Cognition 114 (2010) 285–292

Contents lists available at ScienceDirect

Cognition

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

Brief article

Psychophysical thresholds of face visibility during infancy

Sofie V. Gelskov [a,b], Sid Kouider [a,*]

[a] Laboratoire de Sciences Cognitives et Psycholinguistique, CNRS/EHESS/ENS-DEC, Paris, France
[b] Danish Research Centre for Magnetic Resonance, Copenhagen University Hospital, Hvidovre, Denmark

ARTICLE INFO

Article history:
Received 17 February 2009
Revised 17 September 2009
Accepted 21 September 2009

Keywords:
Infants
Face processing
Visibility
Masking
Psychophysics

ABSTRACT

The ability to detect and focus on faces is a fundamental prerequisite for developing social skills. But how well can infants detect faces? Here, we address this question by studying the minimum duration at which faces must appear to trigger a behavioral response in infants. We used a preferential looking method in conjunction with masking and brief presentations (300 ms and below) to establish the temporal thresholds of visibility at different stages of development. We found that 5 and 10 month-old infants have remarkably similar visibility thresholds about three times higher than those of adults. By contrast, 15 month-olds not only revealed adult-like thresholds, but also improved their performance through memory-based strategies. Our results imply that the development of face visibility follows a non-linear course and is determined by a radical improvement occurring between 10 and 15 months.

1. Introduction

Preverbal infants spend most of their awake time exploring their visual world and react very early on to salient objects. Right after birth, they are attracted by moving objects and tend to prefer face-like stimuli over other objects (Johnson, Dziurawiec, Ellis, & Morton, 1991). This attraction for faces improves progressively during the first year of life (Frank, Vul, & Johnson, 2009). Detecting and focusing on faces allows infants to learn about their social environment, identify conspecifics and interact with them (Baron-Cohen, 1994; Gliga & Csibra, 2007). While it is common knowledge that infants react more slowly than adults, in the sense that they exhibit a delayed motor response, it remains unclear how much sensory evidence is needed by the infant brain to trigger a behavioral response. In addition, it remains an unsettled question how efficient the infant brain is compared to the adult brain in detecting faces, and how this ability develops during infancy.

In adults, the temporal thresholds of visibility (i.e., the lowest duration at which a stimulus can be reported) have been studied intensively using visual masking and psychophysical estimates (Breitmeyer & Ogmen, 2006; Del Cul, Baillet, & Dehaene, 2007; Gescheider, 1997). When presented with a flashed stimulus (followed by a masking pattern to avoid retinal persistence and lingering afterimages), a few tens of milliseconds are sufficient for reporting the identity of the stimulus correctly (Del Cul et al., 2007; Kouider & Dehaene, 2007). Yet, because preverbal infants cannot overtly report what they see, it remains unclear whether they can react to such brief stimuli and, otherwise, how high their threshold is in comparison to adults. Until now, although there has been a great deal of research on visual acuity (Kellman & Arterberry, 1998), the temporal limits of infants' perception have been largely uncovered. A few notable exceptions are studies who investigated the speed of processing in preverbal infants (Lasky & Spiro, 1980; Rose, Jankowski, & Feldman, 2002). Yet, these studies have relied on memory-dependent estimates of perceptual abilities, such as habituating infants with a stimulus and testing whether it induces

* Corresponding author. Address: Ecole Normale Supérieure, 29 rue d'Ulm, 75005 Paris, France.
E-mail addresses: sid.kouider@ens.fr, sid.kouider@gmail.com (S. Kouider).
URL: http://www.lscp.net/persons/sidk/ (S. Kouider).

0010-0277/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.cognition.2009.09.012

familiarity/novelty preference in a later session, and none has thus quantified on-line perception at the time of stimulation.

Here, we used an on-line measure of perceptual abilities and assessed how the temporal threshold of visibility (i.e., the lowest duration at which infants respond to a visual stimulus) develops during infancy. We presented faces briefly (i.e., from 50 to 300 ms in steps of 50 ms) in a paradigm combining preferential looking (Kouider, Halberda, Wood, & Carey, 2006; Teller, 1979) and face masking (Kouider, Eger, Dolan, & Henson, 2009). In order to study whether the development of visibility increases linearly or rather discontinuously towards maturity, we measured thresholds at three ages in steps of 5 months. Participants were infants of 5 months ($N = 67$), 10 months ($N = 37$) and 15 months ($N = 29$) of age. Our method (Fig. 1) involved the simultaneous presentation of two streams on each side of a screen: a face side where a face was temporally surrounded by mask stimuli and a control side containing only mask stimuli matched for overall contrast and luminance to the faces. The two streams were thus identical except for the critical stimuli appearing on four occurrences during each trial. We capitalized on the fact that infants are highly attracted by faces compared to other objects (see e.g., (Gliga, Elsabbagh, Andravizou, & Johnson, 2009), for evidence in 6 month-olds). To further induce interest towards faces, each trial was followed by a 2 s reward period where the face re-appeared alone and was spatially surrounded by blinking colored crosses. Given both the natural and feedback-induced saliency of faces, we hypothesized that infants would look preferentially towards the face side than towards the control side only for durations at which they could detect a face. This method in combination with a frame-by-frame analysis of eye movements allowed us to obtain real-time psychophysical estimates of the amount of visual information needed to trigger a behavioral response in infants. In order to compare the thresholds of infants with that of adults, we also asked university students ($N = 10$) to perform a face detection task (i.e., absence vs. presence of a face) under the same masking conditions and for critical stimuli ranging from 17 ms to 250 ms.

