Perceptual narrowing in face and speech perception during infancy

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Declaration

I declare that I have completed this dissertation single-handedly without the unauthorized help of a second party and only with the assistance acknowledged therein. I have appropriately acknowledged and cited all text passages that are derived verbatim from or are based on the content of published work of others, and all information relating to verbal communications. I consent to the use of an anti-plagiarism software to check my thesis. I have abided by the principles of good scientific conduct laid down in the charter of the Justus Liebig University Giessen „Satzung der Justus-Liebig-Universität Gießen zur Sicherung guter wissenschaftlicher Praxis“ in carrying out the investigations described in the dissertation.

Gießen, August 2021 ______________________________

Anna Krasotkina

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I. SYNOPSIS

1. INTRODUCTION

Starting from birth, infants are surrounded by an incredible amount of distinctive stimuli from various domains. Generally, infants encounter certain types of stimuli more often than others. For example, usually an infant's environment contains more examples of same-race faces than examples of other-race faces (Sugden et al., 2014). Likewise, infants are typically exposed to their native language more frequently than to non-native languages.

In order to process these stimuli as efficiently as possible, the human perceptual system attunes itself towards the stimuli which are more common in the infant's environment. This attunement is accompanied by a decrease in the ability to distinguish between stimuli infants do not encounter frequently. This change in discrimination ability, known as perceptual narrowing, usually happens during the second half of the first year of life.

The overall goal of the studies presented here was to understand the process of perceptual narrowing as it applies to two crucial sensory modalities for the perception of socially relevant stimuli: faces and speech. Our studies not only examined the process of perceptual narrowing within each of these modalities individually, but also focused on the potential relations between these modalities in terms of perceptual narrowing. Additionally, we also examined the potential mechanisms which may drive perceptual narrowing in these domains such as statistical learning and the gaze behavior infants use to encode faces. Below, the reader will find a brief overview of the state of the literature concerning perceptual narrowing, statistical learning, and infants' gaze behavior for faces, after which our studies will be discussed in greater detail.

1.1. Perceptual narrowing

During the first 6 months of life infants can discriminate novel and familiar stimuli regardless of whether or not they have been exposed to that particular type of stimulus before. Starting from the second half of the first year, infants maintain and improve their discrimination abilities only with regard to stimuli that they frequently encounter in their daily life. This developmental change has been observed in several domains, such as speech perception (e.g., Höhle et al., 2009; Werker & Tees, 1984), human face perception (e.g., Kelly et al., 2005; Kelly et al., 2007), animal face perception (Simpson et al., 2016), and music (Hannon & Trehub, 2005; Soley & Hannon, 2010).

In the domain of speech perception, the perceptual narrowing process arises differently for various types of speech sound contrasts within the first year of life (e.g., Werker & Tees, 1984; Höhle et al., 2009). Infants start to show a decrease in sensitivity for non-native speech elements such as vowels at around 6 months, (Polka & Werker, 1994), to consonants at around 10–12 months, (Werker & Tees, 1984), to word stress at 10 months (Bijeljac-Babic et al., 2012), and to lexical tone contrasts between 6 and 9 months (Götz et al., 2018; Mattock & Burnham, 2006; Yeung et al., 2013). Thus, an infant's initially broadly tuned speech-processing system is gradually attuned to the set of speech sound contrasts that are common in their native language.

Around the same time, the infant's face-processing system becomes similarly attuned to faces which are more common in the infant's environment. At 3 months of age, Caucasian and Asian infants do not yet exhibit differences in discrimination ability for same- and other-race faces, and can successfully discriminate between Caucasian, Asian, African, and middle-Eastern faces (Kelly et al., 2007; Kelly et al., 2009). However, by the age of 9 months, infants have been shown to discriminate only between same-race faces (Kelly et al., 2007; Kelly et al., 2009). Thus, an infant's face-processing system becomes attuned to same-race faces over the course of the second half of the first year of life due to the high frequency with which the infant is exposed to them (Kelly et al., 2007; Kelly at al., 2009; Krasotkina et al., 2020; Spangler et al., 2013).

These similarities between the perceptual narrowing processes in infants' speech-perception and face-perception have led to the suggestion that these domains might share some underlying developmental (Maurer & Werker, 2014) and neural mechanisms (Belin et al., 2011). Since face and speech perception share some neural structures such as the superior temporal sulcus (Pascalis et al., 2014), and show a similar timeframe of perceptual narrowing, several researchers have suggested that an underlying domain-general principle or mechanism might drive perceptual narrowing in these domains (Hadley et al., 2014; Pascalis et al., 2014; Scott et al., 2007).

1.2. Statistical learning

It is not yet known precisely what underlying mechanisms might link perceptual narrowing in speech and face perception. One possibility is that domain-general statistical learning processes contribute to cross-domain similarities in the development of face and speech perception. Statistical learning theory relies on observations that infants are sensitive to clusters of similarity between objects, and can form object categories centered on those clusters (e.g. Younger, 1985). This mechanism is thought to affect the reorganization of perception based on statistical patterns embedded within the frequency and distribution of stimuli that individuals encounter.

Statistical learning posits that if the distribution of stimuli differs along a sensory dimensional, infants will use that dimension to discriminate among those stimuli. For example, Maye et al. (2002) exposed 6- to 8-month-old infants to voicing contrasts to which they had already lost sensitivity due to perceptual narrowing. Afterward, infants who were exposed to a bimodal continuum (vocal contrasts which were nearer to the two endpoints of the voicing continuum were presented more frequently) were able to discriminate the vocal contrasts from the ends of this continuum. By contrast, infants who were exposed to a unimodal continuum (vocal contrasts which were nearer to the middle of the voicing continuum were presented more often) were unable to discriminate the vocal contrasts at the ends of this continuum. This method was also successfully used to re-sensitize 10-month-old infants to non-native sound contrasts (Yoshida et al., 2010).

