Cognition 257 (2025) 106077

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/cognit

The impact of rhythm on visual attention disengagement in newborns and 2-month-old infants

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ARTICLE INFO

Keywords:
Rhythm
Attentional disengagement
Visuospatial attention
Newborns
Infants

ABSTRACT

Rhythm entrains attention in both human and non-human animals. Here, the ontogenetic origins of this effect were investigated in newborns (Experiment 1; $N = 30$, 16 females) and 2-month-old infants (Experiment 2; $N = 30$, 17 females). Visuospatial attentional disengagement was tested in an overlap task where a static peripheral stimulus (S2) appeared while a central rhythmic, non-rhythmic or static stimulus (S1) remained visible on the screen. Results indicated a developmental pattern, with 2-month-olds, but not newborns, showing equally faster disengagement of fixation when S1 was static or rhythmic compared to non-rhythmic. Infants' preferential looking behaviour indicate that this difference in saccadic latencies was not due to stimulus salience (Experiment 3; $N = 30$, 18 females). Results point to the importance of the temporal structure of dynamic stimuli as a specific feature that modulates attentional disengagement at 2 months of age.

1. Introduction

Human biology and behaviour, along with many natural phenomena, exhibit rhythmic patterns, generally intended as patterns of regular events in time (McAuley, 2010). These patterns can be classified into two major categories: isochronous rhythms, with equal intervals between events, and anisochronous rhythms, where intervals between the events are unequal. While isochronous rhythms, with perfectly equal intervals, theoretically minimise signal entropy (i.e., the amount of information in a signal, irrespective of its meaning), most natural rhythms, such as human heartbeat and respiration, often deviate from perfect isochrony with accelerations and decelerations (Ravignani & Madison, 2017).

Both isochronous and anisochronous rhythms pervade human perceptual experience throughout the life cycle: rhythmicity is present in the mother's heartbeat and breathing during foetal life, in body movements while walking, in prosody while speaking, in the ebb and flow of ocean waves, and in the cyclic progression of days and nights. Given its ubiquitous nature, it has been argued that rhythm might serve as a wellspring of temporal information that our cognitive system harnesses to optimise its interaction with the environment (e.g., Keitel et al., 2022).

1.1. Rhythm and attention

One cognitive process that benefits from the rhythmicity of the events in the environment is attention, which allows us to select and prioritise relevant information in the incoming flow of environmental stimuli. By supporting the building of temporal expectation on when events will occur, rhythm entrains attention and modulates the perceptual gain of the incoming sensory inputs that occur according to the rhythmic stream. This idea is at the heart of the Dynamic Attending Theory (i.e. DAT; Jones & Boltz, 1989), which builds on the notions of expectancy and entrainment (i.e., the process of synchronisation of endogenous brain rhythms with periodic external stimulation) to describe real-time attentional tracking of time-varying events. Pioneer studies in this field were conducted using auditory stimuli, and showed that individuals are more accurate at differentiating between the pitch

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https://doi.org/10.1016/j.cognition.2025.106077
Received 17 February 2024; Received in revised form 28 January 2025; Accepted 29 January 2025

and duration of sounds when these are presented precisely at the predicted beat, and accuracy decreases progressively as the temporal mismatch between the target and the beat increases (Barnes & Jones, 2000; Jones et al., 2006).

The profitable effects of rhythm on attention and perception are also well-established in the visual domain. For example, saccadic latencies to orient to a peripheral target are faster when the target appears on phase with a rhythmic and predictable auditory stimulus than with a random and unpredictable beat (Miller et al., 2013). Accordingly, the conscious perception of near-threshold visual stimuli can be facilitated when these are presented on-beat with a visual or auditory rhythm (e.g., Elbaz & Yeshurun, 2020; Mathewson et al., 2010). Moreover, converging evidence from electroenchephalografic (EEG) investigations shows that temporal expectation of a target modulates ongoing oscillatory brain activity, and that the strength of such anticipatory activity is predictive of the outcome of subsequent target processing (e.g., Besle et al., 2011; Rohenkohl & Nobre, 2011).

1.2. *Developmental origins of the link between rhythm and attention*

The temporal expectation facilitates perception especially in the context of dynamic streams of complex stimuli, such as in language and music. Nonetheless, the ability to leverage temporal regularities to allocate attention at relevant moments in time is not uniquely human, as it has also been found in non-human primates. For example, Lakatos et al. (2008) trained monkeys to respond to infrequently presented oddball stimuli embedded within rhythmic streams of visual and auditory events and found that delta-band oscillations in the monkeys' primary visual cortex entrained to the rhythm of the stream, and resulted in increased response gain and decreased reaction times. Also, a growing body of evidence shows that rhythm and synchronisation abilities are crucial aspects of animal movements and communication (see review in Ravignani, 2019). These findings suggest that the ability to rely on temporal regularities to guide behaviour is not a uniquely human trait but rather has evolved throughout phylogeny as an adaptive strategy across various animal species, enabling optimised responses to environmental events through selective processing at key time points (Kotz et al., 2018).

In humans, both prenatal and postnatal environments are replete with temporal regularities. Regular and temporally structured sensory inputs are pervasive in the intrauterine life, which the foetus can perceive through the auditory, tactile, and vestibular modalities (see Provasi et al., 2014 for a review). For instance, foetal heart rate varies in response to tempo variations in music (Kisilevsky et al., 2004) and rhythm associated to maternal movements when sitting in a rocking chair (Lecanuet & Jacquet, 2002). Additionally, it is well established that both foetuses (Minai et al., 2017) and newborns (Nazzi et al., 1998; Ramus et al., 2000) use rhythmic cues to discriminate between different languages. A significant proportion of the sensory input reaching the foetus are auditory in nature, as the auditory system matures rapidly in utero, becoming functional and actively processing sounds coming from both inside and outside the uterus by around 20 weeks' gestation (Hepper & Shahidullah, 1994). This is particularly relevant to our research question, given the well-established role of the auditory modality in encoding abstract temporal structures and temporal rhythm discrimination (e.g., Guttman et al., 2005). This suggests that the intrauterine environment is rich in rhythmic information, particularly in the auditory domain. This is significant for rhythm encoding, as foetuses are highly sensitive to auditory stimuli.

Accordingly, recent studies on premature infants suggest that the brain is capable of processing and discriminating auditory rhythms beyond simple sensory coding (Edalati et al., 2023) even before birth. Further, research has established that prenatal auditory experiences can influence later auditory processing abilities (e.g., Abboub et al., 2016; Mampe et al., 2009; Moon et al., 1993; Sato et al., 2010; Vogelsang et al., 2022). It is therefore possible that the combined in-utero auditory processing experience, coupled with the rhythmicity of intrauterine sensory inputs, could contribute to making rhythm a prominent feature of environmental stimulation that may guide attention in early postnatal life. Accordingly, studies have shown that 2-month-old infants prioritise audio-visual temporal synchrony (i.e. a toy moving in synch with a sound's rhythm) over spatial co-location in learning arbitrary cross-modal associations, with spatial co-location becoming more influential by 6 months (Morrongiello et al., 1998). This suggests that reliance on temporal attributes predominates in the early stages of life, while spatial attributes become more important later.

Infants are increasingly exposed to a wider variety of rhythmic patterns after birth and refine their ability to process this information. From the very onset of postnatal life, parents provide rhythmic inputs through multiple sensory channels during face-to-face interactions. These inputs include patting, rocking, speaking, and singing, and involve infants in vocal turn-taking. Concurrently, neonates develop expectations based on temporal cues, as evidenced by brain activity associated with violated sensory expectations when a rhythmic cycle within complex auditory streams is omitted (Winkler et al., 2009). Tempo and rhythm are two amodal stimulus properties whose discrimination becomes more flexible and robust as perceptual experience increases. This developmental trend is supported by studies showing that discrimination initially benefits from intersensory redundancy (e.g. when changes occur in both the visual and auditory modalities) and only few months later becomes more consistent in the context of nonredundant unimodal (e.g., visual or auditory) stimulation (e.g., Bahrick & Lickliter, 2004).

