

**Brain responses reveal that infants' face discrimination is guided by statistical
learning from distributional information**

RUNNING HEAD: Statistical learning of faces

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RESEARCH HIGHLIGHTS

- 6.5-month-olds were familiarized with morphed faces spanning a continuum from one identity to another, using either a uni- or a bimodal frequency distribution.
- Results show that distributional information influences infants' subsequent face categorization, suggesting that statistical learning guides face perception.

ABSTRACT

Infants' perception of faces becomes attuned to the environment during the first year of life. However, the mechanisms that underpin perceptual narrowing for faces are only poorly understood. Considering the developmental similarities seen in perceptual narrowing for faces and speech and the role that statistical learning has been shown to play for speech, the current study examined whether and how learning from distributional information impacts face identity discrimination. We familiarized 6.5-month-old infants with exemplars of female faces taken from a morphed continuum going from one identity to another. Using event-related brain potentials (ERPs), we show that only infants who were familiarized with a bimodal frequency distribution, but not infants familiarized with a unimodal frequency distribution, discriminated between identities. These results are the first to demonstrate the influence of probabilistic information on infants' face identity discrimination, suggesting that statistical learning contributes to perceptual attunement for both faces and language.

Keywords: Face perception, statistical learning, perceptual attunement, ERP, priming

INTRODUCTION

Both speech and faces are of prime importance for infants as they provide rich sources of relevant information concerning their environments. From birth, infants preferentially listen to speech and look at faces compared to non-speech auditory and non-face visual stimuli (Valenza et al., 1996; Vouloumanos & Werker, 2007). This initial preference is rather broadly tuned but becomes more specialized to the particular environments during the first year of life (for a review see Maurer & Werker, 2014). While infants initially show a general preference for face-like stimuli, around 3 months of age a preference for own-race over other-race faces emerges (Kelly et al., 2005). Infants are still able to discriminate other-race and other-species faces at this age, but sensitivity to such within-category differences substantially decreases between 6 and 9 months of age (Kelly et al., 2007; Pascalis, de Haan & Nelson, 2002; Simpson et al., 2011). Similarly, infants adapt to the characteristics of their native language. During the first months of infancy, a preference for the native language over other, rhythmically similar languages develops (Nazzi, Jusczyk & Johnson, 2000). Between 6 and 12 months of age infants' sensitivity for native speech sounds improves, whereas sensitivity to most non-native sound contrasts declines (Kuhl et al., 2006; Werker & Tees, 1999).

In both the auditory and the visual domain, experience has been shown to shape perception: infants attune to the faces and the language that they are exposed to in their environments. For instance, in multi-ethnic societies infants show no preference for faces of their own race (Bar-Haim et al., 2006). Similarly, infants who are raised bilingually adapt to the characteristics of both languages spoken around them (Byers-Heinlein & Fennell, 2014). The crucial role of experience in these attunement processes is further supported by findings showing that additional input can increase – or prevent the loss of – sensitivity to non-native differences. Specifically, labeling different monkey faces with individual names and pairing similar non-native sounds with different faces or objects heightens infants' sensitivity to within-category differences that would otherwise be ignored (Pascalis et al.,

2005; Mani & Schneider, 2013; Yeung & Werker, 2009). The parallels in infants' attunement to faces and speech sounds have been taken to suggest a common underlying mechanism (Scott et al., 2007). Yet, the exact nature of such a domain-general mechanism is still poorly understood.

