpha frequency. Although these findings did not support our hypothesis and even ran somewhat contradictory to our expectations, they might be able to provide supporting evidence to the argumentation of Angelini and colleagues, who, in a recent study, reported enhanced alpha activity in congruent object-gaze conditions during a real-live joint attention situation with 9-month-old infants. They argued that this increase in alpha oscillations could be based on the involvement of alpha in internally controlled attention, which develops during the first year of life (Angelini et al., 2023). Complementary, the

role of alpha oscillations as an inhibitor of “task-irrelevant” stimuli might result in better encoding of the social cues provided by the centred face and thus facilitate an accurate response to the gaze cue. This is, of course, assuming that the rhythmic visual stimulation corresponding to the infant alpha or theta frequency band had some entrainment effect on the participants’ brain oscillations.

Alternatively, a group-level preference for looking at stimuli flickering at a higher frequency could also explain the observed differences in gaze-following behaviour between trial conditions. Exploratory analysis supported the idea of a group-level preference for the higher frequency stimulus. Comparing the average proportion of time infants spent oriented towards the higher versus the lower frequency stimulus over all trial conditions, 6-month-old infants spent significantly more time looking at the stimulus flickering at the higher frequency regardless of the gaze cue. Similar findings were reported by a study from Lewkowicz, who found that 6-month-old infants spent increasingly more time looking at the stimuli as their flickering frequency increased. This study presented visual stimuli as two rhythmically flickering black-and-white random check patterns at frequencies of 2, 4 and 8 Hz (Lewkowicz, 1985). A visual preference for higher temporal frequencies might also partially explain the difference in looking behaviour between conditions with stimuli presentation in alpha, theta or mixed frequencies in our sample, as the difference between high and low-frequency flickering would have been most pronounced and recognisable for the mixed frequency trials. This was supported by the results showing a significant difference in the average time infants spent looking at the gaze-cued stimulus in the mixed alpha versus the mixed theta condition, which was significantly higher for the alpha frequency at 6.55 Hz than the theta frequency flickering at 4.5 Hz. On the other hand, in the alpha or theta condition, where both peripheral stimuli were flickering within the same frequency bands and where the frequencies, therefore, lay closer together, thus making it more difficult to distinguish between the higher and lower frequency, this preference for the faster rhythm would have influenced the looking behaviour to a lesser degree.

Regarding the EEG data analysis, we expected to observe a theta power increase during the viewing of the baseline video in 6-month-old infants and a correlation between the magnitude of this baseline theta power change and the infants’ performance in the gaze-cue task. Even though we found a group-level increase in theta power throughout the baseline video, our data did not indicate a measurable effect of the baseline theta power change on the infants’ gaze following performance during the subsequent gaze-cue task. This outcome was contrary to our expectations based on studies such as Braithwaite et al. (2020) and Jones et al. (2020), which had found baseline EEG activity to be associated with performance in various tasks and measures of intelligence. Nevertheless, successfully replicating previous reports on the theta power increase during the baseline video viewing further corroborates theta’s involvement in information encoding processes.

This connection between frontal theta power and information encoding becomes especially clear when considering findings that showed a non-linear relationship between repeated viewing of the same video and frontal theta power. An initial increase in theta power while the video content is novel, followed by a decline in theta power with increasing familiarity, could reflect the cognitive process of encoding and depletion of novel information (Piccardi et al., 2020). As the content of our baseline video did not repeat itself, the observed increase in theta power could thus represent theta's involvement in encoding the visual information.

5.1 Limitations and Future Research

Based on prior studies reporting successful entrainment in infants, the current study assumed some degree of entrainment effect of the rhythmically flickering stimuli on the infants' looking behaviour. Thus, if we had observed the expected differences between conditions, it would support the notion of successful entrainment occurring. As we did not find the hypothesised differences in gaze-following behaviour between the conditions, our results did not support the notion that we were able to cause functional neural entrainment in 6-month-old infants. While this has little impact on the alternative explanation mentioned on infant preferences for higher frequency rhythms, it could mean that hypotheses two and three had to be rejected because the rhythmic visual stimulation in our experimental set-up did not result in any neural entrainment rather than the hypothesis being incorrect. This should be kept in mind when interpreting the results.