Alongside the development of rhythm perception abilities, the infants' brain exploits this information to guide the development of various motor (Liparoti & Minino, 2021), cognitive, social and communicative skills (e.g., Goswami, 2022; Trainor & Cirelli, 2015). However, only a few studies explored the link between rhythm and attention in early infancy. By measuring visual scanning via eye-tracking, Lense et al. (2022) showed that 2-month-old infants synchronise their looking behaviour to the rhythm of infant-directed singing by increasing their looking responses to the eyes of the caregiver in synchrony with the beat. When the rhythm is experimentally disrupted, reducing its predictability, infants' time-locked eye-looking is also disrupted. Using a Visual Expectation paradigm, Adler et al. (2008) showed that 3-month-old infants are sensitive to the flow rate of visual events. In the study, the Authors manipulated the temporal predictability of visual events that appeared alternately on the left and right sides of the screen, and measured infants' gaze latency to these stimuli. The results revealed that infants exhibited increased anticipation (i.e. gaze shifts occurring before the event onset) when the timing of the events was predictable compared to when it was not, suggesting that they formed their temporal expectations based on the average flow rate of event sequences. Mento and Valenza (2016) showed that by 9 months of age, infants exhibit expectancy-based anticipatory cortical activity, as indicated by the Contingent Negative Variation (CNV), which occurs before the appearance of a smiling face during the peek-a-boo game (i.e. a game with predictable patterns and occasional disruptions) when the face is delayed compared to the usual timing.

This evidence suggests that infants are sensitive to regularities embedded in the environment, especially in social context, and exploit such regularities to allocate their visual attention resources. However, to gain a more thorough understanding of how rhythm influences attention in infants, it is crucial to elucidate the specific attentional mechanisms that are susceptible to the temporal structure of the stimuli. One possible target for such an investigation is attentional disengagement, a core component of visual orienting which is available from birth.

1.3. *Visual attentional disengagement in newborns*

Attentional disengagement is the ability to shift the focus of selective attention from one location to another (Johnson et al., 1991), a necessary step for orienting visual attention and exploring the environment.

The gap-overlap paradigm has been extensively utilised to assess infants' disengaging abilities in controlled laboratory settings, spanning from infancy (e.g., Blaga & Colombo, 2006; Hunnius & Geuze, 2004; Matsuzawa & Shimojo, 1997) to the newborn period (Farroni et al., 1999; Valenza et al., 2015). In this paradigm, infants' gaze is initially drawn to a central visual stimulus, followed by the presentation of a peripheral stimulus. This typically produces a shift of gaze from the midline to the peripheral stimulus. If the central stimulus disappears before the peripheral stimulus appears (i.e., gap condition), the latency for initiating a saccade to the new stimulus is reduced, as disengagement is not required. However, if the central stimulus remains visible while the peripheral stimulus appears (i.e., overlap condition), the latency to orient to the target increases, reflecting the need to disengage attention from the central stimulus before shifting it to the periphery. Therefore, the overlap condition is commonly used to investigate infants' disengagement abilities and their flexibility in response to stimulus characteristics.

Despite limited research, few studies documented the gap effect (i.e. shorter saccadic latency in the gap condition compared to the overlap condition) in newborns, indicating that the core components of visual orienting are functional already at birth (Farroni et al., 1999; Valenza et al., 2015). However, this ability improves with brain maturation, and the latency for infants to shift their gaze to the peripheral target in the overlap condition decreases with age (e.g., Hood & Atkinson, 1993; Matsuzawa & Shimojo, 1997). Between 1 and 2 months of age, infants exhibit a phenomenon known as 'sticky fixation' or 'obligatory attention', where they struggle to disengage their gaze from a fixated stimulus, even if they are no longer attending to it. This phenomenon is attributed to the inhibitory influence of the maturing primary visual cortex, projecting from the substantia nigra to the superior colliculus, the subcortical structure responsible for saccade generation from birth through adulthood. As the cortical route for eye movement control matures, regulating activity in the superior colliculus through the middle temporal area, obligatory attention resolves around 2 months, allowing for smooth visual tracking (Johnson, 1990). By 3 months, further developments within the upper layers of the primary visual cortex enhance projections to other cortical areas, particularly the frontal eye fields in the frontal cortex. This enables infants to disengage their gaze more readily, initiating rapid saccades (e.g., Butcher et al., 2000) and making anticipatory eye movements towards prospective target locations (e.g., Canfield & Haith, 1991).

Attentional disengagement in the overlap condition is also affected by the attributes of both the central and peripheral stimuli, which modulate saccadic latency. In the study by Farroni et al. (1999) newborns were presented with a flashing light as the central fixation stimulus and either a flashing light, an upright schematic face, or an inverted schematic face as the peripheral target. When the same stimulus (i.e. a flashing light) was presented in both the centre and periphery, saccade latencies were significantly slower compared to when the peripheral target was an upright or inverted schematic face. Valenza et al. (2015) further investigated this phenomenon by using upright and inverted images of real faces as central and peripheral stimuli. They found that newborns were faster to shift their gaze when the central face was static and the peripheral face had animated eyes and mouth movements, compared to the reverse condition. In the same study, 4-month-old infants displayed faster saccadic latencies when the peripheral face was upright and the central one was inverted, as opposed to the reverse arrangement. These studies show that the relative saliency of the central and peripheral stimuli modulates the speed of attentional disengagement in newborns, which is faster when the two stimuli differ compared to when they are equal (Farroni et al., 1999), and when a moving face is at the periphery compared to when it is central (Valenza et al., 2015).

1.4. *Aim of the study*

The present study aimed to investigate the ontogeny of the connection between rhythm and attention specifically exploring the hypothesis that the ability to direct visuospatial attention in the environment is influenced by the rhythmic structure of visual stimulation from the earliest stages of postnatal life, i.e. at birth and 2 months of age.

We employed a gap-overlap task to assess the impact of rhythmic stimulation on infants' visuospatial attention, and specifically the disengagement component. Specifically, we investigated whether rhythmic stimuli influence infants' ability to disengage their visual attention from a central stimulus (S1) and shift it towards a peripheral target (S2) at birth (Experiment 1) and 2 months of age (Experiment 2), when the phenomenon of obligatory attention is either absent (birth) or has resolved (2 months). To assess this hypothesis, we manipulated the temporal characteristics of the central stimulus (S1), creating three conditions: static, rhythmic (i.e. flickering at a consistent rate), and non-rhythmic (i.e. flickering at an irregular rate). Notably, our experimental manipulation focused on the presence or absence of a recurrent temporal pattern rather than variations within the pattern itself, as this approach was deemed more appropriate for the considered young age group in the context of unimodal (i.e. visual) stimulation (Bahrick & Lickliter, 2004).

Unlike S1, the temporal characteristics of S2 remained consistent across conditions. This decision was made to isolate the effect of rhythmicity on disengagement from the central stimulus and avoid potential confounding factors. Given that movement in the periphery, particularly in the temporal visual field (Lewis et al., 1996), is known to enhance of visual orienting at birth and early infancy (e.g., Lewis et al., 1996; Valenza et al., 2015), maintaining S2 as a stationary version of S1 ensured that the effects of rhythmicity on disengagement were not overshadowed by the salience of the peripheral stimuli.

The inclusion of a static condition, where identical stationary stimuli appeared at both the center (S1) and periphery (S2), served two purposes. Firstly, it facilitated the segregation of rhythmic and non-rhythmic trials during the task's presentation, ensuring a clear differentiation between the conditions. Secondly, it enhanced the comparability of the current study with previous research. Both Farroni et al. (1999, Study 2 and 3) and Valenza et al. (2015, Study 1) employed a condition in which the central and peripheral stimuli were identical (i.e., a flashing light in Farroni et al., an upright or inverted schematic face in Valenza et al.), in addition to other conditions in which the two stimuli differed. Valenza et al. (2015) found no significant differences across these conditions. Farroni et al. (1999) reported that newborns exhibited longer saccadic latencies when S1 was the same as S2 compared to when they differed, tentatively attributing this difference to the heightened salience of S2 relative S1 in the latter conditions but not in the former one.

Experiment 1 and 2 were presented as separate experiments due to the methodological differences in the tasks used to assess visual attention in newborns and 2-month-old infants. While the 2-month-old task incorporated both the overlap and gap conditions, requiring a within-subjects design, the lability of newborns' neurobehavioral states and their limited collaborativeness restricted our ability to test them in both conditions. Instead, we focused on the overlap condition for examining visual attention disengagement in newborns.

