



SHORT REPORT

The attentional ‘zoom-lens’ in 8-month-old infants

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Abstract

The spatial attention mechanisms of orienting and zooming cooperate to properly select visual information from the environment and plan eye movements accordingly. Despite the fact that orienting ability has been extensively studied in infancy, the zooming mechanism – namely, the ability to distribute the attentional resources to a small or large portion of the visual field – has never been tested before. The aim of the present study was to evaluate the attentional zooming abilities of 8-month-old infants. An eye-tracker device was employed to measure the saccadic latencies (SLs) at the onset of a visual target displayed at two eccentricities. The size of the more eccentric target was adjusted in order to counteract the effect of cortical magnification. Before the target display, attentional resources were automatically focused (zoom-in) or spread out (zoom-out) by using a small or large cue, respectively. Two different cue–target intervals were also employed to measure the time course of this attentional mechanism. The results showed that infants’ SLs varied as a function of the cue size. Moreover, a clear time course emerged, demonstrating that infants can rapidly adjust the attentional focus size during a pre-saccadic temporal window. These findings could serve as an early marker for neurodevelopmental disorders associated with attentional zooming dysfunction such as autism and dyslexia.

Research highlights

- The orienting and zooming of spatial attention cooperate to properly select visual information and plan eye movements.
- Despite the fact that orienting ability has been extensively studied in infancy, the zooming mechanism has never been tested before.
- We evaluated attentional zooming in 8-month-old infants with an eye-tracker device by measuring saccadic latencies (SLs) at the onset of a visual target displayed at two different eccentricities.
- Results showed that infants’ SLs varied as a function of the pre-target cue size and that infants can rapidly adjust the attentional focus size during the pre-saccadic temporal window.

Introduction

The ability to select visual information from a noisy environment is an essential skill, especially considering the limited capacity of our visual system. In infancy, this is a crucial ability in order to process information and to learn efficiently (Karmiloff-Smith, 1998; Johnson, 2011; Johnson, Posner & Rothbart, 1991). Spatial attention allows us to simultaneously highlight relevant information and inhibit irrelevant details, thus mediating the selection of the stimuli that are important to our current behavior (for a recent review, see Roelfsema, van Ooyen & Watanabe, 2010). There are two main modalities by which exogenous spatial attention can ‘covertly’ (i.e. without eye and/or head movements) select information in the visual environment. First, the focus of

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attention can be moved to a particular region in the visual space, as described by the 'spotlight' metaphor (i.e. covert attentional orienting; Posner, 1980). Second, the focus of attention can be adjusted in its size – as predicted by the 'zoom-lens' model (Castiello & Umiltà, 1990; Eriksen & St James, 1986) – in a way that attentional resources are focused in a narrow region (zoom-in) or spread out in a broader portion (zoom-out) of the visual field.

These two mechanisms, though with a certain degree of independence (Castiello & Umiltà, 1992; Fu, Caggiano, Greenwood & Parasuraman, 2005; Turatto, Benso, Facoetti, Galfano, Mascetti *et al.*, 2000), cooperate to select visual information that is relevant to our current behavior. This cooperation allows us to plan accurate eye movements and target the source of relevant information, as suggested by the premotor theory of attention (Rizzolatti, Riggio, Dascola & Umiltà, 1987). The link between covert deployment of attention and explicit ocular movement programming has been supported by neuroimaging (Beauchamp, Petit, Ellmore, Ingeholm & Haxby, 2001; Corbetta, Akbudak, Conturo, Snyder, Ollinger *et al.*, 1998; de Haan, Morgan & Rorden, 2008; Nobre, Gitelman, Dias & Mesulam, 2000; Perry & Zeki, 2000) and transcranial magnetic stimulation studies in human adults (Ro, Farnè & Chang, 2003; Ronconi, Basso, Gori & Facoetti, 2014a; Taylor, Nobre & Rushworth, 2007), thus showing that the same neural circuit responsible for eye-movement planning, involving a fronto-parietal network, is also implicated in the covert orienting and focusing of visual attention.