One mechanism that has received increasing attention in the research on language development is statistical learning. Saffran, Newport & Aslin (1996) first showed that 8-month-olds track transitional probabilities between syllables to parse words from the speech stream. This inspired numerous studies investigating how infants extract statistical regularities from auditory (Gomez & Gerken, 1999; Marcus et al., 1999), visual (Fiser & Aslin, 2002; Kirkham, Slemmer & Johnson, 2002) and audiovisual streams (Smith & Yu, 2008; Yurovsky, Yu & Smith, 2012). However, infants exploit statistical distributions in the input not only to acquire rules and words, but also to form sound categories. Maye, Werker & Gerken (2002) familiarized 6- and 8-month-olds with sounds spanning the continuum from /da/ to /ba/. One group of infants received a unimodal frequency distribution of the individual sounds, hearing the sound representing the midpoint of the continuum most often. The other group of infants received a bimodal frequency distribution, hearing the two sounds that were closer to the endpoints of the continuum most often. In a subsequent test phase, only infants in the bimodal group discriminated /da/ and /ba/, while infants in the unimodal group showed no sensitivity to the sound contrast. Since speech sounds tend to form clusters in natural speech (Allen & Miller, 1999), this provides a powerful mechanism to attune perception to native language sound categories. Given the above-described similarities in infants' attunement to native speech sounds and faces, the question arises whether infants similarly make use of statistical information to learn about faces. This is a plausible scenario as most models of face recognition assume that faces are represented with respect to a norm-based face, i.e. that facial identity information is encoded relative to a prototype or average face (for a discussion, see de Haan et al., 2001).

The current study therefore examined infants' ability to rely on distributional properties in the input to discriminate individual faces. Following Maye et al.'s (2002) procedure we familiarized 6.5-month-old infants with morphed female faces spanning a continuum from one identity to another, using either a unimodal or a bimodal frequency distribution. We then tested infants' perception of the two women in an ERP repetition priming paradigm (Bristow et al., 2008; Peykarjou, Pauen & Hoehl, 2014). Each test trial presented two faces rapidly after each other. Faces were either identical (match trials) or different (mismatch trials) in terms of their identity and were taken from each end of the morphing continuum. We hypothesized that infants from the unimodal group form one category while infants from the bimodal group form two face categories (as reported for auditory syllables by Maye et al., 2002) and therefore expected that only in the bimodal learning group, the detection of the identity difference between prime and target to be reflected in a mismatch response in the ERP of infants. Specifically, infants familiarized with a bimodal distribution of morphed face images are expected to show a mismatch response for mismatch trials but not for match trials. In contrast, infants familiarized with a unimodal distribution are expected to show no mismatch response to either type of test trial. It is important to emphasize that infants in both groups view the same face images, ensuring that images are perceptually identical and any ensuing ERP differences can be attributed to the detected difference between the stimuli used as a prime and the target.

MATERIAL AND METHODS

Participants

A total of 117 6.5-month-old infants were randomly assigned to a bimodal (n=58) or unimodal familiarization group (n=59). Infants were recruited via the subject pool of the authors' institute. All infants were born full-term with normal birth-weight. Only infants completing the familiarization phase were considered for analysis of the EEG data. The final groups consisted of 29 infants each (bimodal

group: mean age 201 days, range 183 – 211, 12 female; unimodal group: mean age 197 days, range 182 – 210, 11 female). Sample size was determined with respect to previous perception studies testing infants of similar age (Pascalis et al., 2002; Maye et al., 2002), adding a sufficient number of infants to accommodate a typical attrition rate in visual infant ERP research (Stets, Stahl & Reid, 2012). Additional 8 infants fulfilled inclusion criteria in the bimodal group, but to ensure an equal number of infants per group the last 8 infants tested were excluded from the final sample without further analysis. Parents gave written informed consent and received 7.50 Euro and a toy for their infant for participation. The study was approved by the local ethics committee and conducted according to the declaration of Helsinki.

Material

Colored portrait photographs of two young women (age 25 and 28) were taken in front of a grey wall. Both wore a black shirt and had similar hair color and style. Using Norrkross MorphX software, morphed versions of these two photos were created, changing from 100% woman1 (100/0%) in steps of 5% to 100% woman2 (0/100%). This resulted in a continuum of a total of 21 pictures. Pictures had a width of 14.5 cm and a height of 21 cm.