Based on adult evidence (Miller et al., 2013), we hypothesised that rhythm would enhance infants' attention to peripheral targets appearing on phase with the central rhythm. Accordingly, we predicted shorter saccadic latencies in the rhythmic condition compared to the non-rhythmic condition, with this effect becoming more pronounced at two months due to maturational and experiential factors. However, we were cautious about making specific predictions regarding the static condition, as the relative salience of S1 and S2 differs in this condition compared to the dynamic (rhythmic and non-rhythmic) ones. In the static condition, S1 and S2 are identical (i.e. both static), while in the dynamic conditions, one stimulus is dynamic and the other is static. Previous research (Farroni et al., 1999) has shown that this can impact newborns' saccadic latencies in overlap tasks like the one used in the current study. Therefore, any difference (or lack thereof) between the static and the rhythmic and-or non-rhythmic conditions might not be unequivocally attributable to the temporal structure of the central stimulus.

To further investigate the mechanisms underlying the observed effects of temporal regularities on visual attention, Experiment 3 employed a preferential looking paradigm with 2-month-old infants. This task directly compared the relative saliency of static, rhythmic and non-rhythmic stimuli by presenting pairs of stimuli simultaneously on the screen. Infants' visual preference for a given stimulus was interpreted as a measure of its potential to hold attention when presented centrally as S1 in the overlap task.

2. Experiment 1 (newborns)

Experiment 1 investigated the influence of the temporal structure on visual attention disengagement by testing few-day-old infants in an overlap task. The central stimulus (S1) varied among a static shape, a rhythmically flickering shape, and a randomly flickering shape. The peripheral target (S2) was always a static version of the central stimulus. The number of valid trials and saccadic latency (i.e. the time taken to initiate a saccade towards S2 after its appearance) served as the dependent variables.

2.1. Methods

2.1.1. Participants

The final sample consisted of 30 healthy full-term newborns (16 girls; mean age: 42.97 h, range: 17.45–68.40 h; mean birth weight: 3223,46 g, range: 2520–4400 g; mean gestational age: 39.06, range: 37–41; APGAR score: at least 9 after 5 min). They all came from middle-class families. All participants were recruited at the Neonatal Intensive Care Unit of the Fondazione IRCCS Ca' Granda Ospedale Maggiore Policlinico and tested when in awake alert state. Seventeen other babies were tested but excluded from the final sample because of fussiness ($N = 6$), technical issues ($N = 3$) and the lack of a sufficient number of trials (i.e., a minimum of 2 across at least 2 conditions; $N = 8$). Sample size was predetermined using a Monte Carlo simulation via the SIMR package in R (Green & Macleod, 2016). We conducted an a priori power analysis on the basis of a pilot sample (N = 6), and after 1000 simulations, a sample size of 30 participants was considered sufficient to achieve a power of 82.40 %. Parents filled out the written informed consent form before the experimental session. The protocol met the ethical standards of the Declaration of Helsinki (BMJ 1991; 302: 1194), and was approved by the relevant Ethics Committee (Comitato Etico Milano Area 2; ID: 694; Approval N. 952_2021).

2.1.2. Stimuli

Three white geometrical shapes (full circle, empty circle, and 2 × 2 checkerboard) generated using *E*-Prime 2.0 served as stimuli both for S1 and S2. From a distance of about 30 cm, each shape subtended approximately 13° (7 cm) x 13° (7 cm) of visual angle. The distance between the nearest edges of the peripheral and central image subtended approximately 22.62° of visual angle (12 cm). The appearance of S1 was manipulated to create three conditions: a static condition where S1 remained stationary on the screen, a rhythmic condition where S1 flickered with a regular on-off pattern (500 ms on, 400 ms off; 1 Hz average presentation rate), and a non-rhythmic condition where S1 flickered without any discernible pattern (on and off phases ranging between 200 and 3000 ms and between 200 and 800 ms; 1.15 Hz average presentation rate). S2 always remained static on the screen. Presentation rates were selected based on the temporal contrast sensitivity function (tCSF), which describes the visual system's sensitivity to time-varying information, and the findings of the few available studies measuring evoked brain responses to rhythmic visual stimulation in newborns (Apkarian, 1993; Buiatti et al., 2019). Since no data are available on tCSF in newborns, the rate of the rhythmic pattern (approximately 1 Hz) was chosen to align with the peak sensitivity of 1.5-month-old infants to time-varying information at high contrast (Hartmann & Banks, 1992).

2.1.3. Apparatus

Infants were tested in a dimly lit room, with black panels covering the windows and the sides of the screen where the stimuli were displayed. Each infant sat on one of the experimenters' laps, facing a 27-in. monitor (1920 × 1080 pixel resolution, refresh rate: 60 Hz) placed approximately 30 cm away. A video camera placed above the stimulus presentation screen captured the newborn's face in real time, transmitting the footage to a laptop computer. A second experimenter monitored the live video feed to initiate each trial and control the appearance of the peripheral stimulus based on the infant's visual behaviour. A second monitor, positioned above the stimulus presentation screen, enabled the experimenter holding the infant to maintain their eyes aligned with the screen's midline. The video footage was also recorded on a Mini-Dv digital recorder for offline coding of saccadic latencies to orient to S2. Parents were permitted to observe the entire experimental session and could interact with their infant in case of discomfort.

2.1.4. Procedure

Testing commenced when the infant was oriented towards the screen with their eyes open, at which point an experimenter pressed a key to initiate the first trial. The infant's mother was present in the testing room throughout the procedure but remained out of the infant's line of sight. The procedure was infant-controlled, so that each trial started as soon as the infant's gaze was directed towards the screen. This activated the presentation of a static, rhythmic, or non-rhythmic geometrical shape (S1) at the centre of the screen. After the experimenter coded 3.6 s (equivalent to four repetitions of the rhythmic pattern) of continuous looking, a second identical shape (S2) appeared peripherally to either the left or right of the central stimulus and remained stationary. The lateral position of the peripheral stimulus varied randomly across trials, ensuring an equal distribution of occurrences on both the left and right sides for each condition. Throughout each trial, S1 continued to appear, overlapping with S2 (Fig. 1). To maintain temporal consistency across conditions, the presentation of S2 was always synchronised with the onset of S1, ensuring that the temporal flow of the overall stimulus presentation sequence was identical. This means that, in the rhythmic and non-rhythmic conditions, even once the 3.6-s-fixation criterion was met, the appearance of S2 was kept on hold until S1 went on. Once the infant shifted their gaze away from S1 or 10 s had elapsed since the onset of S2 without a saccade, both stimuli were withdrawn. The experimenter then initiated the next trial by presenting a new central stimulus. Each participant completed a maximum of 18 trials, grouped into six blocks across the three S1 type conditions. The first three blocks included four trials each, followed by three subsequent blocks with two trials each, allowing more cooperative participants to contribute more trials across all conditions. The six trial blocks were presented in either of two possible orders: rhythmic - static - non-rhythmic - non-rhythmic - static - rhythmic ($N = 17$), or non-rhythmic - static - rhythmic - rhythmic - static - non-rhythmic ($N = 13$). The static condition was always placed between the two dynamic conditions to facilitate the distinction between rhythmic and non-rhythmic trials during the task and ensure a clear differentiation between the two. Trial presentation continued until the infant became fussy or inattentive. Only infants who contributed at least two trials (i.e. executed valid saccades to S2) in two different conditions, for a total of at least 4 trials, 4 trials, were included in subsequent analyses.