A wide range of studies have investigated the orienting component of visual attention in infancy (e.g. Clohessy, Posner, Rothbart & Vecera, 1991; Hood, 1993; Johnson *et al.*, 1991; Johnson & Tucker, 1996; Richards & Hunter, 1998; Ronconi, Facoetti, Bulf, Franchin, Bettoni *et al.*, 2014b; Valenza, Simion & Umiltà, 1994). It has been shown that its efficiency develops dramatically in the first year of life (Hood, 1995; Johnson *et al.*, 1991), with neural circuits responsible for the spatial orienting getting faster over the first 6 months (Johnson & Tucker, 1996; Richards, 2003, 2005). On the other hand, the ability to modulate the attentional focus size – hereafter, 'attentional zooming' – has yet to be explored in infants.

In the present study, we developed the first paradigm able to measure attentional zooming in infancy. In previous work, the efficiency of attentional zooming was evaluated in children affected by developmental dyslexia and autism spectrum disorder (Facoetti & Molteni, 2001; Ronconi, Gori, Ruffino, Franceschini, Urbani *et al.*, 2012; Ronconi, Gori, Ruffino, Molteni & Facoetti, 2013b; Mann & Walker, 2003), and the neural under-

pinnings of this process were clarified using neurophysiological, neuroimaging, and transcranial magnetic stimulation in human adults (e.g. Chen, Marshall, Weidner & Fink, 2009; Fu *et al.*, 2005; Ronconi *et al.*, 2014a). Here, the attentional zooming paradigm (Facoetti & Molteni, 2001; Facoetti, Paganoni & Lorusso, 2000) was readapted in order to fit the experimental needs required by an infant study. An eye-tracker system was employed to measure the saccadic latencies (SLs), defined as the time it took for the infants to initiate an eye movement toward a target (Colombo, 2002). SLs are the most reliable measure of covert visual attention deployment in infants employing an eye-tracker system (e.g. Gredeback, Johnson & von Hofsten, 2010; Oakes, 2012).

SLs were measured in response to a visual target appearing at two possible eccentricities, near-fixation (NF) and far-from-fixation (FF), along the horizontal axis. Attentional resources were focused or distributed by using a small or large cue, respectively, consisting of a ring that surrounded a central fixation object. In the small cue condition, the NF target appeared inside the cue, while the FF target appeared outside. In the large cue condition, both the NF and FF target appeared inside the cue.

Our prediction was that if the attentional zooming mechanism was already developed in 8-month-old infants, SLs should vary between the small and the large cue condition as a function of target eccentricity. Specifically, if infants can zoom-in their attentional focus in the small cue condition, the detection of the NF target should be accelerated relative to the large cue condition (i.e. cue-size effect; e.g. Castiello & Umiltà, 1990; Eriksen & St James, 1986; Turatto *et al.*, 2000). Furthermore, if infants can zoom-out their attentional focus in the large cue condition, the detection of the FF target should be accelerated relative to the small cue condition. To ensure a balanced perceptual saliency between eccentricities, the size of the FF target was enlarged in order to counteract the effect of the cortical magnification (Daniel & Whitteridge, 1961). To evaluate the optimal time to adjust the focus of attention at this early stage of development, we manipulated the cue-target interval (100 or 300 ms). Evidence of the time course of the attentional zooming for adults has shown that the mechanism takes between 33 and 66 ms to be initiated (Benso, Turatto, Mascetti & Umiltà, 1998). Previous data for both typically developing children and adults showed that an optimal cue-target interval to perform the attentional zooming is 100 ms, while at longer cue-target intervals (e.g. 500–800 ms), the attentional focus 'collapsed' (Benso *et al.*, 1998; Ronconi *et al.*, 2013b, 2014a).

Method

Participants

Eighteen 8-month-old infants (nine females, mean age = 250 days, $SD = 7.45$, range = 240–264) comprised the sample. Parents provided informed consent. The entire research protocol was approved by the departmental ethic committee and was conducted in accordance to the principles elucidated in the Declaration of Helsinki.

Stimuli

The stimuli were presented on a black background, using a computer screen. The attention getter was a dynamic cartoon (a colored moving clown) with a musical soundtrack. The cue was a central empty gray circle, concentrically displayed relative to the fixation point,

and with a radius of 4 deg or 12.5 deg in the small or the large cue condition, respectively.