The lower alpha frequency cut-off point at 5.5 Hz might be a possible limitation. As the limits for infant brain oscillation frequency bands are not well defined and vary between studies, our cut-off point for the lower alpha frequency would still be defined as part of the theta frequency band by other literature. A common definition for infant theta oscillation is 3 to 6 Hz, which would incorporate 5.5 Hz. Thus, it might be possible that the lower alpha frequency in the current study still corresponded with the infant's theta frequency band instead of the alpha band. In this case, the alpha condition would have more of a mixed condition character. A follow-up investigation could help determine if adjustments to the alpha and theta frequency cut-off points would influence the results.

As the current study did not investigate orientation latency or the first direction of orientation as other possible measures of gaze-following ability, future research should inquire into different ways of operationalizing looking behaviour in infants and how this can impact the reliability and validity of the study results.

5.2 Conclusion

The present study aimed to add to a growing body of literature around infant gaze-following by investigating the looking behaviour of 6-month-old infants during a gaze-cue task with rhythmically flickering stimuli. We also investigated the association of baseline brain oscillations with the infants' subsequent gaze-following behaviour. In line with existing literature, we found that at 6 months of age, infants showed consistent gaze-following behaviour on the group level and spent, on average, significantly more time looking at the gaze-cued than the gaze-averted stimulus. Contrary to our expectations, looking behaviour varied very little between the conditions. Thus, this study did not find any evidence that the stimuli's frequency significantly influenced infants' looking behaviour beyond the point of a possible group-level preference for looking at faster flickering stimuli. These results did not support the notion that this study was able to cause functional neural entrainment in 6-month-olds. Furthermore, infants in our sample showed a theta power increase throughout the baseline video, strengthening findings Braithwaite et al. (2020) reported in a recent study with 6-month-old infants. However, this study found no positive correlation between baseline theta power increase and infant gaze-following behaviours in the subsequent gaze-cue task.

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Abstract (English)

The ability to follow gaze cues is a crucial skill for infants, as it plays a significant role in their early development and learning. In this study, we examined the looking behaviour of 6-month-old infants during a gaze-cue task that utilized rhythmic flickering stimuli at different frequencies. The chosen frequencies corresponded to infant alpha and theta frequency bands, which have been associated with attentional processes. The goal of the study was to investigate whether infants exhibit differences in gaze-cue following depending on the frequency of stimuli presentation. Consistent with previous research, we found that at 6 months of age, infants demonstrated consistent gaze-following behaviour at the group level. However, contrary to our expectations, we did not find any evidence that the frequency in which the stimuli were flickering significantly influenced infants' looking behaviour beyond a possible group-level preference for faster flickering stimuli. These results do not support the notion that this study was able to cause functional neural entrainment in 6-month-olds.

Given that previous research suggested a link between infant theta modulation and subsequent task performance, we also examined whether the magnitude of theta power change during the baseline video was predictive of consistent looking behaviour during the gaze-cue task. Infants in our sample showed a theta power increase throughout the baseline video, which supports findings reported by Braithwaite et al. (2020) in an earlier study with 6-month-old infants. However, we found no positive correlation between the magnitude of baseline theta power increase and infant gaze-following behaviour in the subsequent gaze-cue task.