2. Methods

2.1. Participants

A total of 133 infants were included in the final analysis: sixty-seven 5 month-olds (age range: 151–178 d. $M = 163$ d. $SD = 5.5$ d. 25 girls), thirty-seven 10 month-olds (age range: 286–322 d. $M = 301$ d. $SD = 9.2$ d. 17 girls) and twenty-nine 15 month-olds (age range: 451–473 d. $M = 465$ d. $SD = 5.9$ d. 12 girls). An additional seventy-two infants were tested (nine 5 month-olds, twenty-seven 10 month-olds and thirty-six 15 month-olds), but were not included in the analysis due to fussiness ($n = 52$), tech-

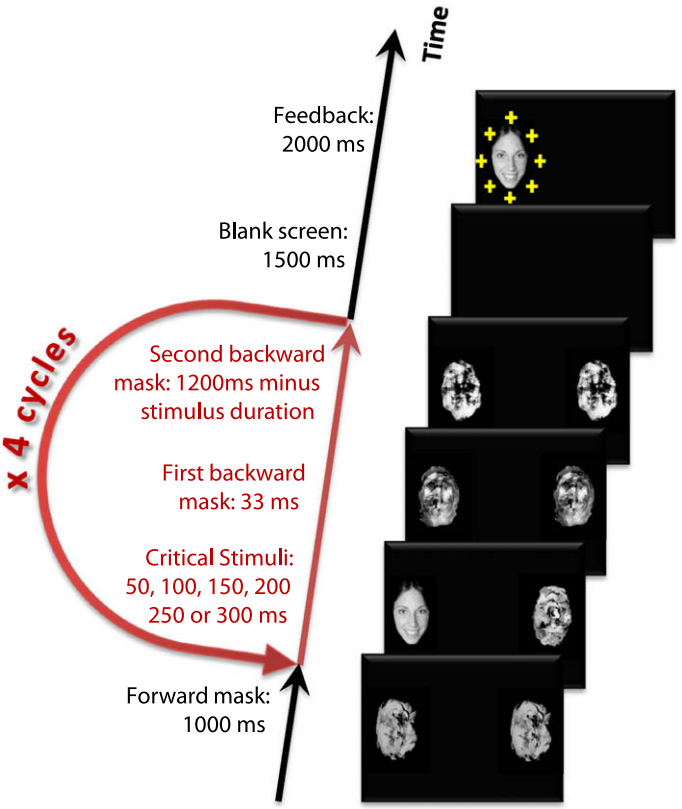

Fig. 1. Schematic description of the combined preferential looking and face masking paradigm.

nical error ($n = 6$), insufficient number of trials (i.e. less than three trials per duration; $n = 13$) or outlier status (more than three standard deviations from the overall mean effect of face preference; $n = 1$). All parents signed written consent forms before the experiment started. For the adult version of the experiment, an additional group of 10 students (age range: 18–25 years) were recruited from Paris universities.

2.2. Stimuli and procedure

Infants sat in the lap of their blindfolded parent, in eye-height with the stimuli and about 60 cm from the screen. Trials were initiated by the experimenter who could see the infant but not the stimuli. The experiment ran for 12 min or until infants became fussy. Greyscale photos of 30 females and 30 patterns made of scrambled photos of objects served as critical stimuli and masks, respectively. Faces and masks had the same contour size and shape, and were matched for overall contrast and luminosity. All faces had smiling to neutral facial expressions, and all had frontal view with eye-contact. Ears and necks were removed and hair merged into the black background. Luminosity, contrast, size of faces and placement of eyes were equalized between pictures. Each mask was constructed by overlaying the upside-down images of a face and three round objects (e.g., a flower, a watch and a muffin) and finally scrambling the layers. The on-screen stimulus size was approximately 10 cm in height and 7 cm in width, with a distance of 31 cm between the middle points of the two streams. The experiment took place in a sound-proof cabin with black interior and a 21" CRT (i.e., cathodic ray tube) screen with a refresh rate of 60 Hz. Infants' looking was recorded by a hidden camera mounted under the screen for subsequent coding of eye movements. The two streams started simultaneously with a first forward mask for 1000 ms and were then followed by four successive cycles of three visual events: a critical stimulus which was a face on the one side and a control mask on the other side, and which was presented for a variable duration (50, 100, 150, 200, 250 or 300 ms), then a first backward mask (33 ms), and finally a different second backward mask with a variable duration such that each cycle had a length of 1200 ms. This face masking procedure was similar to our past work in adult populations (Henson, Mouchlianitis, Matthews, & Kouider, 2008; Kouider et al., 2009). Critical stimulus durations were kept constant within a trial, but randomly distributed across trials. The two backward masks were replaced by new ones from one cycle to the next. To increase interest, critical stimulus onsets were accompanied by a bell sound, creating a melody (i.e., "C" "D" "E" "F"). After the end of the last backward mask of the fourth cycle, a blank screen was presented for 1500 ms, after which feedback was provided: the face reappeared on the face-stream side, surrounded by blinking colored crosses, and accompanied by a final bell sound (i.e., "G"). The duration of this reward period was 2000 ms. Side of face presentation was randomly attributed with a ceiling of five consecutive trials at a given side. In addition, the word CODE was displayed by the presentation program on the video tape just prior to the stimulus sequence in order to ensure the synchronisation of stimulus presentation and blind coding.