The target was a colored smiley face that could appear at either of two eccentricities, 3 deg (NF) or 9 deg (FF) from the fixation along the horizontal axis. In the small cue condition, the NF target appeared inside the cue, while the FF target appeared outside. In the large cue condition, both the NF and FF target appeared inside the cue (Figure 1, panels A and B). Targets at the NF eccentricity measured 2×2 cm (1.9×1.9 deg), whereas targets at the FF eccentricity measured 5×5 cm (4.8×4.8 deg).

We enlarged the size of the FF targets based on the results of a pilot study where we employed targets of the same dimension across eccentricities (see Supporting Information). In the pilot study, infant participants detected FF targets systematically slower than NF ones. We removed this perceptual bias by adjusting the size of

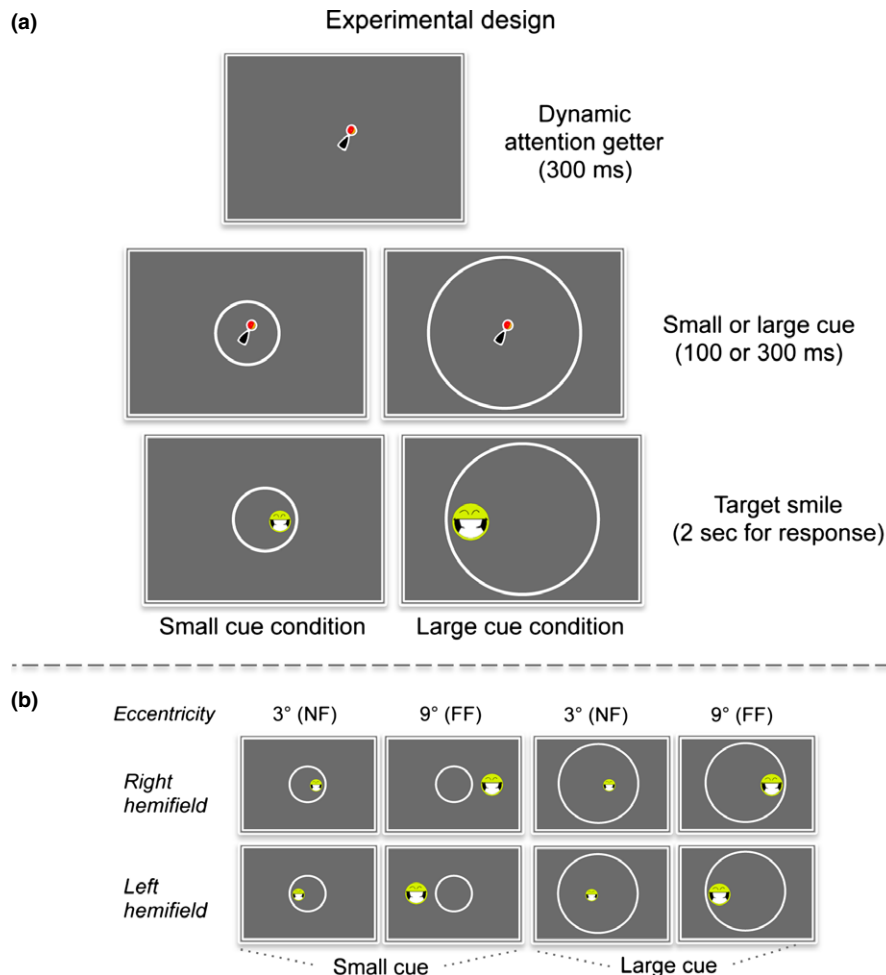


Figure 1 Schematic representation of the attentional zooming task design (panel A) and possible targets location for every combination of visual hemifield, cue size and target eccentricity (panel B). NF = near-fixation, FF = far-from-fixation.

the FF target in order to counteract the cortical magnification factor (Daniel & Whitteridge, 1961). Cortical magnification describes the number of neurons in the visual cortex that are involved in processing a stimulus of a given size and as a function of its spatial location in the visual field. In the center of the visual field, a large number of neurons process information from a small region. If the same stimulus is seen in the periphery, it would be processed by a much smaller number of neurons. Moreover, the receptive field size in the center of the primary visual cortex is much smaller than the receptive field size of the periphery (e.g. Yazdanbakhsh & Gori, 2008). Consequently, a stimulus in the peripheral visual field will be much less salient than a stimulus of the same size in the center. Therefore, the perceptual saliency of the target was balanced across eccentricities by changing the size of the target according to the procedure elucidated by Rovamo and Virsu (1979) and Virsu and Rovamo (1979).