Abstract (Deutsch)

Die Fähigkeit, anderer Blicke zu folgen, ist eine entscheidende Fähigkeit für Säuglinge, da sie eine wichtige Rolle in ihrer frühen Entwicklung und ihrem Lernen spielt. Diese Studie untersuchte das Blickverhalten von 6 Monate alten Säuglingen, während eines „gaze-cue tasks“, bei der rhythmische Flackerreize mit unterschiedlichen Frequenzen verwendet wurden. Die gewählten Frequenzen entsprachen den Alpha- und Theta-Frequenzbereichen von Säuglingen, die bereits in früheren Studien mit Aufmerksamkeitsprozessen in Verbindung gebracht wurden. Das Ziel dieser Studie bestand darin, zu untersuchen, ob Säuglinge abhängig von der Frequenz der Reizpräsentation Unterschiede in Blickfolgeverhalten zeigen. In Übereinstimmung mit bestehender Literatur fand diese Studie, dass Säuglinge im Alter von 6 Monaten auf Gruppenebene ein konsistentes Blickfolgeverhalten aufwiesen. Entgegen den Hypothesen gab es jedoch keine Hinweise darauf, dass die Frequenz, mit der die Reize flackerten, das Blickverhalten von Säuglingen signifikant beeinflusste, abgesehen von einer möglichen Präferenz auf Gruppenebene für schneller flackernde Reize. Die Ergebnisse weißen demnach nicht darauf hin, dass dieses Studiendesign bei 6 Monate alten Kindern ein funktionelles neuronales Entrainment hervorrufen konnte.
Da frühere Studien einen Zusammenhang zwischen der Theta-Modulation des Säuglings und späterer kognitiver Entwicklung nahelegten, wurde auch untersucht, ob das Ausmaß der Veränderung der Gehirnaktivität im Thetafrequenzbereich, während des Baselinevideos, das Blickverhalten während des „gaze-cue tasks“ vorhersagte. Säuglinge in unserer Stichprobe zeigten während des Baslinevideos einen Anstieg der Thetaaktivität, was die von Braithwaite et al. (2020) berichteten Ergebnisse stützte. Im Gegensatz zu Braithwaite und Kollegen fand diese Studie jedoch keine positive Korrelation zwischen dem Ausmaß des Anstiegs der Thetaaktivität während des Baselinevideos und dem Blickfolgeverhalten der Säuglinge bei dem anschließenden „gaze-cue task“.

Appendix

A. Figure Caption

B. Table Caption

C. Looking Side-Bias

We tested whether excluding infants with left-right looking bias would significantly impact the analysis results. We did not find that this is the case. Overall, the exclusion of biased cases resulted in insignificant changes in group means and slightly smaller standard deviations but no difference in the significance levels of the tests.

D. Bayesian Statistics

Bayesian factor can be interpreted as a measure of strength in favour of one particular theory compared to a competing theory. Analyses that support the alternative hypothesis were reported using BF_{10}, while all other results were reported as BF_{01}. Therefore, BF_{10} reports how much more likely the alternative hypothesis is over the null hypothesis, whereas BF_{01} depicts the likelihood of the null hypothesis over the alternative hypothesis.

H1:

Bayesian Wilcoxon signed-rank test

$BF_{10} = 55.899$

H2:

Bayesian ANOVA

$BF_{01} = 18.891$

Pairwise comparison

alpha vs theta: $BF_{01} = 14.967$ (Wilcoxon)

alpha vs mixed alpha $BF_{01} = 26.651$ (paired samples *t*-test)

alpha vs mixed theta $BF_{01} = 20.813$ (Wilcoxon)

H3:

Bayesian ANOVA

$BF_{10} = 0.213$

Pairwise comparison

theta vs alpha condition (Wilcoxon)

$BF_{01} = 21.208$

theta vs mixed alpha condition

$BF_{01} = 41.286$ (paired samples *t*-test)

theta vs mixed theta condition (paired samples *t*-test)

$BF_{01} = 3.983$

mixed theta vs mixed alpha (pared samples *t*-test)

$BF_{01} = 32.775$

Exploratory Analysis:

alpha vs theta (Wilcoxon)

BF_{01} = 7.225

alpha vs mixed alpha (paired samples *t*-test)

BF_{10} = 0.894

alpha vs mixed theta (paired samples *t*-test)

BF_{01} = 2.989

theta vs mixed alpha

BF_{10} = 14.278 (paired samples *t*-test)

theta vs mixed theta (paired samples *t*-test)

BF_{01} = 6.496

mixed alpha vs mixed theta (paired samples *t*-test)

BF_{10} = 1.997