There is also an indication that the manipulation of statistical learning through the use of varying frequency distributions re-shapes infants' perception abilities in the face-processing domain, and can counteract the typical effects of perceptual narrowing. By using unimodal and bimodal frequency distributions, Altvater-Mackensen, et al. (2017) were able to modify infants' ability to discriminate among same-race faces. After familiarization using a bimodal distribution continuum of same-race faces, 6.5-month-old infants could discriminate between the endpoint faces during testing. On the other hand, infants who were familiarized with a unimodal distributional continuum were unable to discriminate between the endpoint faces during testing. Thus, the frequency distribution of stimuli appears to influence infants' subsequent discrimination of faces, suggesting that statistical learning shapes face perception.

1.3. Infants' gaze behavior for face perception

During the perceptual narrowing process, the infant's sensory system attunes itself to the most efficient way of acquiring information based on characteristics that are common to familiar stimuli. For example, after being exposed to a predominance of same-race faces, the infant's face recognition system calibrates itself such that the infant begins to examine faces in in a manner optimized for the perception of same-race faces. This hypothesis was supported by evidence that infants display different fixation patterns when looking at same- versus other-race faces (Liu et al, 2011; Wheeler et al., 2011; Xiao et al., 2014).

For example, Wheeler et al. (2011) found that while looking at same-race faces, 6- to 10-month-old Caucasian infants showed more fixations for the eyes of same-race faces and fewer for the mouth of same-race faces with increasing age. By contrast, no such adjustment of gaze fixation patterns was shown for other-race faces. In another study, Xiao et al. (2014)

found that at 9 months of age, Caucasian infants looked longer at the eyes of same-race faces compared to other-races faces, and less at the mouth of same-race faces compared to other-race faces.

The way infants look at same-race and other-race faces during familiarization or habitation also affects infants' ability to distinguish between familiar and novel exemplars of such faces afterwards. For example, in a study by Xiao et al. (2014), 6- and 9-month-old Asian infants looked significantly longer at the nose and mouth of same-race faces than of other-race faces during familiarization. Moreover, the amount of time these infants looked at the eyes and nose of faces was positively correlated with their recognition performance during testing.

Overall, these findings suggest that Caucasian and Asian infants look differently at same-race and other-race faces, and that at least in the case of Asian infants, these differences in their gaze patterns are related to their ability to distinguish between faces.

1.4. Objectives

In summary, although perceptual narrowing has been thoroughly investigated in the domains of face and speech perception, there is a lack of research on the possible connections between these domains in terms of perceptual narrowing. Therefore, one of the objectives of the present set of studies was to investigate the relations between perceptual narrowing in these two domains by testing the effects of perceptual narrowing in both domains within the same infants. Within this broad framework, Study 1 (Krasotkina et al., 2018) investigated whether perceptual narrowing in face and speech perception might be driven by shared mechanisms. To examine this question, we tested Caucasian 9-month-old infants from monolingual German households on their ability to discriminate among non-native Cantonese speech tones, as well as among same-race German faces and other-race Chinese faces. The goal of Study 2 (Krasotkina et al., 2021b) was to further explore this question from a longitudinal perspective by testing Caucasian infants at both 6 and 9 months using the same tasks as Study 1. By taking a longitudinal approach, we were able to investigate whether the same infants would show a similar decrease in their sensitivity towards both other-race faces and non-native speech.

Study 3 (Krasotkina et al., 2021a) was aimed at exploring whether statistical learning is indeed one of the underlying mechanisms driving perceptual narrowing in face perception, by attempting to re-sensitize infants to other-race faces after they have already started to undergo the perceptual narrowing process in the face domain. To accomplish this goal, we manipulated the statistical distribution of stimuli as we familiarized 12-month-old German infants to other-race Chinese faces. Thus, we were able to evaluate to impact of statistical learning at this age by comparing the effects of different frequency distributions of stimuli used during familiarization on the infants' ability to discriminate among those faces.

Study 4 (Krasotkina et al., 2020) continued to explore the effects of perceptual narrowing on the encoding of familiar and unfamiliar stimuli by examining the gaze behavior of Caucasian 9-month-old infants in relation to their discrimination of same-race and other-race faces by using eye-tracking. Thus, the main goal of this study was to search for a link between gaze behavior and face discrimination ability in Caucasian infants after the onset of perceptual narrowing, similar to the study carried out by Xiao et al. (2014) with Asian infants.

2. STUDY 1 - PERCEPTUAL NARROWING IN SPEECH AND FACE RECOGNITION: EVIDENCE FOR INTRA-INDIVIDUAL CROSS-DOMAIN RELATIONS (KRASOTKINA ET AL., 2018)

In previous studies, perceptual narrowing has been observed in the domains of face and speech perception. For face perception, the decline in infants' ability to discriminate among other-race faces typically occurs around 9 months of age (Kelly et al., 2007; Kelly et al., 2009). Around the same time, infants also start to show a decrease in sensitivity for non-native speech, with some variation for different language constructs (Polka & Werker, 1994; Werker & Tees, 1984; Höhle et al., 2009; Mattock & Burnham, 2006; Yeung et al., 2013; Götz et al., 2018). This similarity in the timeframes of such developmental changes in these two domains has led to the suggestion that these changes could be driven by shared domain-general processes (Maurer & Werker, 2014).

In this study we investigated whether the effects of perceptual narrowing in the domains of face and speech perception are related, by testing 9-month-old infants on their ability to discriminate among same-race and other-race faces, as well as among non-native Cantonese tone contrasts. If the face and speech perception domains indeed share a domain-general mechanism driving perceptual narrowing, an infant's ability to discriminate among other-race faces should be associated with their ability to discriminate among non-native speech contrasts, and vice versa.