2.3. Data analysis

Looking-time was coded off line frame-by-frame from video recordings of the sessions, at 30 frames per second,

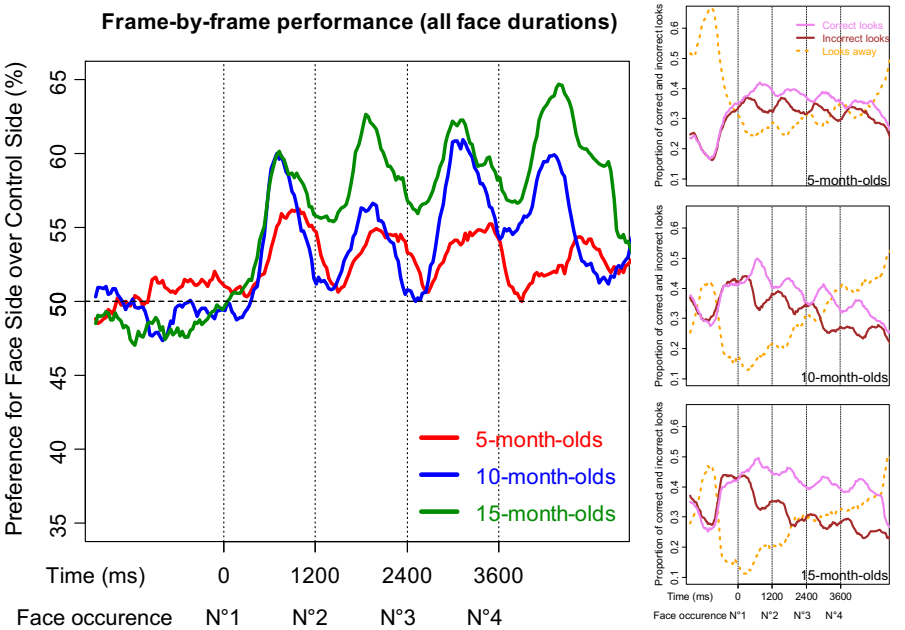

Fig. 2. Frame-by-frame analysis of performances over trial time for the three age groups of infants (collapsed across all face durations). Each data point corresponds to a video frame of 33 ms. Left: face preference over trial time (chance-level = 50%). Right: proportion of looking to the face side, to the control side or to neither side (sum = 1).

using the SuperCoder (1.5)© software. For each frame, two highly trained coders assessed whether the infant was fixating the left side of the screen, the right side, or neither, while being blind as to the location of the stimuli. Inter-coder reliability was calculated on the coding of 10% of the participants in each age group. Percent agreement on looking time (i.e., whether a frame was considered as left, right or neither) was 95% and the Pearson *r* correlation between the rating results of the two different coders was 0.96, indicating a high level of inter-coder reliability. Analysis focused on a measurement period ranging from the onset of the first face to the offset of the last mask of the fourth cycle, both shifted forward by a 300 ms visuo-motor delay for programming and launching eye movements (Haith, Wentworth, & Canfield, 1993; Swingley & Aslin, 2000). Trials where infants looked away more than 90% of the time were excluded. Statistics were performed on absolute looking time scores in milliseconds quantifying the respective amount of looking at the face-stream and at the control-stream, through an ANOVA with ages, face durations and sides (face vs. control). For graphical illustrations, we additionally computed proportion scores to quantify the proportion of looks at the correct, incorrect and neither side (Fig. 2 right), and percentage preference scores corresponding to looking towards the face-stream compared to looking towards either stream, allowing us to compare performance to the chance-level of 50% (Fig. 2 left and Fig. 3).