Apparatus

The stimuli were presented with E-Prime 2.0 on a 19-inch monitor (resolution of 1024 × 768). A remote, pan-tilt infrared eye-tracking camera (Model 504, Applied Science Laboratories, Bedford, MA) using bright-pupil technology, and placed directly below the stimulus screen, recorded the participant's eye movements at a temporal resolution of 50 Hz. Four main areas of interest (AOI) that corresponded to the possible positions of the target (left and right NF targets; left and right FF targets) were selected. The AOI measured 2.5 × 2.5 cm (2.4 × 2.4 deg) at the NF eccentricity and 5.5 × 5.5 cm (5.25 × 5.25 deg) at the FF eccentricity.

Procedure

The infant sat in an infant car seat placed 60 cm away from the monitor. Parents were usually seated behind the infant seat. The calibration phase was conducted by showing participants three markers presented one by one on the top-left, centre and bottom-right of the screen. Subsequently, the experimental trials began with the presentation of the central dynamic attention getter. As soon as the participants looked at this central fixation point, the attention getter disappeared and the small or large cue was presented. After a variable interval of 100 or 300 ms from the cue presentation (Stimulus Onset Asynchrony or SOA), the target appeared randomly on the left or on the right visual hemifield, and at two different eccentricities (NF = 3 deg or FF = 9 deg). The target remained visible until the participant made a

saccade toward it or for a maximum of 2 seconds, after which the trial terminated.

A total of 48 trials (6 repetitions × 2 cue size × 2 SOA × 2 target eccentricities) were administered for each infant and randomly intermixed and arranged in two blocks so they could take a break halfway through. The entire experiment lasted about 15–20 minutes.

Trials were considered valid and were analyzed only if saccades started from the central fixation point, were directed toward the target, and reached it.

Results

A mean of 10.2 trials ($SD = 7.3$) for each infant were excluded from the analysis for the following reasons: Because infants looked outside the defined AOI (mean = 2.4 trials; $SD = 2.3$), the signal of the eye-tracker was lost during the stimuli presentation (mean = 6.4 trials; $SD = 6.5$), the saccadic latencies were lower than 100 ms (i.e. anticipations) (mean = 0.4 trials; $SD = 1.0$), or the saccadic latencies were greater than 500 ms (mean = 0.9 trials; $SD = 1.3$). The final number of trials in which infants correctly detected the target was on average 37.8 trials ($SD = 7.3$) (see Supporting Information for SLs mean and other measures collected).

SLs were analyzed using a repeated measure $2 \times 2 \times 2$ ANOVA with the following within-subjects factors: Cue size (small vs. large), SOA (100 vs. 300 ms), and Target eccentricity (NF vs. FF). The main effects were not significant. It is worth noting that the absence of a significant effect of the factor Target eccentricity demonstrated that the manipulation of FF target size was effective in balancing the perceptual saliency between eccentricities. Importantly, a significant Cue size by SOA by Target eccentricity interaction emerged ($F_{(1, 17)} = 10.62$, $p = .005$, $\eta^2_p = .38$; Figure 2). This three-way interaction was further explored with two 2×2 ANOVAs performed at each SOA. At the first SOA (100 ms), the ANOVA revealed a significant Cue size by Target eccentricity interaction ($F_{(1, 17)} = 22.49$, $p < .001$, $\eta^2_p = .57$). Planned comparison revealed that SLs at the NF eccentricity were faster when anticipated by a small rather than a large cue (mean \pm SEM SLs were 235 ± 6 vs. 249 ± 5 ; $t_{(17)} = 2.69$, $p = .008$, $\eta^2_p = .30$), while the opposite was obtained for targets appearing at the FF eccentricity, which were detected faster when anticipated by a large rather than a small cue (230 ± 5 vs. 245 ± 7 ; $t_{(17)} = -2.39$, $p = .014$, $\eta^2_p = .25$).