Design

The experiment consisted of a familiarization and a test phase. During familiarization, all 21 pictures were presented. For the unimodal group, frequency of occurrence of the different pictures was such that the 50/50% morph was the most common, occurring 15 times. For the bimodal group, the most frequently occurring pictures were the 25/75% and the 75/25% morphs, each occurring 15 times (see Figure1 for the frequency distributions in the two familiarization groups and example pictures). Importantly, the pictures 0/100%, 35/65%, 65/35%, and 100/0% that were used in the test phase occurred with the same frequency in both familiarization groups. In total, 159 pictures were presented

during familiarization. Each picture was presented for 1000 ms with a varying interstimulus interval of 400-600 ms, during which a fixation star on a grey screen was presented. Stimulus presentation duration was kept as short as possible to reduce the time necessary to complete the familiarization phase and a sufficient number of test trials, while taking the timing of face-sensitive event-related potential components into consideration (cf. de Haan et al., 2003).

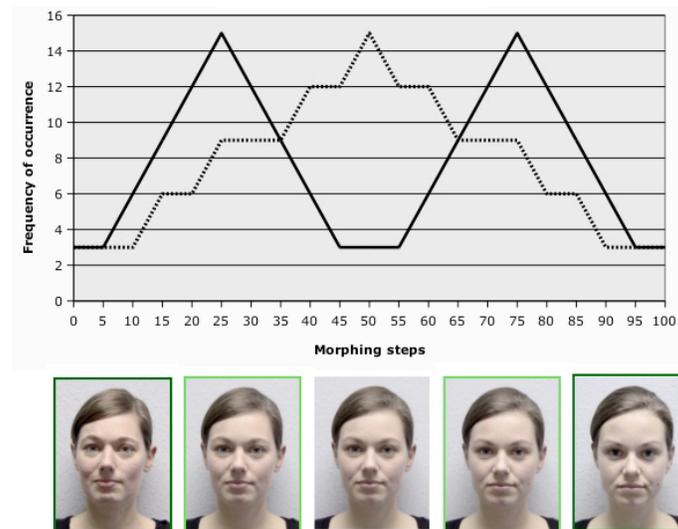


Figure 1: Statistical distribution and stimulus examples.

The upper part of the figure illustrates the frequency distributions used in the familiarization phase for the unimodal (dotted line) and the bimodal group (regular line). Example pictures are depicted in the bottom part of the figure. The unframed picture represents the 50% morph. The remaining pictures represent the 0% and 100% morphs (framed in dark green) and the 35% and 65% morphs (framed in light green) that were used during both familiarization and test phase.

The test phase was identical for both familiarization groups and followed without interruption after the familiarization phase. In each test trial, two pictures that could be either identical (match trials) or different (mismatch trials) were shown consecutively. Test trials used the 0/100%, 35/65%, 65/35%, and 100/0% morph pictures. During match trials the prime and the target picture were identical (simple repetition). During mismatch trials a prime picture was followed by a target picture from the opposite

end of the continuum. In particular, a 35/65% picture was followed by a 65/35% picture (or vice versa), or a 0/100% picture was followed by 100/0% picture (or vice versa). This resulted in a 2 x 2 design with the factors Congruency (match, mismatch) and Morph (35&65, 0&100). Each picture was shown for 750 ms with a jittered interstimulus interval of 300-500 ms in between during which a grey screen was shown. Each trial was followed by an intertrial interval of 1000-1400 ms, during which again a grey screen was shown. A fixation star was presented for 300 ms before the beginning of the next trial. A maximum of 80 test trials (20 per condition) were presented.

For both familiarization groups, 15 different randomization lists for familiarization and test phase were created and one of these lists was randomly assigned to each infant. Lists were pseudorandomized, ensuring that the same picture (during familiarization) or condition (during test phase) did not occur more than twice in a row. Furthermore, trials in the test phase were blocked so that every 16 trials, four trials from each condition had been presented.