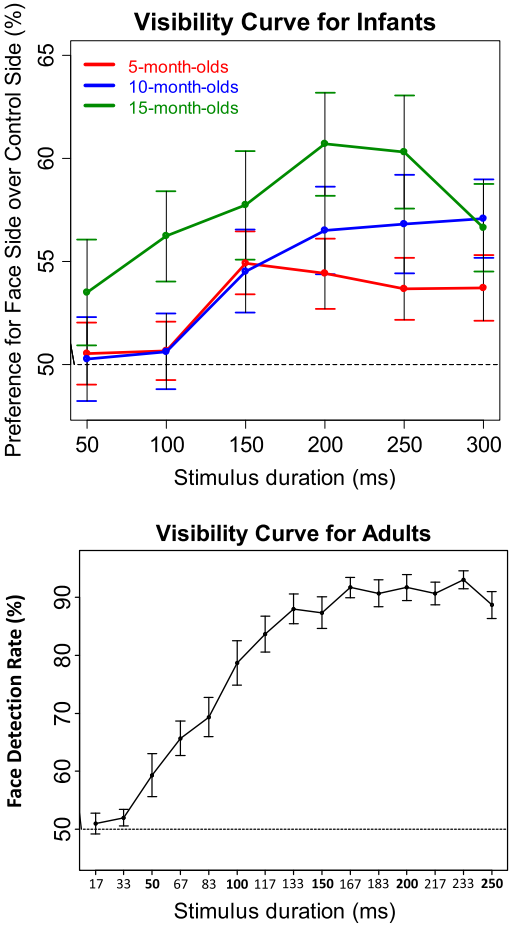

Fig. 3. Top: face preference as a function of face duration for the three age groups of infants. Bottom: face detection rate (i.e., absence vs. presence of a face) for adults. Stimulus durations in bold correspond to the ones used with infants. Chance level = 50% for both adults and infants. Error bars mark standard errors.

2.4. Adult experiment

Adult subjects received 450 trials with a similar display sequence to the one described in Fig. 1, except for the following modifications: (1) the critical stimuli were presented only once; (2) the duration of the forward mask and second backward mask was set to 333 ms and 600 ms, respectively; (3) the size of faces was half the size of those used with infants; (4) there was no feedback; (5) all the possible durations allowed by a 60 Hz monitor up to 250 ms were covered (i.e., the 15 possible durations from 17 ms to 250 ms); and (6) half the trials contained a face on the one side and a pattern on the other side (as in Fig. 1) while the other half contained only patterns, allowing us to estimate face detection. Participants were instructed to report, without time pressure, whether or not a trial contained a face by pressing a left key for "no" responses and a right key for "yes" responses. In case they felt uncertain, they were asked to make their best guess about the presence or absence of a face. Adult performances were estimated both by comparing the face detection rate to the chance-level baseline of 50% (Fig. 3), and a signal detection index (*d'* with presence as signal and absence as noise) to the chance-level baseline of zero. The *t*-tests reported in the results section are two-tailed and reflect both indexes.

3. Results

The frame-by-frame performances across the three age groups are displayed in Fig. 2. Analyses of variance on absolute looking-times confirmed that face preference (i.e., longer looking at the face side compared to the control side) was highly significant at all ages (5 months → 224 ms: $F(1, 66) = 29.37$, $p < 0.001$; 10 month → 347 ms: $F(1, 36) = 39.93$, $p < 0.001$; 15 month → 634 ms: $F(1, 28) = 59.34$, $p < 0.001$), and interacted significantly with duration for the 5 month-olds ($F(5330) = 2.53$, $p < 0.05$) and the 10 month-olds ($F(5180) = 2.61$, $p < 0.05$), but not for the 15 month-olds ($F(5140) = 1.75$, $p = 0.13$), evidencing that face preference varied as a function of duration solely in the two younger age groups. We then focused specifically on these duration-dependent variations (Fig. 3). We found that 5 month-old infants exhibited chance-level performance; that is, they looked equally at both sides, for the 50 ms and 100 ms face durations (both Fs < 1) while they showed face preference for the 150 ms, 200 ms, 250 ms and 300 ms durations (all ps < 0.05). These results evidence that the face visibility threshold of 5 month-old infants lies in between 100 ms and 150 ms. We then turned to the 10 month-old infants and we found that their looking pro-

file was remarkably similar to the 5 month-old infants. Indeed, 10 month-olds also showed face preference for all the durations ranging from 150 ms to 300 ms (all $ps < 0.05$) while they were at chance for 50 ms and 100 ms durations (both $Fs < 1$). In addition, their performance was only marginally higher than for the 5 month-olds, whether or not it included face durations below 150 ms (all $ps \geqslant 0.08$). By contrast, we found that 15 month-old infants not only exhibited significantly higher performance when compared to the 5 month-olds ($F(1, 94) = 24.51$, $p < 0.001$) as well as to the 10 month-olds ($F(1,64) = 9.02$, $p < 0.005$), but also that their visibility threshold was lower. Indeed, 15 month-old infants reacted to the faces at all durations (all $ps < 0.05$), although it is of note that the effect was barely significant for the 50 ms faces ($p = 0.049$). This last aspect of the data is important because even though we did not test for shorter durations, it is very likely that the 15 month-olds would not show face preference at shorter durations.