2.1.5. Data reduction and analysis

The video recordings of newborns' gaze behaviour were coded offline on a frame-by-frame basis (40-ms resolution) using VirtualDub, a

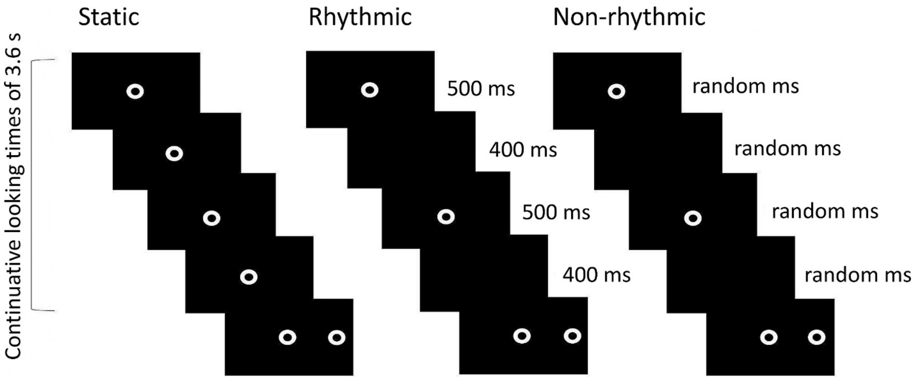

Fig. 1. Trial structure for each of the three S1 conditions: the static condition in which S1 remained static on the screen, the rhythmic condition in which S1 flickered according to a 500 ms on-400 ms off temporal pattern, and the non-rhythmic condition in which S1 flickered without any predictable pattern. S2 always remained static on the screen.

video capture/processing utility for 64-bit Windows platforms. Two independent coders, blind to research questions and S1-type condition being tested, coded each infant's gaze on each trial, recording the cumulative looking times on S1 and the saccadic latencies to orient to S2 (i.e., the time elapsed between the appearance of S2 and the moment when the infant initiated a saccade towards it). Cumulative looking time was one of several criteria used to identify valid trials, which is included as a dependent variable in the few studies adopting the gap-overlap task in newborns (Farroni et al., 1999; Valenza et al., 2015). To check the effectiveness of our task in eliciting the orienting of visuospatial attention and to ensure comparability, we entered the number of valid trials into statistical analyses. For a trial to be considered as valid, the infant had to meet the following criteria (based on Valenza et al., 2015): (1) maintain continuous fixation on S1 for a minimum of 2.7 s (equivalent to three repetitions of the rhythmic pattern), (2) fixate continuously on the midline stimulus for at least 500 ms immediately before the appearance of S2, (3) initiate a saccade towards S2 within a range of 200 to 10,000 ms after its appearance, and (4) execute a direct saccade towards S2 without lingering towards other directions. Saccadic latency was also used for statistical analyses after log-transformation, as recommended for measures of infants' looking behaviour (Csibra et al., 2016). For saccadic latencies, the average of the two coders' measurements was used in the analyses. In cases where the coders' judgements differed by more than 1 frame (9 % of all trials), the video was re-coded by both coders. If they still failed to reach an agreement, the trial was excluded from the analyses (0.93 % of all trials).

Statistical analyses were conducted using the R statistical software (RStudio Team, 2020) employing the *lme4* (Bates et al., 2009) and *lmerTest* (Kuznetsova et al., 2017) packages for linear mixed-effects modelling (Baayen et al., 2008). Two separate models were constructed, one for each dependent variable: the number of valid trials (i.e., trials in which the infant fixated on S2) and the log-transformed saccadic latency to orient to S2. Both models included the predictor S1 type (static, rhythmic, non-rhythmic) and a random intercept for each subject to account for individual differences in saccadic latency responses. In a second sets of analyses conducted for both models, we examined whether trial block order (i.e., RH-ST-NRH-NRH-ST-RH or NRH-ST-RH-RH-ST-NRH) and the interaction between S1 type and trial block order significantly improved the model fits. No significant improvement in goodness-of-fit was observed for any of the models (all $ps > 0.07$), suggesting that trial block order did not account for additional variance in the data; this led to data being collapsed across this factor. To assess the robustness of the original models, we removed overly influential outliers using model criticism (3 SD of standardized residuals). This procedure resulted in the exclusion of 1.11 % of the data points for the analysis of valid trials and no data points for the analysis of saccadic latencies.

2.2. Results

The mean number and percentage of valid trials, along with the mean saccade latency exhibited by newborns in the static, rhythmic, and non-rhythmic S1 conditions are presented in Table 1.

2.2.1. N of valid trials

The linear mixed-effects model applied to the number of valid trials failed to reveal any significant differences between the static, rhythmic, and non-rhythmic conditions, $p > .9$.

2.2.2. Saccadic latencies

The linear mixed-effects model applied to the latency of saccadic eye movements towards S2 did not detect any main effects or interactions, all $ps > 0.06$ (Fig. 2).

2.3. Interim discussion

The aim of Experiment 1 was to investigate whether manipulating the temporal structure of the central stimulus (S1) influenced the efficiency of attentional disengagement in newborns, as measured by the number of valid trials and saccadic latency to fixate on to the peripheral target (S2) in an overlap task. No significant differences were detected between the three conditions.

While null results pose interpretative challenges, the lack of significant differences between the three conditions fails to provide empirical support for the notion that rhythm enhances the allocation of visuospatial attention in newborns. It is crucial to emphasise that this outcome does not necessarily imply that newborns failed to differentiate between the three fixation stimuli. Rather, it suggests that the temporal pattern embedded in the central stimulus did not exert a discernible influence on visual orienting mechanisms. Notably, this observation aligns with previous findings demonstrating that attentional disengagement is not differentially modulated by stimuli that newborns readily discriminate and even preferentially attend to. For instance, notwithstanding newborns' well-established preference for upright over inverted faces (e.g., Valenza et al., 1996), Valenza et al. (2015, Study 1b) failed to detect differences in newborns' saccadic latencies to orient towards upright versus inverted moving faces as a function of the orientation of the central fixation face. The authors ascribed this outcome to the overshadowing effect of motion on newborns' attention. Similarly, in the current study, it is possible that the high salience of the flickering stimuli could have masked any potential influence of rhythm, rendering it equally difficult for newborns to disengage attention from S1 in the two dynamic conditions.

This interpretation is not at odds with the lack of significant differences between the dynamic (rhythmic and non-rhythmic) conditions

Table 1
Mean (SD) number and percentage of valid trials and mean (SD) saccadic latency (ms) for each S1 type condition exhibited by newborns (Experiment 1) and 2-month-old infants (Experiment 2).

Experiment	Measure	Overlap task				Gap task			
		Static	Rhythmic	Non-rhythmic	Total	Static	Rhythmic	Non-rhythmic	Total
1. Newborns	N. valid trials	2.83 (0.2)	2.84 (0.2)	2.77 (0.2)	7.3 (2.7)				
	% valid trials	47.2 %	47.3 %	46.2 %	40.5 %				
	Sac. latency	1705 (181)	1702 (194)	2347 (192)					
2. 2-month-olds	N. valid trials	2.80 (0.1)	2.70 (0.1)	2.77 (0.1)	8.26 (1.1)	2.83 (0.2)	2.75 (0.2)	3 (0.2)	8.58 (2.3)
	% valid trials	70 %	67.5 %	69.3 %	69 %	71.75 %	68.75 %	75 %	71.5 %
	Sac. latency	712 (52.4)	754 (53)	1021 (54.2)		509 (75.9)	558 (74.5)	499 (76.8)	

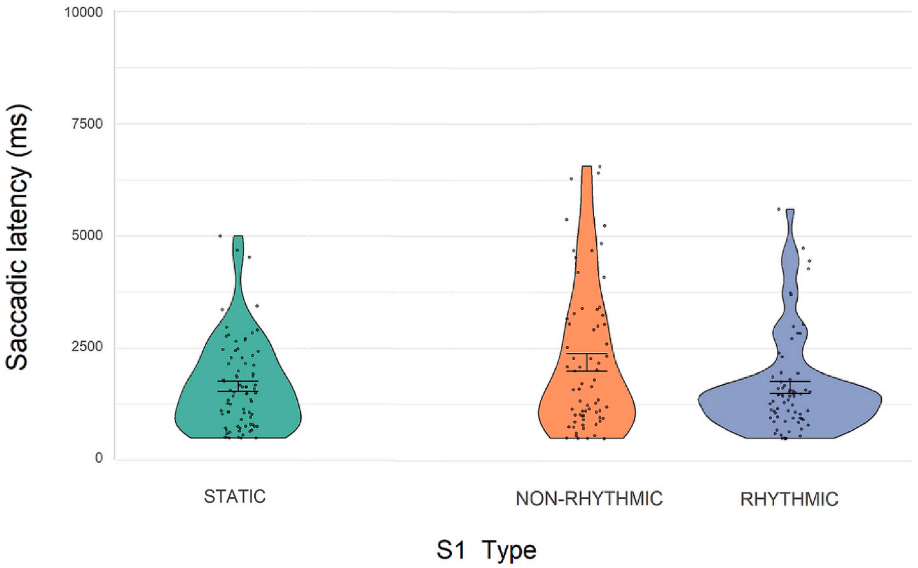

Fig. 2. Newborns' saccadic latencies to orient to S2 (i.e. the time elapsed between the appearance of S2 and the moment when the infant initiated a saccade towards it) in the three S1 conditions - i.e. when S1 remained static, flickered non-rhythmically or flickered rhythmically - of Experiment 1.

and static condition: the salience of the flickering stimuli may indeed have slowed attentional disengagement from S1 in both the rhythm and non-rhythm conditions, but the low salience of S2 in the static condition may have as well led to slow attentional disengagement from the static S1, resulting in the lack of latency differences between the dynamic and static S1 conditions.