The ANOVA performed at the second SOA (300 ms) did not reveal any significant main effect or interaction between factors.

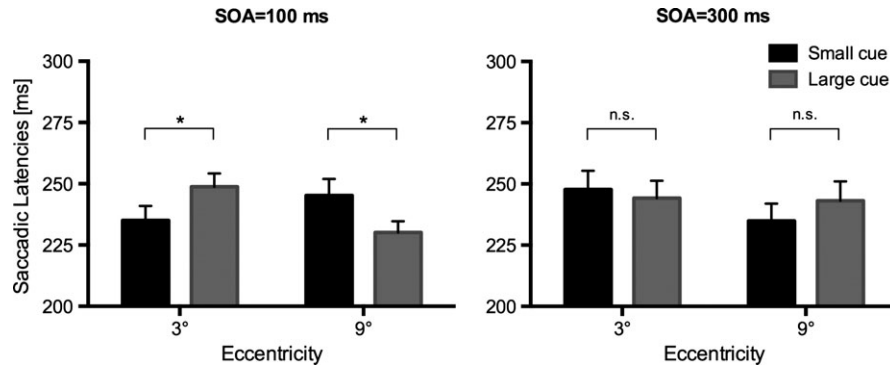


Figure 2 Mean saccadic latencies (SLs) plotted as a function of SOA, cue size and eccentricity. Error bars represent within-subjects SEM, n.s. = not significant, * $p < .05$.

Discussion

In the developed human brain, the focus of attention can be adjusted in size to process information from a narrow (zoom-in) or a broad (zoom-out) region of the visual field (Chen *et al.*, 2009; Ericksen & St James, 1986; Müller, Bartelt, Donner, Villringer & Brandt, 2003). This mechanism is fundamental for selecting relevant information from a complex visual environment. Attentional zooming ability has never been investigated in infants. Here, we demonstrated, for the first time, that 8-month-old infants were able to accurately adapt the size of their attentional focus.

Our results are in agreement with an appropriate modulation of the attentional focus size, thus demonstrating that zoom-in and zoom-out attentional mechanisms are already developed in 8-month-old infants. At the NF eccentricity, SLs were faster in the small relative to the large cue condition (i.e. the cue-size effect on NF target; Turatto *et al.*, 2000). The target at the FF eccentricity, on the other hand, was detected faster when anticipated by a large cue (i.e. the cue-size effect on FF target). Since these results were found only at the short cue–target SOA, we propose that an attentional zooming mechanism was rapidly and automatically adapted to the object size but collapsed shortly after, confirming an exogenous deployment of visual selective attention (for reviews, see Petersen & Posner, 2012; Posner & Petersen, 1990). The cue size did not affect the response at the longer SOA (300 ms), presumably because the attentional network needs to develop a mechanism that can sustain the deployment of attention in time, according to the spatial coordinates that the objects automatically trigger. These results are congruent with previous studies employing manual reaction times to investigate the attentional zooming for children and adults (Benso *et al.*, 1998; Castiello & Umiltà, 1990, 1992; Facoetti

et al., 2000; Greenwood & Parasuraman, 1999; Luo, Greenwood & Parasuraman, 2001; Müller *et al.*, 2003; Ronconi *et al.*, 2013b, 2014a; Turatto *et al.*, 2000).