Method

Fifty-three Caucasian infants from German speaking households participated in Study 1 (Krasotkina et al., 2018), and were randomly assigned to either Group A or Group B. Each infant took part in both face (other-race face for group A, same-race faces for group B) and speech (non-native stimuli for both Groups A and B) discrimination tasks in random order. For the non-native speech stimuli, we used CV syllables (/tɕʰi/) with mid-level or high-rising tones, which were used in a study by Yeung et al. (2013), who found perceptual narrowing effects for these stimuli in 9-month-old infants. For the face stimuli, we used colored photographs of six other-race Asian (Chinese origin) and six same-race Caucasian (German origin) women (Figure 1).

Figure 1. Examples of other-race (above) and same-race (below) faces used in the habituation and test trials. During habituation faces were shown in 3 poses (¾ left, frontal, and ¾ right), while test trials only featured the frontal pose.

We used an infant-controlled habituation-dishabituation procedure with a maximum of 18 trials to measure the infants' ability to discriminate among non-native Cantonese speech tones, as well among same-race German faces and other-race Chinese faces. During habituation, infants were presented with a stimulus from one category until habituation was achieved, or up to a maximum of 18 trials. After that, infants proceeded to the test phase, where they were sequentially presented with the habituated stimulus and a novel stimulus of the same type (2 test trials in total) in random order. Both habituation and test trials were infant-controlled (trial ended if the infant looked away for more than 2 seconds), and lasted for up to 40 seconds.

Results

For an indicator of discrimination ability, we calculated novelty preference (NP) scores: infants' fixation time toward the novel stimulus divided by the sum of the fixation times toward the novel and habituated stimuli during test trials. Thus, if an infant's NP score was above 0.5 it indicated a preference for the novel stimulus, and thus an ability to discriminate among the stimuli. We used one sample *t*-tests to test the NP scores against chance level (0.5). The results indicated that infants could discriminate between same-race faces (M = .591, SD = .214; $t(25)$ = 2.181, p = .039; d = 0.43), but could not discriminate between other-race faces (M = .517, *SD* = .255; *t*(26) = 0.347, *p* = .732; *d* = 0.03) and non-native speech tones (Group A: *M* = .577, *SD* = .259; *t*(26) = 1.551, *p* = .133; *d* = 0.3; Group B: *M* = .529, *SD* = .276; *t*(25) = 0.538, *p* = .596; *d* = 0.11), see Figure 2. Next, to determine whether there was a relation between infants' NP scores in the speech and face tasks, we calculated Pearson correlations between infants' NP scores in the face and speech tasks separately for Groups A and B. We found that NP scores for the non-native speech tones and other-race faces in Group A were significantly positively correlated, while the NP scores for non-native speech tones and same-race faces in Group B did not correlate (Figure 3).

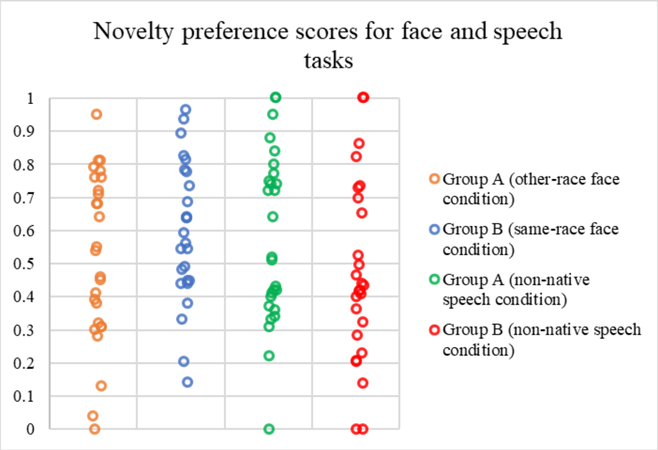

Figure 2. Distribution of individual novelty preference scores for the face and speech tasks.

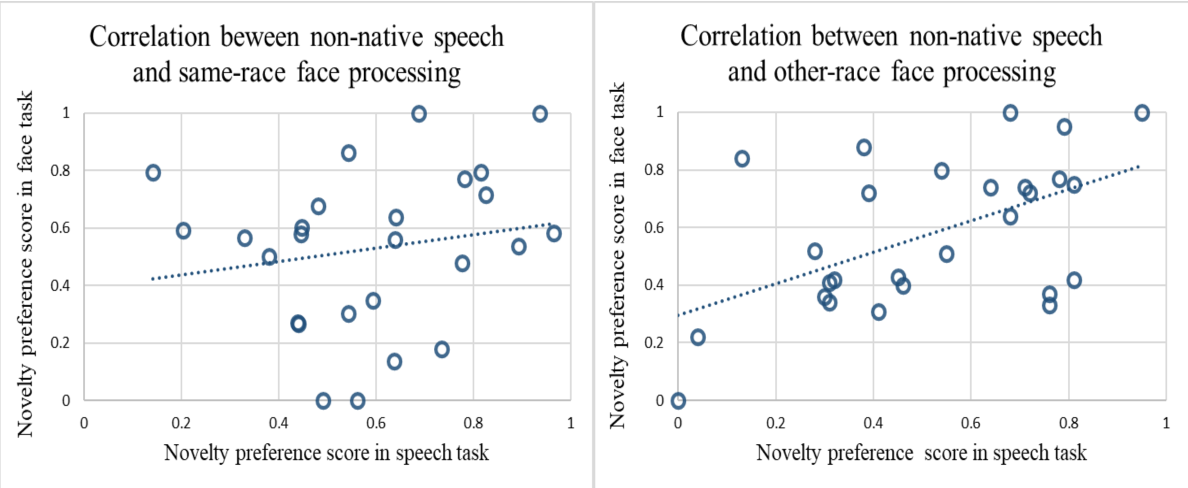

Figure 3. Correlations between novelty preference scores in the non-native speech and same-race face tasks (Group B), and between novelty preference scores in the non-native speech and other-race face tasks (Group A).