Procedure

After arriving in the laboratory, infants and parents were given time to familiarize with the environment, and parents were explained the experiment. EEG recording was prepared while the infant was sitting on the parent's lap. An elastic cap in which 27 Ag-Ag-Cl-electrodes were mounted according to the 10-20 system was used for recording. An additional electrode was attached below the infant's right eye to compute the electrooculogram. The EEG signal was recorded with a PORTI-32/MREFA amplifier (Twente Medical Systems) with a sampling rate of 500 Hz.

The experiment took place in a soundproof chamber, in which the infant was seated on the parent's lap. The parent was instructed not to interact with the infant during the experiment. During the entire experiment, classical music (identical for all infants) was played in the background over loudspeakers. The experimental stimuli were presented on a 1024x786 CRT monitor positioned approximately 90 cm in front of the infant. The infant's looking behavior during the experiment was recorded using a small

camera mounted on top of the monitor. If the infant did not attend to the screen, colorful moving abstract shapes and ringtones were presented to redirect the infant's attention to the screen. The experiment continued until the infant became too fussy or the maximum number of trials was presented.

Data analysis

All infants included in the final sample successfully completed the entire familiarization phase. Video recordings of the infants' looking behavior during familiarization were checked to ensure that the pictures to which infants attended were uni- or bimodally distributed. Data were rereferenced offline to the mean of TP9 and TP10 (linked mastoids), and filtered between 0.2 and 20 Hz. Data were segmented into 1050 ms epochs, ranging from 300 ms before to 750 ms after picture onset. Only the second of the two pictures presented during the trials in the test phase was considered for analysis. In 10 infants (6 in the bimodal and 4 in the unimodal group), one electrode was noisy and interpolated using spherical spline interpolation (Perrin et al., 1989). To detect trials contaminated by artifacts, the standard deviation in a sliding window of 200 ms within these epochs was computed. If the standard deviation exceeded 80 μV at any electrode the entire trial was rejected. Additionally, the data were inspected visually for any remaining artifacts. Based on the video recordings all trials in which the infant did not look at both, the first and the second picture of a trial, were excluded from further analysis. All infants included in the final sample contributed at least 2 trials per condition (see below). Note that while this is a low minimal number of trials, previous studies obtained reliable ERP results in infants with very few trials (Stets & Reis, 2011).

Data were averaged for each condition and learning group, and a baseline correction was performed using 150 ms before stimulus onset as a baseline. As we did not expect any differences in response between the two women, we collapsed responses to 0/100% and 100/0% as well as 35/65% and 65/35% pictures. In the bimodal group, infants contributed on average 7.1 trials for each condition

(match0&100: 6.7 (SD = 3.0), match35&65: 7.2 (SD = 2.8), mismatch0&100: 7.3 (SD = 2.4), mismatch35&65: 7.1 (SD = 2.7)); in the unimodal group, infants contributed on average 7.6 trials per condition (match0&100: 7.5 (SD = 3.8), match35&65: 7.3 (SD = 4.4), mismatch0&100: 7.6 (SD = 4.0), mismtach35&65: 8.0 (SD = 4.0)). Based on visual inspection and previous results on the timing and localization of the mismatch effect in repetition priming (Bristow et al., 2008), we analyzed the ERP response in a frontal ROI encompassing F7, F3, FZ, F4, and F8 averaged in a time-window of 100-250 ms after stimulus onset.

RESULTS & DISCUSSION

A repeated-measures ANOVA on the mean frequency of infants' ERP response to the target image with Congruency (match, mismatch) and Morph (35&65, 0&100) as within-subjects factor and Familiarization (unimodal, bimodal) as between-subjects factor revealed an interaction between Congruency and Familiarization ($F(1,56) = 4.39, p=.041, \eta^2=.07$, see Figure 2). Planned comparisons showed that while there was a significant difference in response between matching and mismatching pictures in the bimodal learning group ($F(1,28) = 11.39, p=.002, \eta^2=.29$; matching: $2.58 \pm 2.51 \mu\text{V}$ (mean \pm SE), mismatching: $-7.55 \pm 2.18 \mu\text{V}$), no difference was found for the unimodal learning group ($F(1,28) = 0.14, p=.7, \eta^2=.005$).