The mean number of valid trials and mean saccade latencies observed in our study align with those reported in the only two prior studies that employed the overlap paradigm to assess attentional disengagement in newborns utilising face-like stimuli (Farroni et al., 1999; Valenza et al., 2015). In those studies, mean saccade latencies ranged from 1038 ms (Farroni et al., 1999) to 3500 ms (Valenza et al., 2015), and the average number of valid trials ranged from 6.6 (Farroni et al., 1999) to 9 (Valenza et al., 2015). These values are not dissimilar to those reported in Table 1. This consistency supports the suitability of our stimuli and procedure for examining attentional disengagement in newborns and extends the suitability of the overlap task for assessing visual attentional disengagement even when stimuli lack social cues.

In the light of the evidence that at 2 months infants synchronise their visual behaviour with the rhythm of auditory environmental stimulation (Lense et al., 2022), we hypothesised that similar effects might occur with visual rhythmic stimulation, and that attentional disengagement could be affected by the temporal pattern with which the visual S1 is provided. To test this hypothesis, in Experiment 2 we tested whether the effect of rhythm on attentional disengagement occurred at 2 months. To this end, we administered the same exact overlap task used in Experiment 1 to a group of 2-month-old infants, followed by a gap task in which the central fixation stimulus disappeared from the screen before the appearance of the peripheral stimulus. The gap condition served as a control to check that attentional disengagement was indeed at play in the overlap task, as it would be indexed by overall shorter saccadic latencies in the gap condition compared to the overlap condition (i.e. gap effect). Additionally, the absence of differences between S1 type conditions in gap trials would indicate that the S1 manipulation specifically affected the disengagement process.

3. Experiment 2 (2-month-olds)

3.1. Methods

The methods were the same as in Experiment 1 except as follows.

3.1.1. Participants

Thirty healthy 2-month-old infants (17 girls; mean age: 77.8 days, range: 61–96 days) composed the study sample. All participants were born full-term and had no known visual impairments or developmental abnormalities. They all came from middle-class families. Seventeen additional infants were tested but excluded from the final sample due to technical issues ($N = 1$), fussiness ($N = 4$) or the absence of at least 2 valid trials across 2 conditions ($N = 12$). Sample size was determined following the same approach employed in Experiment 1. Recruitment occurred through written invitations sent to the infants' parents. The study protocol adhered to the ethical guidelines of the Declaration of Helsinki and received approval from the relevant Ethics Committee (Comitato Etico Milano Area 2; ID: 964; Approval N. 952_2021). Informed written consent was obtained from parents prior to their infant's participation in the experimental session.

3.1.2. Stimuli

Stimuli were identical to those used in Experiment 1. When viewed from a distance of approximately 50 cm, each shape subtended 8° (7 cm) x 8° (7 cm) in visual angle, and the distance between the nearest edges of the peripheral stimuli and the central stimulus was approximately 13.68° (12 cm) in visual angle. As in Experiment 1, the central stimulus (S1) could remain stationary (static condition), flicker according to a 500 ms on-400 ms off temporal pattern (rhythmic condition), or flicker in an unpredictable manner (non-rhythmic condition). Once present, the peripheral stimulus (S2) remained stationary on the screen (Fig. 1).

3.1.3. Apparatus and procedure

Each infant was seated on their parent's lap, positioned approximately 50 cm from the screen (24″, 1920 × 1200-pixel resolution). To minimise visual distraction, the room was dimly lit, and black panels were positioned around the display. Parents were instructed to refrain from interacting with their infant unless they exhibited signs of discomfort. Participants underwent a total of 24 trials, divided in six blocks of four trials each, with the blocks organised based on the task condition (overlap or gap) and the S1 type (static, rhythmic, or non-rhythmic). The trial structure mirrored that of Experiment 1: S2 randomly appeared on either the left or right side of the screen after the infant maintained their gaze on S1 for a continuous 3.6 s. For the rhythmic and non-rhythmic conditions, S2's appearance was synchronised with that of S1, and remained on the screen until the infant shifted their gaze or 10 s had elapsed. In overlap trials, S1 remained visible when S2 appeared, while in gap trials S1 disappeared 400 ms before the onset of S2. The trials blocks were presented in either of two possible orders: overlap rhythmic, overlap static, overlap non-rhythmic, gap non-rhythmic,gap static, gap rhythmic, or overlap non-rhythmic, overlap static, overlap rhythmic, gap rhythmic, gap static, gap non-rhythmic. Trial presentation continued until the infant became fussy or inattentive.

3.1.4. Data reduction and analysis

Similar to Experiment 1, infants' looking behaviour was coded offline by two independent coders, and the average of their measurements was used for the analyses on saccadic latencies. Discrepancies between coders exceeding 40 milliseconds (8 % of all trials) resulted in re-coding the video. If agreement could not be reached, the trial was excluded (1.4 % of all trials). To be considered valid and included in the analyses, a trial had to meet the following criteria (see Valenza et al., 2015): (1) the infant maintained continuous fixation on S1 for 2,7 s (i.e. three repetitions of the rhythmic temporal pattern); (2) the infant fixated on S1 for at least 500 ms before S2 appeared; (3) the infant shifted their gaze towards S2 between 200 and 5000 ms after S2's appearance; and (4) the gaze shift directly targeted S2 without lingering in other directions. Participants were included in the analyses if they contributed at least two valid trials in all overlap S1 type conditions. Twelve infants also contributed at least two valid trials in all three gap S1 type conditions, and their data were included in the analyses.

Statistical analyses were conducted using the same approach as in Experiment 1, with the addition of task condition (overlap, gap) and the interaction between S1 type (static, rhythmic, non-rhythmic) and task condition as predictors in linear mixed-effects models for both the number of valid trials (i.e., the number of trials on which participants successfully oriented towards S2) and log-transformed saccadic latency to orient to S2. Similar to Experiment 1, trial block order and its interactions with the other two factors were included in a second set of analyses for both models, and goodness-of-fit improvements were evaluated. No significant improvements in model fit were observed for any of the models (all *ps* > 0.62), leading to the exclusion of this factor from the model. The model criticism procedure, which removed influential outliers deviating from the group standardized residuals by more than 3 SD, resulted in the exclusion of 0.85 % of the trials for the saccadic latencies analysis and no data points for the analysis on the number valid trials.

3.2. Results

Table 1 summarises the mean number and percentage of valid trials, along with the mean saccade latency, observed for infants in the static, rhythmic, and non-rhythmic S1 conditions.

3.2.1. N of valid trials

The linear mixed-effects model applied to the number of valid trials failed to detect any significant differences between the S1 type conditions, $p > .89$, or any other significant effects, *ps* > 0.51.

3.2.2. Saccadic latencies

The linear mixed-effects model on saccadic latencies to orient to S2 revealed a significant main effect of task condition, $F(1,341.66) = 49.65$, $p < .001$, indicating that infants exhibited faster disengagement of fixation in gap trials ($M = 522$ ms, $SE = 55.5$) compared to overlap trials ($M = 829$ ms, $SE = 41.1$). The model also revealed a main effect of S1 type, $F(2,311.14) = 5.94$, $p = .003$, which was qualified by a significant S1 type x Task condition interaction, $F(2,311.33) = 8.65$, $p < .001$. Infants showed longer saccade latencies when S1 flickered randomly ($M = 1021$ ms, $SE = 54.2$) compared to when it flickered rhythmically ($M = 754$ ms, $SE = 53.0$), $t(316) = 5.41$, $p < .001$, or remained static ($M = 712$ ms, $SE = 52.4$), $t(315) = 6.37$, $p < .001$, in overlap trials, but not in gap trials, *ps* $= 1$ (Fig. 3).