Taken together, the results of study 1 showed that at the age of 9 months, infants could discriminate only between same-race faces, and could not discriminate between other-race faces or non-native speech tones. Moreover, infants who performed worse at discriminating among other-race faces also performed worse at discriminating among non-native speech and vice versa. There was no significant correlation between infants' performance in the same-race face and non-native speech tasks, showing that the correlation between the NP scores for other-race faces and non-native speech is unlikely to be a general effect resulting from task structure similarity. These findings add support to the hypothesis that perceptual narrowing in speech- and face-perception might be driven by shared domain-general mechanisms.

3. STUDY 2 - PERCEPTUAL NARROWING IN FACE- AND SPEECH-PERCEPTION DOMAINS IN INFANCY: A LONGITUDINAL APPROACH (KRASOTKINA ET AL., 2021B)

Since perceptual narrowing in the domains of face and speech perception tend to occur within a similar timeframe in infants, it has been proposed that the development of face and speech perception may share some domain-general mechanisms (Pascalis et al., 2014). In our previously study (Krasotkina et. al., 2018), we found that 9-month-old infants who undergo perception narrowing for other-race faces show a similar degree of perceptual narrowing for non-native speech stimuli and vice versa. However, thus far there has been no evidence demonstrating how infants' abilities in discriminating both other-race faces and non-native speech stimuli change during the age range when perceptual narrowing typically occurs. Therefore, the aim of this study was to determine whether perceptual narrowing in the domains of face and speech processing could be observed in progress simultaneously in the same infants. To achieve this, we tested a group of infants longitudinally at 6 months of age, when perceptual narrowing typically begins in these domains, and later at 9 months, when perceptual narrowing should already be clearly manifested.

Method

Fifty Caucasian infants from monolingual German-speaking households took part in this study. All infants were randomly divided into two groups (A and B), with 25 infants in each group. Infants participated in the face and speech tasks at both 6 and 9 months of age. Infants in group A participated in the other-race face task and non-native speech task, while infants from a group B took part in the same-race face task and non-native speech task.

We used the same stimuli material as in Krasotkina et al. (2018): Face stimuli consisted of colored photographs of Caucasian and Asian women for same- and other-race faces respectfully. CV syllables (/tɕʰi/) were used as non-native speech stimuli (Yeung et al., 2013). We followed the same experimental paradigm as Krasotkina et al. (2018), using the same infant-controlled habituation-dishabituation procedure, with a maximum of 18 habituation trials (fewer if habituation was reach earlier), followed by 2 test trials (the habituated and novel stimuli in random sequential order) for both the face and speech tasks. All habitation and test trials were infant-controlled (trial ended if the infant looked away for more than 2 seconds) with a maximum duration of 40 seconds.

Results

As in Study 1, we calculated novelty preference (NP) scores as an indicator of the infants' discrimination ability. We again conducted one-sample t-tests for the infants at 6 and 9 months as described earlier in Study 1 to compare the infants' NP scores against chance-level discrimination (0.5).

The t-tests for the face task showed that at the age of 6 months, infants in both groups A and B showed NP scores significantly above chance-level (other-race faces: $M = .61$, $SD = .15$; $t(24) = 3.734$, $p = .001$, $d = 1.524$; same-race faces: $M = .62$, $SD = .20$; $t(24) = 3.065$, $p = .000$ $d = 1.251$). However, at the age of 9 months only infants in the same-race condition (group B) showed NP scores significantly above chance-level ($M = .66$, $SD = .18$; $t(24) =4.811$, $p = .000$, $d = 1.964$), while infants in other-race condition (group A) showed NP scores that did not significantly differ from chance-level ($M = .48$, $SD = .17$; $t(24) = -.699$, p = .491, d = -0.285). These results indicate that at 6 months infants could successfully discriminate between novel and habituated same- and other-race faces, whereas at the 9 months, infants could only discriminate between same-race faces (Figure 4).

The t-tests for the speech task (combining data from Groups A and B) showed that at the age of 6 months, infants showed NP scores significantly higher than chance-level ($M = .60$, $SD = .14$; $t(49) = 5.204$, $p = .000$, $d = 1.487$). At the age of 9 months, the same infants no longer showed NP scores significantly higher than chance-level ($M = .49$, $SD = .08$; $t(49) = -0.73$, $p = .4688$, $d = -0.209$). These results therefore indicate that at the age of 6 months infants could differentiate between the novel and habituated non-native speech tones, but by 9 months the same infants could not discriminate between the novel and habituated non-native speech tones (Figure 5).

To analyze age-dependent changes in stimulus discrimination we conducted separate repeated-measures ANOVAs for Group A and Group B with novelty preference as the dependent variable, and with age (6 months, 9 months) and task type (face task, speech task) as within-subject factors.

In group A (other-race faces, non-native speech contrasts) we found a significant main effect of age ($F(1, 24) = 19.701$, $p = .000$, $d = 1.281$), indicating that infants' novelty preferences for both types of stimuli decreased significantly from 6 months (*M* = .634, *SD* = .023) to 9 months of age (*M* = .490, *SD* = .020). We found no significant main effect of task type ($F(1, 24) = 1.001$, $p = .327$, $d = 0.289$), and no significant interaction between age and task type ($F(1,24) = .010$, $p = .922$, $d = 0.029$), indicating that novelty preferences decreased similarly for both the face and the speech stimuli as the infants grew older.