The results show that infants' neural processing of faces is modulated by the frequency with which different faces occur: Infants exposed to a unimodal frequency distribution during familiarization showed similar repetition effects for identical face pictures and different face pictures taken from each end of the presented continuum. This suggests that they perceived them as being similar, either because they did not discriminate between the faces or because they categorized them as being the same. In contrast, infants who were familiarized to a bimodal frequency distribution showed discriminatory brain responses to faces from each end of the continuum, suggesting that they detected them as being

different. Note that the specific face pictures used in the test phase were identical across groups and have been presented equally often during familiarization in both groups. The processing difference can thus not be attributed to stimulus differences or exposure *per se*, but can only result from the different statistical characteristics of the familiarization phase. The ERP results therefore indicate that infants learn about face identity from distributional information.

Specifically, we found that repeated exposure to two different faces as compared to repeated exposure to two identical faces elicited a more negative ERP response at frontal sites in an early time window (100-250 ms) after stimulus onset in the bimodal, but not the unimodal, familiarization group. We interpret the more negative ERP response that we observed for different as compared to identical faces in the bimodal group, as a mismatch response, indexing that infants perceive the presented faces as belonging to different categories. While mismatch responses have mainly been reported for auditory stimuli, they can also be elicited by visual stimuli (for a review see Stefanics et al., 2014). For instance, Bristow et al. (2008) report a similar effect in a multimodal priming paradigm with infants. Specifically, this study found a frontal mismatch negativity peaking around 150-250 ms after target onset when two consecutively presented syllables were different but not when they were identical. The effect occurred regardless of whether both syllables were presented in the same modality or not, indicating that it reflects category rather than simple stimulus matching. We therefore take our results as evidence that infants in the unimodal group formed one face category while infants in the bimodal group formed two face categories based on the distribution of the morphed exemplars they saw.