3.2.3. Comparisons between the two studies

A combined analysis of the findings from Experiments 1 and 2 unveil a developmental trajectory where the impact of rhythmicity on attentional disengagement becomes evident exclusively at 2 months of age, not before. To directly compare the results between the two age groups, a linear mixed-effects model was conducted on saccadic latencies during overlap trials, with S1 type, participants' age and their interaction as predictors, as well as a by-subject random intercept. A second analysis that included Trial block order and its interaction with the other factors as fixed predictors failed to demonstrate significant improvements in model fit ($p = .1$). As a result, the original model was retained. After removing relevant outliers (0.21 % of the trials) through model criticism, the results revealed a main effect of participants' age, $F(1,59.46) = 71.89$, $p < .001$, as well a significant interaction between participants' age and S1 type, $F(2,422.44) = 3.14$, $p = .044$. These findings corroborate the existence of age-related differences in the effects of rhythm on saccadic latency. Two-month-old infants were faster than newborns in disengaging fixation under all S1 type conditions, (*ps* < 0.001). Additionally, their saccadic latencies were slower in the non-rhythmic S1 condition ($M = 1154$ ms, $SE = 105$) compared to both the rhythmic ($M = 751$ ms, $SE = 104$), $t(410) = 4.97$, $p < .001$, and static ($M = 716$ ms, $SE = 103$), $t(410) = 5.70$, $p < .001$, S1 conditions, while none of these differences were statistically significant for the newborns (all *ps* > 0.1).

3.3. Interim discussion

Overall, the results of Experiment 2 revealed that, unlike newborns, 2-month-old infants exhibited faster saccadic latencies to orient towards a peripheral stimulus when the central stimulus was either static or presented dynamically in a rhythmic-predictable pattern compared to the random-unpredictable condition.

Notably, this difference in disengagement time was observed exclusively during overlap trials, not in gap trials. Unfortunately, the comparison between overlap and gap trials was uneven, as only 12 infants out of the 30 included in the sample contributed at least two valid trials in all S1 type conditions on both gap and overlap trials. Although results should be approached with caution, as the analysis may lack sufficient power, they suggest that the temporal characteristics of the central stimulus specifically influenced the disengagement process, which was

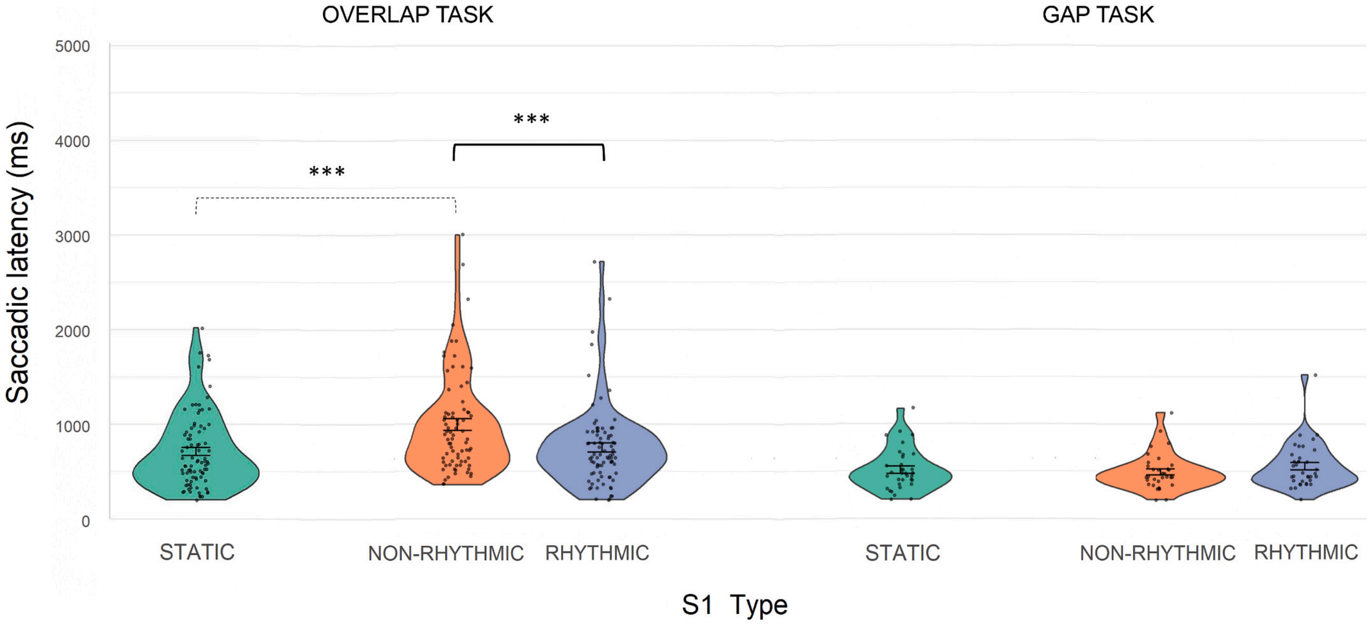

Fig. 3. Two-month-old infants' saccadic latencies to orient to S2 (i.e. the time elapsed between the appearance of S2 and the moment when the infant initiated a saccade towards it) in the Rhythmic, Static and Non-Rhythmic trials of the Overlap and Gap tasks of Experiment 2. *** $p < .001$.

facilitated by the disappearance of S1 in gap trials and occurred prior to the onset of S2. Moreover, consistent with what is typically observed in gap-overlap tasks, infants' saccadic latencies to orient towards S2 were generally faster on gap trials compared to overlap trials, resulting in a gap effect of varying magnitudes ranging from 198 ms to 774 ms ($M =$ 390 ms), comparable to findings from earlier studies involving infants aged 0–2.5 months (e.g., Farroni et al., 1999; Hood & Atkinson, 1993; Matsuzawa & Shimojo, 1997).

In relation to our primary research question, infants shifted their gaze faster away from S1 when it was rhythmic or static, compared to when it was flickering non-rhythmically. The finding that rhythmic overlap trials yielded shorter saccadic latencies than non-rhythmic ones aligns with the DAT's (Jones & Boltz, 1989) prediction that rhythm plays a facilitative role in the dynamic allocation of visual attention. According to this prediction, rhythmically induced temporal expectations establish a template for the dynamic orientation of attention over time. In the current task, the rhythmicity of S1 created a state of heightened alertness at each expected time, making infants more receptive to the peripheral stimulus appearing on phase with the encoded rhythm. In contrast, the absence of a predictable temporal pattern in the non-rhythmic S1 condition prevented infants from aligning their attention with the stimulus, resulting in slower disengagement at the onset of the time-locked peripheral stimulus.

To further support this interpretation, future studies shall explore whether faster orienting towards the on-phase target in the rhythmic condition is accompanied by slower orienting responses to targets appearing out of phase - right before or after the onset of S1. A similar effect was reported in Miller et al. (2013), where participants were slower in detecting a target when it was presented out of phase with an auditory rhythm compared to when it was on phase, while this same effect did not occur when the auditory stimulus was non-rhythmic. Whether this same effect would generalise to infants as well remains a question for future investigation as in the present study S2 always appeared on-phase with S1.

Although the observed results appear to confirm our hypothesis that rhythm enhances infants' focusing of attention to the relevant time-points, other factors related to stimulus saliency might have also played a role. For example, the unfamiliar nature of the non-rhythmic S1, relative to the prevalent rhythmic patterns in infants' perinatal environment (see review by Provasi et al., 2014), might have contributed to the observed delay in saccadic latencies. This might have stemmed from infants' difficulty disengaging their attention from a stimulus perceived as cognitive demanding due to its novelty and complexity. This hypothesis would fit with previous studies using the overlap paradigm, which have shown that saccadic latencies to peripheral targets in 3–4-month-old infants are influenced by the processing load imposed by fixation stimuli, particularly their saliency, complexity, or familiarity (e.g., Blaga & Colombo, 2006; Finlay & Ivinskis, 1984; Russo et al., 2021; Valenza et al., 2015).

The finding that infants' saccadic latencies on non-rhythmic trials were slower not only compared to the rhythmic trials but also to the static ones would also fit with the hypothesis that stimulus saliency may have played a role in the saccadic latency delay observed in Experiment 2. Although the comparison between the static and dynamic conditions is not fully fair due to the differences in the relative salience of S1 and S2, this finding further suggests that the processing of the non-rhythmic stimulus might be more cognitive demanding.