When tested on the face detection task, adults exhibited chance-level performance for durations below 50 ms (17 ms faces: rate = 51.0%, $d' = 0.49$; 33 ms faces: rate = 52.0%, $d' = 0.45$; all $ts < 2$) and could only detect faces presented for 50 ms and above (all $ps < 0.05$; all d' values $\geqslant 1.20$). Noteworthy, although adults could detect faces at 50 ms in the sense that they were better than the chance-level of 50%, it was not without experiencing important difficulties, as their performance remained relatively low (59.3%). In sum, it appears that 15 month-olds and adult university students exhibited the same threshold of visibility at 50 ms. This result is particularly impressive given that, contrary to adults, infants could of course not be instructed to actively focus all their attention on the screen and actively search for the faces. In addition, it suggests that face visibility in 15 month-olds is much closer to that of adults than to that of the 10 month-olds[1].

Can we evidence additional behavioral consequences of visibility following the detection of a face stimulus? A visible object can not only attract attention and trigger a visuo-motor response, but it can also be held into working memory in order to influence subsequent behaviors in an endogenous manner. In our paradigm, the multiple appearances of the same face at the same location could be used to increase performance, pending that infants could memorize and use that information. To address this aspect, we focused on whether performance returned to baseline in between face occurrences. We found that, in addition to having better performance and a lower threshold compared to the other age groups, only the 15 month-old infants revealed a memory-based strategy for looking at the correct side. Indeed, the 15 month-old infants continuously maintained looking at the correct side following the first face occurrence (Fig. 2), suggesting that they could use that information to predict where the next face would appear. By contrast, 5 month-old infants systematically returned to baseline in between face occurrences, as did the 10 month-old infants although to a lesser extent. In order to verify the reliability of this result, we analyzed whether infants were constantly above baseline following the first face occurrence, by collapsing the looking-time data for all the face occurrences (excluding the first one) as a function of duration and by then performing statistical tests on each 100 ms segment (Fig. 4). This analysis revealed that for all duration above 100 ms, 15 month-olds never returned to baseline (i.e., they looked significantly more to the correct side for any segment). By contrast, infants in the two younger age groups always returned to baseline at one point for any of the durations. These results have important implications regarding the behavioral consequences of visibility during development. They indicate that infants in the two younger age groups primarily reacted to the faces in an exogenous manner while the 15 month-old infants could keep track of the face side in working memory.

4. Discussion

Collectively, our results reveal a developmental discontinuity in the perceptual abilities of preverbal infants. In particular, we found that there is little difference in the amount of visual information needed to trigger a behavioral response to faces between 5 and 10 months of age while, by contrast, an important qualitative change in face visibility occurs between 10 and 15 months. What are the reasons for this non-linear development? Below we discuss three non-exclusive factors that can explain this shift: a dramatic increase in low-level visual processes, the development of the face processing system, the maturation of the mechanisms underlying endogenous attention.

Regarding the first, low-level interpretation, several studies have indeed shown that the visual system of infants undergoes enormous changes during the first year of life (Teller, 1997). At birth visual abilities are characterized by low acuity, no depth-perception and poor color discrimination. Then, visual capacities develop at a staggering rate. Yet, although the visual system undergoes enormous changes during the first year of life, the general increase in visual abilities happens rather during the first 6 months of life. In particular, the acuity level improves at least sixfold from birth to the age of 6 months, while it then only increases by approximatively 50% from 6 to 12 months (Courage & Adams, 1990). As such, a purely low-level

[1] Noteworthy, the performance of 15 month-olds did not follow an increase as a function of duration but actually appeared to drop at the longest duration (Fig. 3). We hypothesized that this decrease in performance results from habituation to the face at the longer duration, in agreement with past research revealing that infants start to look less for over-repeated stimuli (Sirois & Mareschal, 2002). In our case, infants would become uninterested by the over-repetition of the most visible faces. Although a comparison of performances between the 250 ms and 300 ms durations did not reveal a significant difference ($F < 1$), a further analysis including the four face occurrences (i.e., the four repetitions of the same face within a trial) revealed that performance at 300 ms gradually increased for the first occurrences but then drastically decreased on the last occurrence and actually became significantly lower compared to the 250 ms duration ($F(1, 28) = 5.48$, $p < 0.05$). Also consistent with this interpretation, we found a three way interaction between performance (correct vs. incorrect), duration (250 ms vs. 300) ms and occurrence (earlier vs. last face) ($F(1, 28) = 6.12$, $p < 0.05$). This result suggests that after influencing infants' response during their first occurrences, the most visible faces can subsequently lead to a processing saturation and paradoxically result in less interest compared to faces with a lower visibility.