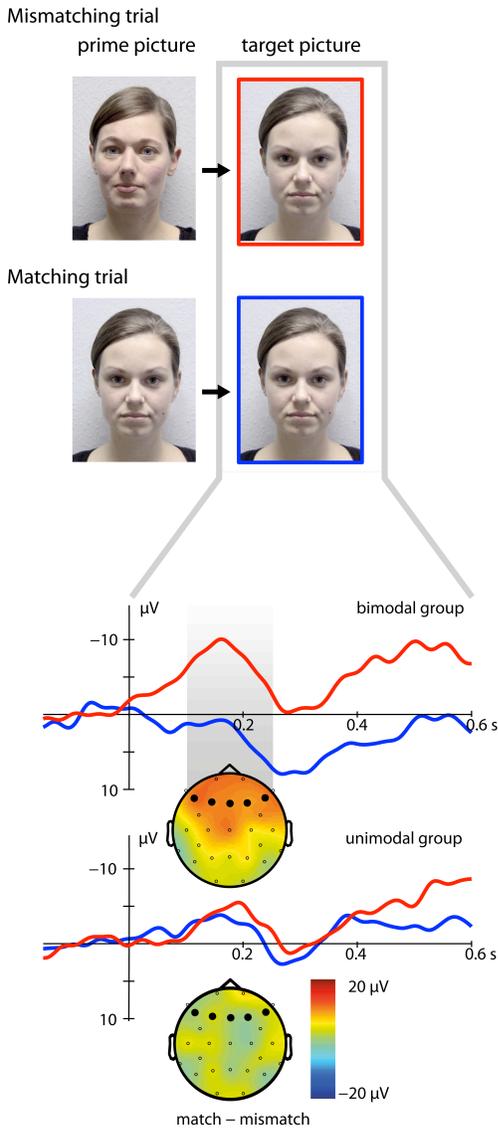


Figure 2: ERP results. The upper part of the figure illustrates two test trials, a mismatch trial (upper row) and a match trial (lower row). ERP responses at frontal electrodes elicited by matching (blue) and mismatching (red) target pictures are depicted in the bottom part of the figure. The upper graph shows the responses in the bimodal learning group, while the bottom graph shows the responses in the unimodal learning group. The topographical representations show the difference between the matching and the mismatching condition between 100 and 250 ms. Black dots mark the electrodes included in the analysis.

This finding concurs with previous reports that statistical information influences the categorization of auditory speech sounds (Maye et al., 2002) and visual objects (Raijmakers, van Rooien & Junge, 2014), and extends the findings to the domain of face processing. The finding that limited exposure to a set of morphed faces can induce changes in face perception is especially noteworthy as infants have been shown to show robust discrimination and recognition of individual faces (Snyder et al., 2010; Webb & Nelson, 2001; but see Peykarjou et al., 2014). The findings imply that limited exposure to different distributions of morphed faces can induce different categorization of these faces in infants as young as 6 months of age, extending earlier work on face categorization. For instance, Younger and Fearing (1999) report that 7-month-olds who were habituated to male and female faces formed one global face category and did not differentiate faces according to gender, while 10-month-olds formed more elaborate categories that took the faces' gender into account. Based on these results and previous studies (e.g. Younger, 1992), they suggested that younger infants focus on specific salient attributes that are shared across exemplars to form categories while older infants attend to correlations among attributes, which facilitates the formation of distinct categories. Our results indicate that younger infants are also already able to form differentiated face categories, and that statistical information can guide such category formation. Note, however, that infants increasingly lose sensitivity to within-category differences, such as differences between other-race and other-species faces, between 6 and 9 months of age (cf. Maurer & Werker, 2014). Infants around 6 months of age are thus still sensitive to a wide variety of differences in facial features, which might have helped them to focus on relevant differences to differentiate between identities in our study.

The finding that infants form a face representation based on encountered exemplars also complies with current models of face recognition. Most models of face recognition assume that faces are represented in a multidimensional space and that the identity of an individual face is encoded relative to a prototype or average face representation that is based on the perceived exemplars (Rhodes et al.,

1998; Valentine, 1991). These models assume a statistical mechanism that computes an average or prototype face. When presented with a range of faces varying in terms of emotion, gender and identity (de Fockert & Wolfenstein, 2009; Haberman & Whitney, 2009) adults form a representation that averages across the input – even if the individual faces are well-known (Neumann, Schweinberger & Burton, 2013). Similarly, infants have been shown to form average faces from presented exemplars after short exposure (de Haan et al., 2001; Rubenstein, Kalakanis & Langlois, 1999). Our results extend these findings by indicating that infants are not only able to calculate an average face from a set of different exemplars. Rather, the specific statistical distribution in the input can trigger the formation of one or two face representations from the same set of exemplars. Our results thus show the influence of probabilistic information in the input above and beyond pure averaging, and suggest that infants are sensitive to the perceived overall similarity between different face exemplars. It is critical to note that a similar mechanism might also be at play in adults. However, to our knowledge, the influence of distributional information on adult face recognition has not been directly examined.

CONCLUSIONS

To conclude, our findings suggest that statistical learning provides a useful mechanism to shape face perception by highlighting meaningful across-category differences while obscuring accidental within-category variation. This might help to form categories at different levels of perception, allowing not only to detect faces from different species or races, but also to reliably differentiate individuals even though they do not always look exactly the same at each encounter. Face perception might thus be similarly shaped by the distributional properties of the input as speech perception. Statistical learning is therefore a promising candidate for a domain-general mechanism that shapes native attunement for both faces and language.

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