To further elucidate the mechanism driving the observed patterns of disengagement latencies in 2-month-old infants, we explored the relative capacity of the stimuli used in Experiment 2 to capture and maintain attention through a third experiment employing a pairwise visual preference task with a separate cohort of 2-month-old infants. The visual preference task allows testing for preferential looking behaviour induced by specific stimulus characteristics by measuring the duration of looking times allocated to each stimulus in a pair (Fantz, 1961). In Experiment 3, we examined infants' looking time preference for the rhythmic and non-rhythmic temporal patterns of the stimuli, as well as for the static stimulus, by presenting them simultaneously and bilaterally on the screen.

4. Experiment 3 (2-month-olds)

A new group of 2-month-old infants was tested in a visual preference task where, over six trials, the three stimulus types used in Experiments 1 and 2 were presented in three pair comparisons (non-rhythmic vs. rhythmic; rhythmic vs. static; non-rhythmic vs. static) bilaterally on the screen. If infants fixated longer on the non-rhythmic stimulus compared to the rhythmic and the static ones, this would indicate that the higher saliency of this stimulus was a driving factor in the latency delay observed in Experiment 2. On the other hand, the absence of differences in looking times between the non-rhythmic stimuli and the rhythmic and static would strengthen the hypothesis that infants as young as 2 months incorporate temporal regularities into their spatial allocation of visual attention.

4.1. Methods

4.1.1. Participants

Participants were 30 healthy and full-term 2-month-old infants (18 females, mean age = 84.13 days, range = 68–104). They all came from middle-class families. Eight additional infants were tested but excluded from the final sample due to fussiness. Not all infants contributed to all the comparisons, resulting in varying sample sizes across analyses (rhythmic versus non-rhythmic: $N = 25$; rhythmic versus static: $N = 30$; non-rhythmic versus static: $N = 24$). During the trial session, parents were instructed to refrain from interacting with their infants unless the baby exhibited signs of discomfort. The protocol adhered to the ethical standards of the Declaration of Helsinki and received approval from the relevant Ethics Committee (Comitato Etico Milano Area 2; ID: 964; Approval N. 952_2021). Parents gave informed written consent prior to their infant participation in the study.

4.1.2. Stimuli

The same *E*-Prime 2.0 generated white full circle used in Experiments 1 and 2 served as stimulus. The circle was displayed bilaterally against a black background. When viewed at a distance of about 50 cm, it subtended approximately 12° of visual angle. As in Experiment 1 and 2, the circle could either remain stationary (static), flicker at a consistent 500 ms on-400 ms off temporal pattern (rhythmic), or flicker without any discernible pattern (non-rhythmic). The three types of stimuli were paired to create three pairs: rhythmic vs. non-rhythmic, rhythmic vs. static, and non-rhythmic vs. static. These stimulus pairs were presented bilaterally on the screen at a distance of 30°.

4.1.3. Apparatus and procedure

Infants were tested in a preferential looking task with a fixed presentation procedure using the same apparatus as in Experiment 2. Each trial began when the infant fixated on a red flickering dot appearing in the centre of the screen. This automatically deactivated the central dot and initiated the presentation of the stimuli, which were displayed bilaterally on the screen for 8 s. All infants underwent 6 trials, two for each stimulus pair, with the left-right position of the stimuli counterbalanced across trials and the initial stimuli position counterbalanced across participants. Stimulus pairs were presented in three possible orders: (1) rhythmic vs. non-rhythmic, non-rhythmic vs. static, rhythmic vs. static, (2) rhythmic vs. static, rhythmic vs. non-rhythmic, non-rhythmic vs. static, (3) non-rhythmic vs. static, rhythmic vs. non-rhythmic, rhythmic vs. static. Total looking times on each stimulus within the pair across the two presentations of each pair served as the dependent variables.

4.1.4. Data reduction and analysis

All testing sessions were video recorded. Two observers blind to the research question coded video recordings of the trials at a frame-by-frame resolution of 40 ms. Each observer recorded the total looking times for each stimulus in each pair across both trial presentations. The Pearson correlation between the two observers' measurements yielded a strong correlation of $r = 0.93$ ($p < .001$). The average of the two measurements was calculated and log transformed (see Csibra et al., 2016) before being entered into the statistical analyses. Because not all the infants provided consistent data for all stimulus pairs, separate analyses were conducted for each pair. Participants were included only if they met the following criteria: (1) they exhibited no consistent show a position bias, defined as looking more than 90 % of the time to either stimulus in either trial presentation of the pair; (2) they looked at least once at both stimuli continuously for 1 s within at least one of the two pair presentations. This allowed participants to be included in the analysis for each stimulus pair even if they only contributed one single trial, as long as they fixated on both stimuli for at least 1 s.

To assess the saliency of each of the three stimuli compared to the others, three separate mixed models were performed, one for each stimulus pair (rhythmic vs. non-rhythmic, static vs. non-rhythmic, rhythmic vs. static). Log-transformed looking times on each stimulus in the pair served as the dependent variable. The independent variables were stimulus type and pair order. The interaction between stimulus type pair and pair order was also included in the models, and a by-subject intercept served as the random factor. The model criticism procedure was applied to identity and remove potential outliers, but none were found for any of the three models considered.

4.2. Results and discussion

Twenty-five infants contributed to the analysis on log-transformed looking times on rhythmic versus non-rhythmic trials. Results revealed a significant main effect of pair order, $F(2,24.1) = 10.09$, $p < .001$. Post-hoc comparisons using Bonferroni corrections indicated that infants exhibited overall shorter looking times when tested with pair order 3 (M = 1419 ms, SE = 267) compared to the pair orders 1 (M = 2615 ms, SE = 229), $t(23.2) = 4.03$, $p = .002$, and 2 (M = 2556 ms, SE = 205), $t(23.7) = 3.967$, $p = .002$. Additionally, a significant Pair order x Stimulus type interaction, $F(2,45.45) = 4.95$, $p = .011$, also emerged. However, this interaction was deemed spurious after conducting Bonferroni-corrected post-hoc comparisons, which revealed no significant differences between stimulus types across different pair orders (all *ps* > 0.08). The main effect of stimulus type was not statistically significant, $p > .76$ (Fig. 4).

The analysis on log-transformed looking times on rhythmic versus static trials was conducted on a subsample of 30 infants. There was again a significant main effect of pair order $F(2,58) = 6.029$, $p = .004$, and post-hoc comparisons (Bonferroni corrected) showing that infants exhibited shorter overall looking times during Pair order 3 (M = 1518 ms, SE = 310) compared to both pair order 1 (M = 2660 ms, SE = 280), $t(20.7) = 3.093$, $p = .017$, and pair order 2 (M = 2666 ms, SE = 238), $t(18.5) = 3.000$, $p = .023$. Neither the main effect nor the interaction involving the stimulus type factor were found to be statistically significant, *ps* > 0.43 (Fig. 4).

The analysis on log-transformed looking times on non-rhythmic versus static trials included a subsample of 24 infants. A significant main effect of pair order, $F(2,62) = 5.67$, $p = .005$, was observed. Post-hoc comparisons (Bonferroni corrected) showed that infants' overall looking times for pair order 3 (M = 1675 ms, SE = 293) were significantly shorter than those for pair order 1 (M = 2812 ms, SE = 239), $t(22) = 3.226$, $p = .01$, and marginally shorter than to those for pair order 2 (M = 2517 ms, SE = 220), $t(17.1) = 2.613$, $p = .054$. The model failed to detect any significant effect involving the factor stimulus type, *ps* > 0.15 (Fig. 4).