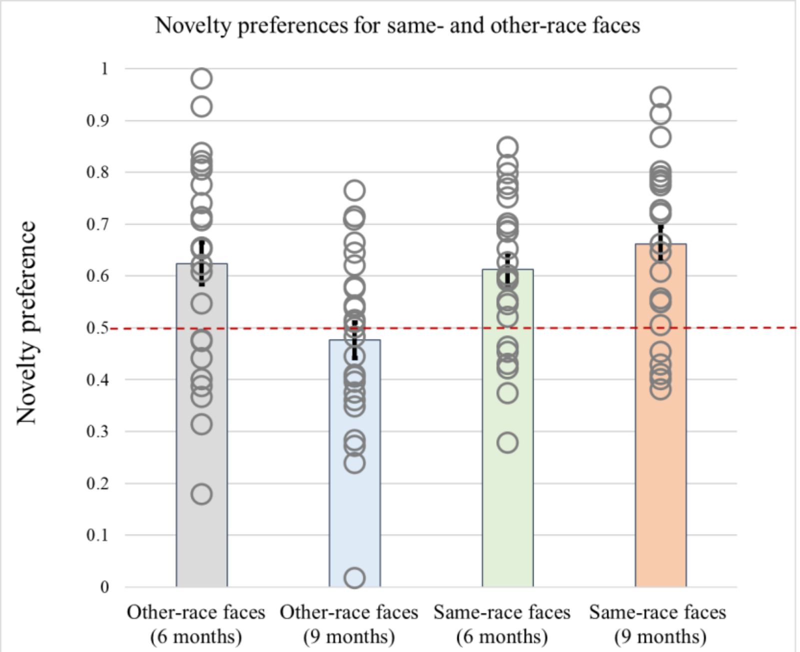

Figure 4. Novelty preference scores for same-race and other-race faces at 6 and 9 months. Bars represent group means, error bars represent standard error, circles represent individual datapoints.

In group B (same-race faces, non-native speech contrasts) we found a significant main effect of task type ($F(1, 24) = 22.817$, $p = .000$, $d = 1.379$), indicating that infants' novelty preferences for faces (*M* = .637, *SD* = .018) were significantly higher than their novelty preferences for speech (*M* = .521, *SD* = .016). We also found a significant interaction between age and task type, $F(1, 24) = 4.972$, $p = .0355$, $d = 0.644$). Post-hoc pairwise comparisons (with Bonferroni corrections for multiple comparisons) showed that while the infants' novelty preferences for same-race faces at 6 months (*M* = .612, *SD* = .030) and at 9 months (*M* = .562, SD = .020) did not differ significantly, their novelty preferences for non-native tones decreased significantly ($p = .012$) from the age of 6 months (*M* = .662, *SD* = .034) to 9 months (*M* = .479, *SD* = .017).

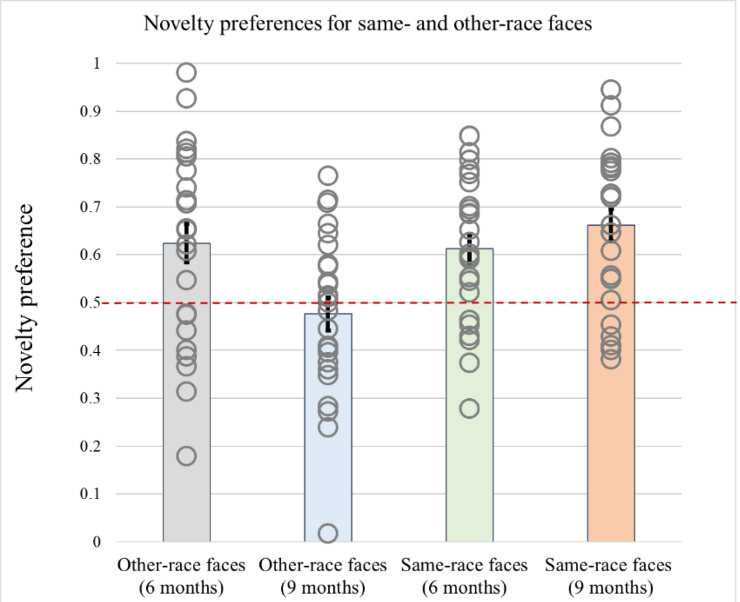

Figure 5. Novelty preference scores for non-native speech in groups A and B at 6 and 9 months. Bars represent group means, error bars represent standard error, circles represent individual datapoints.

Finally, as in Study 1, we calculated a Pearson correlation between the infants' novelty preferences for other-race faces and non-native speech at 9 months of age. However, unlike in Study 1, this time we did not find a significant correlation between these measurements. This suggests that even if there are indeed domain-general mechanisms which drive perceptual narrowing in face and speech perception, their influence may be weaker than the natural variation among the infants in the perception of these stimuli.

Taken together, the findings of study 2 showed that infants undergo simultaneous perceptual narrowing in their discrimination of other-race faces and non-native tones between 6 and 9 months of age. These findings add evidence in support of the theory of domain-general mechanisms driving perceptual narrowing in speech and face processing at least to some degree.