As an alternative to our zoom-lens interpretation, one may argue that the pattern of data we found could be explained by different accounts. One possibility is that a double-step oculo-motor response (Aslin & Shea, 1987; Becker & Jürgens, 1979) could similarly explain the pattern of results obtained. In the typical double-step paradigm, a first visual target is displaced into a hemifield, thereby eliciting a saccade. However, before the saccade can be executed, the first target disappears and a second target is displaced. In our experiment, due to the impossibility of providing verbal instruction to the infants, one can consider the cue as the first target and our target as the second target. However, in our paradigm, the cue was not removed before the target onset but lasted until the end of the trial, which is not optimal for the double-step paradigm. Moreover, what would be expected, based on the double-step interpretation, is that a saccade will be programmed to reach the cue on the horizontal axis. Indeed, the location of the target can only be left or right on the horizontal axis. The target will be in one of the two possible locations 50% of the time. Consequently, if the double-step interpretation is correct, the observer would plan the saccade on the right or on the left of the cue, but only 50% of the time would the target appear in the same location. Since the cue appeared 100–300 ms before the target, there is time to trigger only one saccade. As reported in the literature, when the first and second targets appear in opposite locations, the integration of these two positions delays the execution of the initial saccade by about 200 ms (Becker & Jürgens, 1979). Consequently, based on the double-step interpretation, a bimodal distribution of our single-trial SLs should be found. On the contrary, as it can be seen in Figure 3, this distribution is clearly