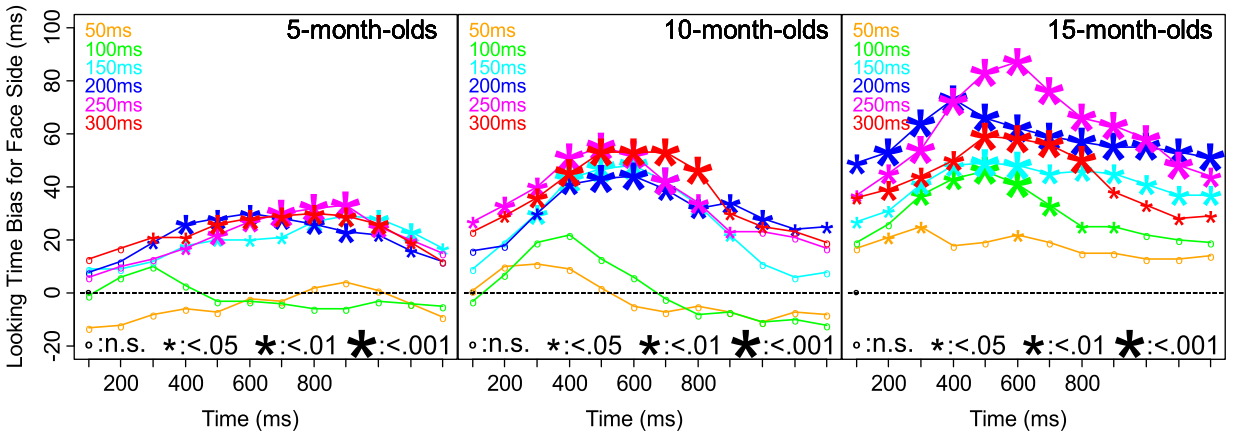

Fig. 4. Statistical graphs on looking-time bias for face side collapsed across face occurrences (excluding n°1) and as a function of face duration. Small circles represent non-significant (n.s.) effects while stars reflect a significant effect proportional to the size of the star. Each data point represents a segment of 100 ms. The origin on the *x*-axis corresponds to the face onset plus a visuo-motor delay of 300 ms (see Section 2).

interpretation in terms of visual acuity is unlikely to account for this developmental pattern.

According to the second interpretation, neuronal populations in face-sensitive brain regions of the ventral visual stream (e.g., the Fusiform Face Area, (Kanwisher, McDermott, & Chun, 1997)) would approach maturity and become more tuned to faces in the older age group.[2] As a consequence, this system would require accumulating less evidence for detecting faces and in turn activating oculomotor processes. Yet, the specialization of the face processing system also appears to occur earlier in development. Indeed, while 6 month-old infants show the ability to discriminate faces in other species (e.g., for monkey faces) (Pascalis et al., 2005) or in other races (Kelly et al., 2007), both aptitudes are lost by 9 months of age. This perceptual narrowing is assumed to reflect synaptic pruning in the infant brain, by eliminating connections that are irrelevant in the environment. Of course, it remains possible that the shift in thresholds occurring later in development follows, for some reasons to be clarified, the fine-tuning specialization of the face processing system.

The third interpretation involving the domain-general system subtending endogenous attention is more likely to fit the developmental pattern observed here. In this case, what would dramatically change around the end of the first year is not the maturity of the domain-specific system dedicated to face recognition, though this system might still develop progressively, but rather the ability to amplify and manipulate face signals through top-down attention. Indeed, this period coincides very well with the marked maturation of the dorso-lateral prefrontal cortex between 8 and 12 months of age (Diamond & Goldman-Rakic, 1989). More generally, the massive reorganization of synaptic connections in the prefrontal cortex is thought to be the reason why 8 to 12 month-old infants show dramatic improvements in a wide range of high level cognitive abilities related to cognitive control (Casey, Tottenham, & Fossella, 2002; Diamond & Doar, 1989). As the prefrontal cortex has been associated in adults with top-down attentional selection and working memory maintenance (Corbetta & Shulman, 2002), it is tempting to assume that the developmental shift in visibility observed here reflects the fact that only 15 month-old infants exhibit the characteristics of endogenous attention (i.e., signal amplification, working memory maintenance, etc.). This would also explain the fact that, in addition to having a much lower threshold, only the 15 month-old infants could keep track of the face side. Accordingly, the processing of visible faces in the younger age groups would reflect a premature stage where stimulus content is highly active in face-sensitive regions (i.e., in occipito-temporal cortices) and largely available to the rest of the system. Yet, because the mechanisms of top-down amplification from prefrontal cortex are not yet operational for younger infants, the sensory traces left by the face stimulus fade away, without further influences on subsequent processing. Further studies will have to address this attentional hypothesis.