4. STUDY 3 - BIMODAL FAMILIARIZATION RE-SENSITIZES 12-MONTH-OLD INFANTS TO OTHER-RACE FACES (KRASOTKINA ET AL., 2020)

The ability of infants to discriminate among other-race faces typically deteriorates from approximately 6 months of age due to perceptual narrowing. This study explored whether 12-month-old Caucasian infants could be re-sensitized to differences between other-race faces by making use of statistical learning as they are familiarized to such stimuli. Statistical learning theory (for a review, see Aslin & Newport, 2012) proposes that infants learn to distinguish between stimuli by identifying the principal dimensions along which those stimuli differ. If exemplars of such stimuli most commonly fall into two clusters at the opposite ends of the dimension (i.e., a bimodal distribution), such a distribution appears to more easily sensitize infants to the differentiating dimension. By contrast, a unimodal distribution with exemplars forming a single cluster seems to make it more difficult for infants to learn to use the differentiating dimension to distinguish between stimuli. Thus, we hypothesized that after familiarization using a bimodal frequency distribution of other-race face, infants should show better discrimination between these faces compared to a unimodal familiarization condition. If our results would indeed show this to be true, this would be an indication that perceptual narrowing can still be counteracted to some degree even months after its manifestation in the domain of face perception.

Method

For this study we tested 40 12-month-old Caucasian infants. The infants were randomly assigned to either the unimodal or bimodal familiarization condition. For our stimuli, we created a morphed continuum between two photographs of Chinese women. The morphed continuum contained 21 faces, gradually transforming from Face A (100% Face A/ 0% Face B) to Face B (0% Face A/ 100% Face B) in 5% increments (Figure 6).

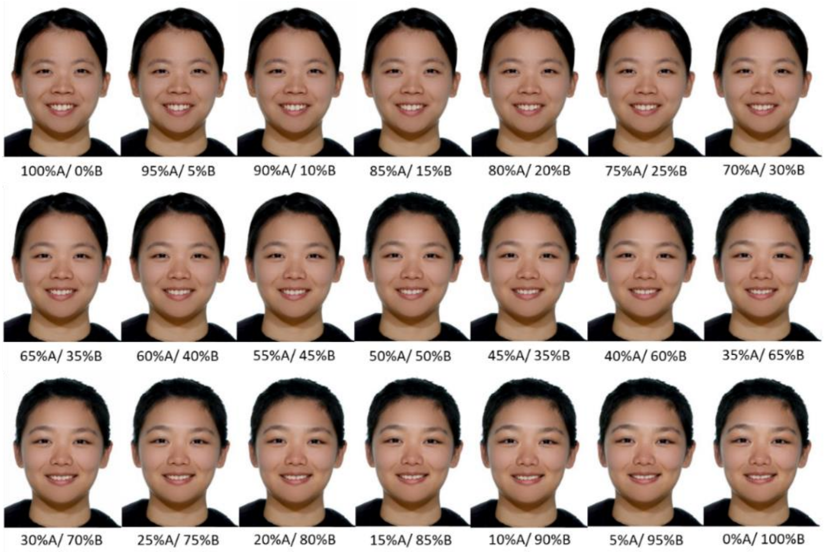

Figure 6. Morphing sequence from Face A to Face B.

To present these stimuli we used the same frequency distributions as described by Altvater-Mackensen et al. (2017). Although infants in both conditions saw the same amount of familiarization faces (159 exposures for 750ms each), infants in the unimodal condition saw the morphs from the middle of the continuum the most frequently, while infants in the bimodal condition saw the morphs near the outside quartiles of the continuum the most frequently (see

Figure 7 for the frequency distributions in the unimodal and bimodal conditions). Infants in both conditions saw the endpoint faces (100%A/ 0%B and 0%A/ 100%B) the same number of times (3 times each) during the familiarization phase.

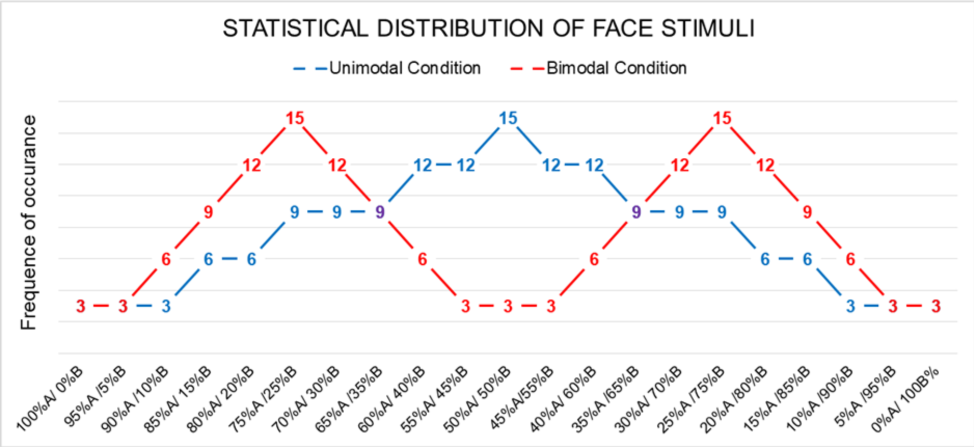

Figure 7. Frequency distribution of morphed face stimuli for the unimodal (blue) and bimodal (red) familiarization conditions.

The test phase started immediately after the familiarization phase, and was identical for both familiarization conditions. For the test trials we used the endpoint faces (100%A/ 0%B and 0%A/ 100%B), as primes and test faces, resulting in match trials (when the prime and the test faces were identical) and mismatch trials (when the prime and the test faces were different). The prime face was presented for 750ms, while the test face exposure was infant-controlled (trial ended if the infant looked away for more than 2 seconds) for up to 20 seconds. Each infant thus saw a total of 4 test trials, consisting of the 4 possible order combinations of face A and face B in the roles of prime faces and test faces (AA, BB, AB, BA). Each infant's test phase could begin either with a match or mismatch trial (randomly assigned), but match and mismatch trials were always presented in an alternating order.