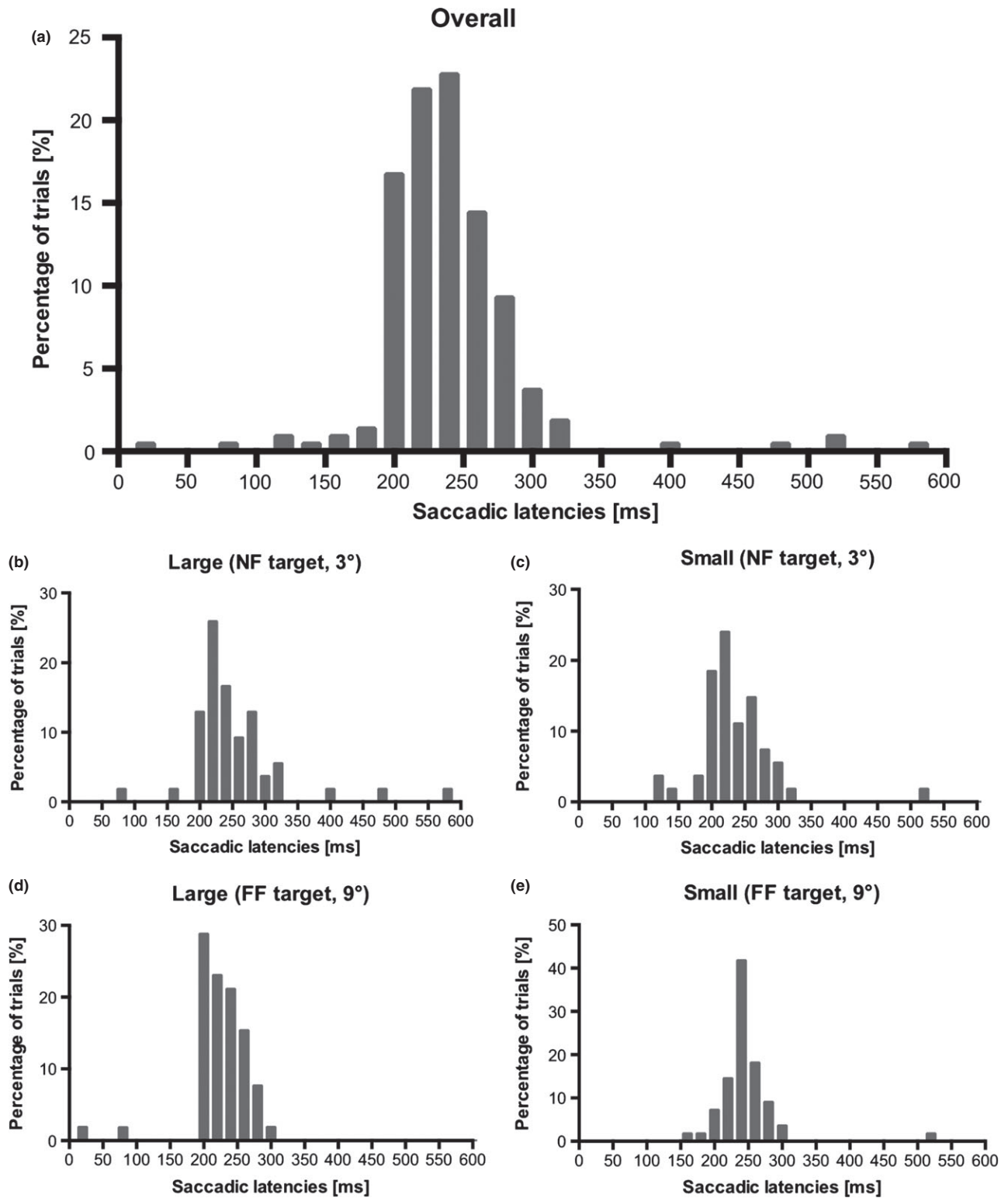


Figure 3 Frequency distribution plot of single trials saccadic latencies (SLs) at the first cue–target interval (SOA = 100 ms). The plot shows the percentage of trials in each of the 20-ms bins of SLs (range 0–600 ms) for the overall trials (panel A), for the large cue trials with NF (near-fixation, 3 deg) target (panel B), for the small cue trials with NF target (panel C), for the large cue trials with FF (far-from-fixation, 9 deg) target (panel D) and for the small cue trials with FF target (panel E).

unimodal, thus ruling out this alternative interpretation. Moreover, the double-step interpretation would also predict that a significant number of saccades would land on the cue border of both directions at the longer SOA (300 ms). On the contrary, only 0.53 (2.2%) trials per participant at the 300 ms SOA effectively landed on the cue border. These combined results should strongly demonstrate that our experimental condition cannot be parsimoniously explained by the double-step interpretation.

Another alternative interpretation could be that infants orient a fixed-size attentional focus along the horizontal axis, and once engaged on the cue boundary, they have to disengage their focus of attention rather than perform zooming. In this case, one would expect that attention is captured by the circular cue in one of the two directions (randomly) along the horizontal axis. SLs should be faster if the random location is consistent with the subsequent target location and slower if the random location is inconsistent with the subsequent target location. However, the almost zero numbers of trials per participant that effectively landed on the cue border, and the unimodal distribution of our single trials SLs, are also clearly inconsistent with this alternative interpretation. In summary, the present findings seem to be more parsimoniously explained by a zoom-lens account. It is worth noting that we interpreted our results according to a space-based attentional selection by means of the attentional focus zooming. However, due to the nature of our cue stimuli (circular shapes with delimited boundaries) other mechanisms could also be involved. For example, an object-based selection can similarly fit our data since the nature of the selective process and neural systems controlling space- and object-based selection greatly overlap (Bisley, 2011; Yantis & Serences, 2003), and, moreover, their time course during infant development seems to be very similar (Colombo, 2001).

The cue-size effect for the FF targets could also be explained by the effect of crossing a boundary that is present in the small but not in the large cue condition. However, according to the main models of visual attention, separate visual subsystems are normally coordinated and converge to process both space (surface) and boundary properties regarding the same selected area or object (e.g. Duncan, 1996; Duncan & Nimmo-Smith, 1996).

The validation of this paradigm and the evidence that the zooming mechanism is already developed in infants at 8 months of age have important implications in the study of developing cognition and neurodevelopmental disorders associated with attentional zooming dysfunctions.

An important aim for future research will be to address how the detection of a peripheral stimulus is related to infants' attentional zooming ability. The previous literature showed that the frequency and the speed of gaze shifts to a target in the periphery in the presence of a persisting stimulus in the center (i.e. disengagement mechanism) increase substantially around 3–4 months of age (Butcher, Kalverboer & Geuze, 2000; Hood & Atkinson, 1990; Johnson *et al.*, 1991; Mallin & Richards, 2012; Richards, 1997). By 4 months of age, infants are able to move their attention and gaze easily and rapidly, and staring behavior becomes rare (Butcher *et al.*, 2000; Hood & Atkinson, 1993; Hunnius & Geuze, 2004). Stimulus attributes also seem to play a role when two stimuli are presented at the same time. A comparatively salient stimulus in the central visual field makes it more difficult for infants to disengage their gaze (Aslin & Salapatek, 1975; Finlay & Ivinskis, 1984). Similarly, a flickering peripheral stimulus increases the likelihood of detection and decreases the latency of eye movement toward the peripheral stimulus (Lewis, Maurer, Burhanpurkar & Anvari, 1996). On the basis of our results, we can speculate that in addition to an efficient disengagement mechanism, an efficient zooming-out of the attentional focus helps peripheral stimulus detection, whereas an efficient zooming-in of the attentional focus is probably linked to an inhibitory process that reduces the possibility for infants to detect and overtly shift their focus to a peripheral stimulus.