Before concluding, we would like to point out that although we used an operational definition of visibility in terms of induced behavioral responses as a function of visual energy (i.e., the amount of information available to the visual system here expressed in stimulus duration), this type of measures has also been traditionally used in adult populations to establish whether someone is conscious of a stimulus (Kouider & Dehaene, 2007). As such, although this remains a speculative hypothesis, it is possible that the developmental shift observed in our study

[2] Given that we compared faces to non-object visual controls, in order to maximize our contrast for visibility, one might still argue that we could have found exactly the same results with other, familiar objects (e.g., toys) instead of faces. However, past studies have shown that this type of contrast is enough for probing face-sensitivity. For instance, Halit, Csibra, Volein, and Johnson (2004) presented 3 month-old infants with faces vs. matched visual noise stimuli similar to our control stimuli. They found an increase in amplitude for the N290, an electrophysiological component though to be the precursor of the face-sensitive N170 in adults and which, importantly, has previously been observed when contrasting faces vs. toys in infants (De Haan & Nelson, 1999). Although these studies suggest that performance in our study were face-sensitive, further work is required to investigate how face-specific they are.

similarly reflects a change in the mechanisms underlying conscious access[3]. In this context, the younger 5 and 10 month-old infants would still lack the attentional mechanisms (stimulus maintenance, global availability implying the prefrontal cortex) that, according to some popular theories (e.g., the Global Neuronal Workspace theory (Dehaene & Naccache, 2001)) are necessary for conscious access. Whether the premature stage in the younger 5 and 10 month-old infants would reflect a rudimentary (i.e., "phenomenal") form of consciousness without access (Block, 2005; Lamme, 2003), or rather a fully non-conscious (i.e., "preconscious") form of processing (Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006) remains an open issue, as research on consciousness does not even agree on the subjective status of supra-threshold (i.e., visible) but unattended stimuli in adult populations (Dehaene et al., 2006; Koch & Tsuchiya, 2007; Lamme, 2003). Although further research is clearly needed to address the neural basis of face detection in infants, as well as the complex issue of how subjective experience develops in humans, the present study reveals that the development of face visibility and its behavioral consequences follow a non-linear pattern, with a qualitative shift occurring between 10 and 15 months.

Acknowledgements

We are grateful to Anne Christophe, Ghislaine Dehaene-Lambertz, Stanislas Dehaene, Emmanuel Dupoux and Scania de Schonen for valuable discussions and comments. We also thank the families who participated in this study and Alba Tuninetti and Vera Cerruti for assistance with testing and coding, as well as Vincent de Gardelle for assistance during preprocessing of the data. This work was supported by a grant from the Fyssen foundation to S.K.

References

Baron-Cohen, S. (1994). How to build a baby that can read minds: Cognitive mechanisms in mindreading. *Current Psychology of Cognition, 13*(5), 513–552.

Block, N. (2005). Two neural correlates of consciousness. *Trends in Cognitive Sciences, 9*(2), 46–52.

Breitmeyer, B. G., & Ogmen, H. (2006). *Visual masking: Time slices through conscious and unconscious vision*. Oxford University Press.

Casey, B. J., Tottenham, N., & Fossella, J. (2002). Clinical, imaging, lesion, and genetic approaches toward a model of cognitive control. *Developmental Psychobiology, 40*(3), 237–254.

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience, 3*(3), 201–215.

Courage, M. L., & Adams, R. J. (1990). Visual acuity assessment from birth to three years using the acuity card procedure: Cross-sectional and longitudinal samples. *Optometry and Vision Science, 67*(9), 713–718.

De Haan, M., & Nelson, C. A. (1999). Brain activity differentiates face and object processing by 6-month-old infants. *Developmental Psychology, 34*, 1114–1121.

Dehaene, S., Changeux, J. P., Naccache, L., Sackur, J., & Sergent, C. (2006). Conscious, preconscious, and subliminal processing: A testable taxonomy. *Trends in Cognitive Sciences, 10*(5), 204–211.

Dehaene, S., & Naccache, L. (2001). Towards a cognitive neuroscience of consciousness: Basic evidence and a workspace framework. *Cognition, 79*, 1–37.

Del Cul, A., Baillet, S., & Dehaene, S. (2007). Brain dynamics underlying the nonlinear threshold for access to consciousness. *PLoS Biology, 5*(10), e260.

Diamond, A., & Doar, B. (1989). The performance of human infants on a measure of frontal cortex function the delayed response task. *Developmental Psychobiology*, 22.

Diamond, A., & Goldman-Rakic, P. S. (1989). Comparison of human infants and rhesus monkeys on Piaget'. *Experimental Brain Research, 74*, 24–40.

Frank, M. C., Vul, E., & Johnson, S. P. (2009). Development of infants' attention to faces during the first year. *Cognition, 110*(2), 160–170.

Gescheider, G. (1997). *Psychophysics: The fundamentals*. Lawrence Erlbaum.

Gliga, T., & Csibra, G. (2007). Seeing the face through the eyes: A developmental perspective on face expertise. *Progress in Brain Research, 164*, 323–339.

Gliga, T., Elsabbagh, M., Andravizou, A., & Johnson, M. H. (2009). Faces attract infants' attention in complex displays. *Infancy, 14*(5), 550–562.