Overall, results indicate that the rhythmic, non-rhythmic, and static stimuli employed in the gap-overlap task of Experiment 2 exhibit equivalent capacity to capture and maintain the visual attention of 2-month-old infants, at least when presented within the framework of a forced-choice paradigm. The lack of preference for dynamic (rhythmic and non-rhythmic stimuli) stimuli compared to the static stimulus may seem to contradict prior demonstrations that 2-month-old infants exhibit a visual preference for flickering over static stimuli (e.g. Hartmann & Banks, 1992; Regal, 1981). However, it is crucial to note that these previous studies employed counterphase-flickering squarewave or sinusoidal gratings of varying contrast intensities in conjunction with a static uniform field, unlike the stimuli employed in the present study. Instead, the absence of a preference for the non-rhythmic over the rhythmic stimulus in Experiment 3 indicates that stimulus saliency or

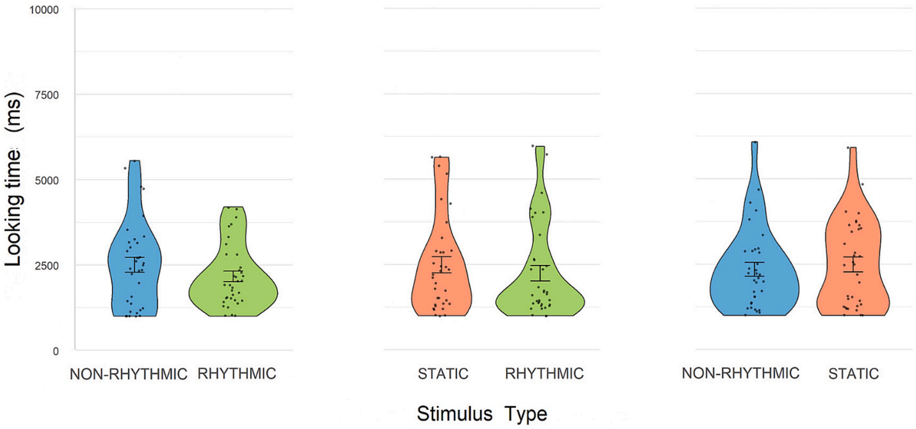

Fig. 4. Total looking times on each stimulus across both trial presentations of each stimulus pair in Experiment 3.

complexity cannot fully account for the differences in attentional disengagement observed in Experiment 2.

5. General discussion

The present studies investigated the impact of rhythm on visuospatial attentional disengagement in infants at birth and at 2 months of age. The primary findings from Experiments 1 and 2 revealed that, under comparable testing conditions, 2-month-old infants, but not newborns, exhibited faster saccadic latencies to disengage from a central fixation stimulus (S1) when it was static and rhythmic, compared to when it was non-rhythmic. These findings point to the importance of the temporal structure of dynamic stimuli as a specific feature that modulates attentional disengagement at 2 months of age.

In particular, the absence of a visual preference for the non-rhythmic stimulus over the rhythmic and static stimuli in Experiment 3 suggests that the differences in saccadic latencies observed across conditions in Experiment 2 likely cannot be attributed to stimulus saliency. Research has shown that in adults, the latency of saccadic eye movements to shift visual attention from a stimulus to another is significantly shorter when the peripheral target appears in synchrony with a rhythmic and predictable auditory beat compared to a random and unpredictable beat (Miller et al., 2013). The current findings extend this evidence to the visual domain, showing that from the earliest stages of postnatal development infants can leverage visual rhythm to enhance the efficiency of their visuospatial attention. These results also align with the recent evidence showing that, at 2 months, audiovisual rhythmic stimulation entrains infants' looking behaviour in social context (Lense et al., 2022).

One aspect of the current findings that appears at odds with the attention alignment interpretation of the observed effects concerns the lack of difference between the static and rhythmic conditions. As already noted, the two conditions differ in the relative salience of S1 and S2, which makes a direct comparison unfair. Nonetheless, one could claim that, if rhythm facilitated the allocation of attention at relevant timepoints, we would have observed shorter saccadic latency on rhythmic trials not only compared to the non-rhythmic trials but also to the static ones. One possible reason why this was not the case is that the static and rhythmic conditions provided a similar (high) level of predictability of the central stimulus, whose processing may have thus been similarly demanding. This may have facilitated attention shift to peripheral S2 in a comparable way. However, if this was the case, we would have observed longer looking times towards the non-rhythmic stimulus in the visual preference task of Experiment 3, as an effect of its higher entropy and lower predictability, which however was not the case. Future studies manipulating the temporal synchrony between the central and the peripheral stimuli are needed to further elucidate the role of attention alignment as primary source of the observed latency effects.

A further notable finding is the presence of a developmental pattern in the impact of rhythm on saccadic latencies, as the effect was evident in older infants (Experiment 2) and not in newborns (Experiment 1). Both maturational and experiential factors may be responsible for this trend. As discussed earlier, newborns' heightened sensitivity to flickering stimuli, which is known to decrease over time (Valenza et al., 2015), could have obscured any potential influence of rhythm during disengagement. Maturational changes in the brain's ability to generate resonant responses to the frequency of an external periodic stimulus – i.e., stimulus tracking or entrainment (Bánki et al., 2022) -, may have also contributed to the observed findings. For instance, isochronous visual stimuli elicit an evoked brain response synchronised to the stimuli frequency in the newborns' brain (e.g., Buiatti et al., 2019), the highest frequency of flickering light eliciting such a response increases rapidly between 1 and 3 months, reaching adult-like levels around 9 months (Apkarian, 1993). It has also been claimed that while neural synchronisation in newborns reflects a simple brain-evoked response to regular pulse stimuli (so called dumb entrainment), more complex forms of neural synchronisation, involving anticipation or prediction (so-called smart entrainment), would emerge later in development (Wass et al., 2022). Similar to previous behavioural studies in adults demonstrating the enhancing effect of rhythm on attention and perception (e.g., Elbaz & Yeshurun, 2020), the present study exposed infants to a limited number of repeated rhythmic patterns (range 4–10), likely insufficient to elicit any form of neural synchronisation. Therefore, the contribution of maturational changes in neural synchronisation to the observed developmental pattern remains to be explored.

Our findings also raise the intriguing possibility that the rich multisensory exposure to rhythmic cues that accompanies social interactions in the early postnatal environment may play a critical role in the emergence of the ability to leverage rhythm to efficiently allocate visuospatial attention. Rhythmicity is at the centre of parental practices. Specifically, infants' environmental exposure during the first two months of life primarily revolves around dyadic interactions, which provide a wealth of rhythmic multisensory stimulation through infant-directed speech, singing, playsongs and lullabies. These forms of auditory stimulation are distinguished by their enhanced temporal regularities (e.g., Nakata & Trehub, 2011), to which the infants' brain and looking behaviour easily entrains (Lense et al., 2022; Nguyen et al., 2023), but rhythmic multisensory stimulation also comes from turn-taking during lactation or parental practices to soothe the baby trough rocking and patting (e.g., Gratier et al., 2015). This rich early exposure to rhythmic cues could make infants increasingly sensitive to rhythm and increase their reliance on rhythmic information for a more efficient attentional deployment. This hypothesis could be further explored in future investigations that manipulate the amount of prenatal and or postnatal rhythmic experience through stimulation interventions and enrichment protocols, observing the effects on infants' capacity to utilise temporal regularities for attentional allocation.

The results of the present study point to the importance of the temporal structure of dynamic stimuli as a specific feature that modulates attentional disengagement at 2 months of age. The ability to effectively disengage visual attention from a fixation point is a crucial skill for navigating the external environment and engaging with new stimuli. Numerous studies have emphasised the significance of this attentional mechanism for a diverse range of capacities, including early state regulation (Rothbart et al., 2011), distress mitigation (McConnell & Bryson, 2005), and spoken word recognition (Venker, 2017). Extended saccadic latencies have been observed in infants at risk for autism spectrum disorder, a finding that may be linked to the self-regulatory and language impairments exhibited by these children (Elsabbagh et al., 2013; Venker, 2017). Consequently, examining strategies to foster the development of efficient attentional disengagement from an early age is of paramount importance. The present studies provide valuable insights in this regard, offering the first evidence that temporal regularities can positively impact visuo-attentional disengagement in the early postnatal period, and paving the way for the identification of early intervention training programs aimed at scaffolding this essential attentional skill.

CRediT authorship contribution statement

Martina Arioli: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Project administration, Writing – original draft. **Valentina Silvestri:** Investigation. **Maria Lorella Giannì:** Resources. **Lorenzo Colombo:** Resources, Supervision. **Viola Macchi Cassia:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – original draft.

Declaration of competing interest

None.

Acknowledgments

This work was supported by a PhD Scholarship from the Ministero dell'Università e della Ricerca (MUR) to the first author, and a grant from the Ministero dell'Università e della Ricerca-NextGenerationEU (PNRR M4.C2.I1.1- Avviso 104/2022, CUP H53D23004090006) to Viola Macchi Cassia. We would like to thank all the families that took part in the studies. Moreover, we are grateful to Carlo Toneatto for helping with the experiment creation.

Data availability

The data and analytic code necessary to reproduce the analyses presented here are publicly accessible at the following URL: https://osf.io/64ktq/?view_only=f72a6ab8a81b489aa61e3d4462bbe5ad.

The materials necessary to attempt to replicate the findings presented here are not publicly accessible, but available under request to the first author. The analyses presented here were not preregistered.

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