Given that the attentional zooming mechanism affects the orienting mechanism, and given that the orienting mechanism is related to a higher-order function such as joint attention (Mundy & Newell, 2007), it is possible to suppose that the attentional zooming mechanism can be related to higher-order cognitive functions. This hypothesis seems to be consistent with the main theory about attentional development, stating that development of attention is accompanied by a (gradual) shift from subcortical processing to cortical control over attention, which involves the prefrontal cortex in particular (for reviews, see Colombo, 2001; Richards & Hunter, 2002). In this later stage, the functions associated with the basic control of attention overlap with the more general domain of executive function (e.g. planning, switching, and inhibitory control), and therefore, subtle differences in the control of the zoom-lens could consequently contribute to differences in higher-order functions (Van de Weijer-Bergsma, Wijnroks & Jongmans, 2008).

Accordingly, the inability to control the attentional zoom-lens during infancy may be considered an early marker of atypical neurodevelopmental conditions such as autism and dyslexia.

Autism spectrum disorder (ASD) has been repeatedly associated with different types of dysfunctions in spatial attention (for a review, see Ames & Fletcher-Watson, 2010), and high-risk infants who later develop the condition manifest a derailed trajectory of attentional orienting (Elsabbagh, Fernandes, Jane Webb, Dawson, Charman *et al.*, 2013). Previous studies also found an impaired zoom-out attentional mechanism in children with ASD (Mann & Walker, 2003; Ronconi *et al.*, 2012; Ronconi, Gori, Giora, Ruffino, Molteni *et al.*, 2013b). This impairment in spreading attentional resources could be already present during the first year of life and be responsible for their strong detail-oriented perception (Dakin & Frith, 2005), as well as their decreased ability to integrate dynamic information (Ronconi *et al.*, 2012, 2013a).

Several studies also suggest a causal role of visual spatial attention in developmental dyslexia (Facoetti, Corradi, Ruffino, Gori & Zorzi, 2010; Franceschini, Gori, Ruffino, Pedrolli & Facoetti, 2012; Franceschini, Gori, Ruffino, Viola, Molteni *et al.*, 2013; for reviews, see Gori & Facoetti, 2014; Gori & Facoetti, 2015; Vidyasagar & Pammer, 2010). In particular, children with dyslexia exhibited a sluggish attentional zoom-in that can impair the selection of relevant graphemes during reading acquisition (e.g. Facoetti *et al.*, 2000; Facoetti & Molteni, 2001).

In conclusion, the current study showed, for the first time, that the essential ability to control the size of the attentional focus develops early (before 8 months) in typically developing children. The relationship between this attentional mechanism and higher-order visual perception (e.g. local/global stimulus analysis, spatio-temporal visual integration) and attentional processes (e.g. joint attention) are yet to be fully explored, thus paving the way for challenging future research. Moreover, our results provide a tool to assess the modulation of the attentional focus size in infancy. This is extremely important since a zoom-lens dysfunction can be an early marker of atypical neurodevelopmental conditions such as ASD and dyslexia.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Schematic representation of the attentional zooming task design (panel A) for the pilot experiment and possible targets location for every combination of visual hemifield, cue size and target eccentricity (panel B).

Figure S2. Mean saccadic latencies (SLs) plotted as a function of cue type and eccentricity. Error bars represent within-subjects SEM, n.s.= not significant, * $p < .05$.

Table S1. Descriptive statistics (mean and SD) of additional relevant eye movements' parameters (i.e., time to target fixation, duration, angle and speed of saccades), other than the saccadic latency, that were collected during the Main Experiment for trials in which the target was successfully detected.

Table S2. Descriptive statistics (mean and SD) of the main measures collected in the Pilot Experiment, separated for each level of each independent variable.