Haith, M., Wentworth, N., & Canfield, R. (1993). The formation of expectations in early infancy. In C. Rovee-Collier & L. Lipsitt (Eds.), *Advances in infancy research* (pp. 251–297). Westport, CT: Ablex.

Halit, H., Csibra, G., Volein, A., & Johnson, M. H. (2004). Face-sensitive cortical processing in early infancy. *Journal of Child Psychology and Psychiatry, 45*(7), 1228–1234.

Henson, R. N., Mouchlianitis, E., Matthews, W. J., & Kouider, S. (2008). Electrophysiological correlates of masked face priming. *Neuroimage, 40*(2), 884–895.

Johnson, M. H. (2005). Subcortical face processing. *Nature Reviews Neuroscience, 6*(10), 766–774.

Johnson, M. H., Dziurawiec, S., Ellis, H., & Morton, J. (1991). Newborns' preferential tracking of face-like stimuli and its subsequent decline. *Cognition, 40*(1–2), 1–19.

Kanwisher, N., McDermott, J., & Chun, M. M. (1997). The fusiform face area: A module in human extrastriate cortex specialized for face perception. *Journal of Neuroscience, 17*, 4302–4311.

Kellman, P. J., & Arterberry, M. E. (1998). *The cradle of knowledge: Development of perception in infancy*. Cambridge, MA: The MIT Press.

Kelly, D. J., Liu, S., Ge, L., Quinn, P. C., Slater, A. M., Lee, K., et al. (2007). Cross-race preferences for same-race faces extend beyond the African versus Caucasian contrast in 3-month-old infants. *Infancy, 11*(1), 87–95.

Koch, C., & Tsuchiya, N. (2007). Attention and consciousness: Two distinct brain processes. *Trends in Cognitive Sciences, 11*(1), 16–22.

Kouider, S., & Dehaene, S. (2007). Levels of processing during non-conscious perception: A critical review of visual masking. *Philosophical Transactions of the Royal Society of London Series B – Biological Sciences, 362*(1481), 857–875.

Kouider, S., Eger, E., Dolan, R., & Henson, R. N. (2009). Activity in face-responsive brain regions is modulated by invisible, attended faces: Evidence from masked priming. *Cerebral Cortex, 19*(1), 13–23.

Kouider, S., Halberda, J., Wood, J., & Carey, S. (2006). Acquisition of English number marking: The singular–plural distinction. *Language Learning and Development, 2*(1), 1–25.

Lamme, V. A. (2003). Why visual attention and awareness are different. *Trends in Cognitive Sciences, 7*(1), 12–18.

Lasky, R. E., & Spiro, D. (1980). The processing of tachistoscopically presented visual stimuli by five-month-old infants. *Child Development, 51*(4), 1292–1294.

Pascalis, O., Scott, L. S., Kelly, D. J., Shannon, R. W., Nicholson, E., Coleman, M., et al. (2005). Plasticity of face processing in infancy. *Proceedings of the National Academy of Sciences of the United States of America, 102*(14), 5297–5300.

[3] One might still argue that although infants directed their gaze towards faces in our study, this behavior could have been the result of a fully non-conscious mechanism. This kind of non-conscious behavior has been demonstrated in blindsight patients, who lack a functional primary visual cortex but can still use subcortical visual pathways to point and orient their attention towards a task-relevant stimulus while still claiming full unawareness of that stimulus (Weiskrantz, 1986). It remains then possible that infants in our study are similarly relying on unconscious subcortical pathways in reaction to faces (Johnson, 2005). Yet, while face attraction might indeed be primarily dependent on subcortical structures in newborns, infants by the age of 2–3 months also rely on occipito-temporal structures (Halit et al., 2004; Tzourio-Mazoyer et al., 2002), suggesting that face processing involves, at least in part, the cortical structures that are necessary for visual awareness.

Rose, S. A., Jankowski, J. J., & Feldman, J. F. (2002). Speed of processing and face recognition at 7 and 12 months. *Infancy, 3*(4), 435–455.
Sirois, S., & Mareschal, D. (2002). Models of habituation in infancy. *Trends in Cognitive Sciences, 6*(7), 293–298.
Swingley, D., & Aslin, R. N. (2000). Spoken word recognition and lexical representation in very young children. *Cognition, 76*(2), 147–166.
Teller, D. Y. (1979). The forced-choice preferential looking procedure: A psychophysical technique for use with human infants. *Infant Behavior and Development, 2*(2), 135–153.
Teller, D. Y. (1997). First glances: The vision of infants. The Friedenwald lecture. *Investigative Ophthalmology and Visual Science, 38*(11), 2183–2203.
Tzourio-Mazoyer, N., De Schonen, S., Crivello, F., Reutter, B., Aujard, Y., & Mazoyer, B. (2002). Neural correlates of woman face processing by 2-month-old infants. *Neuroimage, 15*(2), 454–461.
Weiskrantz, L. (1986). *Blindsight: A case study and implications*. Oxford: Clarendon Press.