Results

We conducted a repeated-measures ANOVA with congruency (match trial, mismatch trial) as a within-subject factor and condition (unimodal distribution, bimodal distribution) as a between-subjects factor, and using the infants' fixation times (in seconds) for the test face as the dependent variable. We found a significant main effect of congruency, $F(1,38) = 9.062$, $p = .005$, partial $\eta^2 = .23$, and a significant interaction between congruency and condition, $F(1,38) = 5.583$, $p = .023$, partial $\eta^2 = .14$. Pairwise comparisons showed that in the unimodal condition there was no significant difference in fixation times for the test faces between match and mismatch trials $F(1,38) = 0.210$, $p = .650$ partial $\eta^2 = .002$, match: $M = 16.886$s, $SE = 1.898$s, mismatch: M = 16.408s, SE = 1.983s. By contrast, infants in the bimodal condition showed a significant difference in fixation times between match and mismatch trials, $F(1,38) = 14.437$, $p = .001$ partial $\eta^2 = .632$, match: M = 15.230s, SE = 1.898s, mismatch: M = 11.260s, SE = 1.983s (Figure 8).

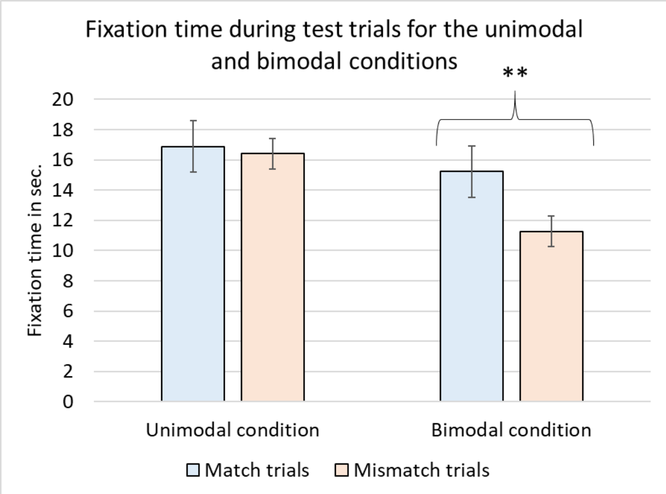

Figure 8. Fixation times during the test trials for the 12-month-old infants in the unimodal and bimodal conditions. Error bars represent standard error.

These results show that after exposure to a unimodal distribution of faces from a morphed continuum during familiarization, Caucasian infants did not discriminate between the endpoint Asian faces during the test. However, infants who were exposed to a bimodal distribution of faces from the same morphed continuum during familiarization showed significant differences in looking times between the match and mismatch trials. This indicates that only infants in the bimodal condition could successfully discriminate between the endpoint faces. These results therefore support the hypothesis that when infants are familiarized to a more varied bimodal distribution of other-race faces (as compared to a unimodal distribution), they can be re-sensitized to the dimension underlying the continuum of morphed faces shown during familiarization.

5. STUDY 4 - INFANTS' GAZE PATTERNS FOR SAME-RACE AND OTHER-RACE FACES, AND THE OTHER-RACE EFFECT (KRASOTKINA ET AL., 2021A)

One often discussed consequence of perceptual narrowing is the so-called other-race effect (ORE). The ORE is usually understood as a reduction in the ability to process faces from ethnicities that one does not have sufficient exposure to, and can already be observed in infants from approximately 9 months of age (Kelly et al., 2007; Kelly et al., 2009; Krasotkina et al., 2018).

Other studies also showed that infants visually explore same-and other-race faces differently (Liu et al., 2011; Wheeler et al., 2011; Xiao et al., 2014). However, it is still unclear how infants' looking behavior for same- and other-race faces is related to their face discrimination abilities. One study (Xiao et al., 2014), has already demonstrated that the looking time of Asian infants toward the eyes and nose of same- and other-race faces was related to their ability to discriminate among these faces. Therefore, the aim of the current study was to extend the above approach to determine whether Caucasian infants old enough to begin exhibiting the ORE would also show a link between gaze behavior and face discrimination.

Method

Sixty-eight 9-month-old Caucasian infants took part in our study. To avoid a carry-over effect, infants were randomly assigned into one of two conditions. Half of the infants took part in the same-race condition, and the half in the other-race condition. We used colored photographs of 6 Caucasian and 6 Asian women as stimuli.

To test the infants, we again used an infant-controlled habituation-dishabituation procedure with a maximum of 18 habituation trials. In the subsequent test trials, infants were shown photographs of the habituated face and a novel face in a random sequential order, for a total of 2 test trials. The durations of both the habituation and test trials were infant-controlled, with the trial ending as soon as the infant looked away for more than 2 seconds, for a maximum duration of 40 seconds. To measure the infants' gaze during the habituation and test trials, we used a Tobii TX300 eye tracker.

Results

To measure the infants' gaze behavior, we created five Areas of Interest (AOIs)—whole-head, left eye, right eye (for the analysis we combined the left and right eyes together into a single AOI), nose, and mouth (see Figure 9 for AOI illustrations). For each AOI we calculated proportional fixation times by dividing the time (in seconds) an infant fixated within this AOI by the infants' fixation time within the whole-head AOI. This calculation was carried out for each individual trial, after which we computed a mean proportional fixation time for each AOI across all habituation trials. To measure the infants' face discrimination abilities, we calculated novelty preference (NP) scores for the test trials, defined as the total fixation time for the novel face (whole-head AOI) divided by of the sum of the total fixation times for the novel and habituated faces. One-sample t-tests were then used to test these novelty preference scores against chance-level (0.5).

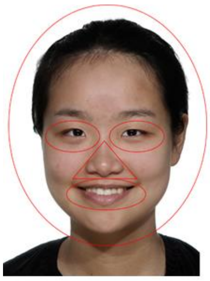

Figure 9. Illustration of the areas of interest (AOIs) corresponding to the left eye, right eye, nose, mouth, and the whole-head.

We found that novelty preference scores were significantly higher than chance for same-race faces (*M* = .669, *SD* = .202; *t*(33) = 4.872, *p* < .001; *d* = 0.176), but not significantly different from chance for other-race faces (*M* =.527, *SD* = .154; *t*(33) = 1.018, *p* = .316; *d* = 0.836). Therefore, the infants could discriminate between the same-race faces, but not between the other-race faces, which confirms findings from previous studies (Kelly et al., 2007; Kelly et al., 2009; Krasotkina et al., 2018).

To test whether infants looked differently at the same-race faces compared to other-race faces during habituation, three separate one-way ANOVAs were then carried out for each of the internal AOIs (eyes, nose, and mouth), with condition (same-race, other-race) as the main factor, and proportional fixation time as the dependent variable. The analysis for the eyes AOI showed that infants fixated significantly longer on the eyes of same-race faces (*M* = .388, *SD* = .218) than of other-race faces (*M* = .216, *SD* = .215), *F*(1, 66) = 10.698, *p* = .002; *d* = 0.805, see Figure 10. However, the differences between same- and other-race faces in proportional fixation times were not significant for the nose or mouth AOIs.

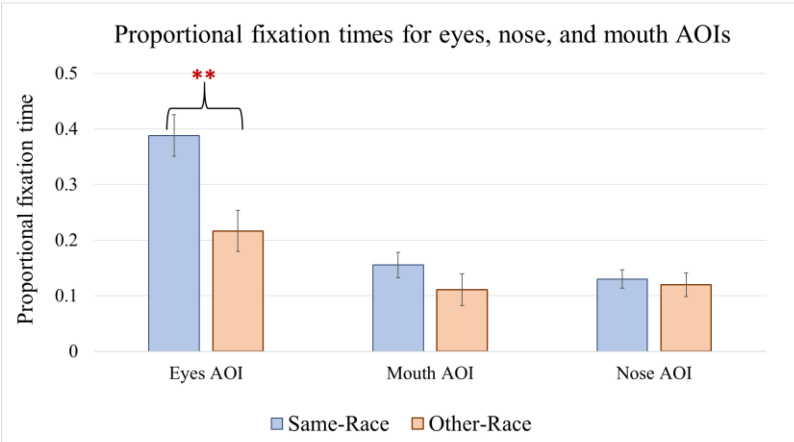

Figure 10. Proportional fixation times for eyes, nose, and mouth AOIs during the habituation phase for the same-race and other-race conditions. Error bars indicate standard error.

We also found a significant positive Pearson correlation in the same-race condition between the infants' proportional fixation times for the eyes AOI during habituation, and their novelty preferences during test trials (r = .380, p= .027). There was no such correlation in the other-race condition (Figure 11). Thus, our data suggest that for 9-month-old infants, gaze behavior during habituation is related to their ability to discriminate between same-race faces.

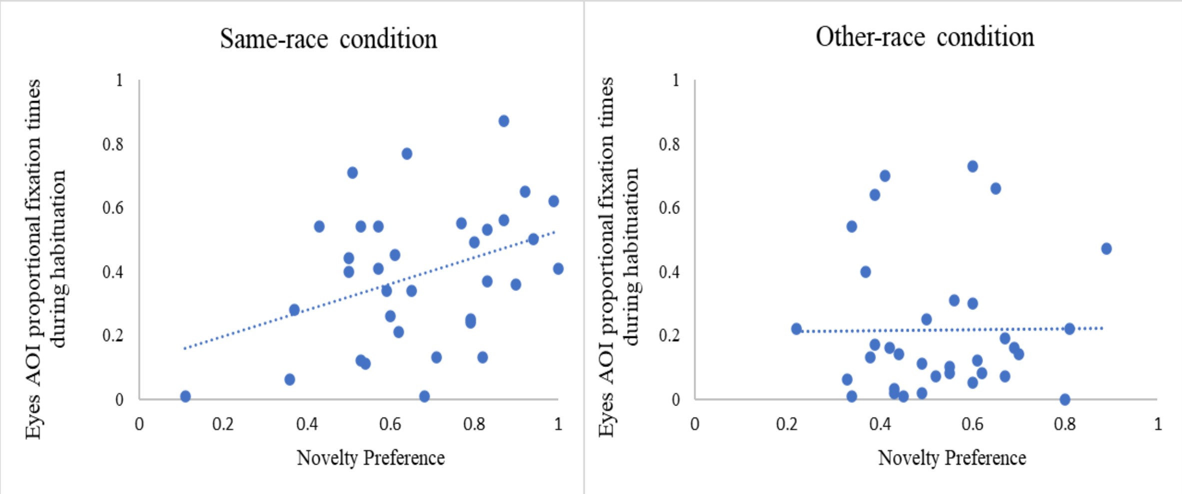

Figure 11. Correlation between infants' novelty preference scores during testing and their proportional fixation times for the eyes AOI during habituation in the same-race condition (left) and the other-race condition (right).

Taken together these results suggest that infants' poorer face discrimination of other-race faces might be connected with a lack of attention to the eye region of other-race faces during encoding.

6. DISCUSSION

The overall objective of the present studies was to improve our understanding of the mechanisms which drive perceptual narrowing during infancy. First, we investigated the hypothesis that there may be shared domain-general processes which drive perceptual narrowing in the domains of face-perception and speech-perception. Next, we investigated whether the manipulation of one such possible mechanism, statistical learning, can be used to counteract the progression of perceptual narrowing in face perception. Finally, we also examined the role of gaze behavior in the appearance of the other-race effect, a common manifestation of perceptual narrowing in the domain of face perception. The findings and possible implications of these studies will be discussed in greater detail below.

6.1. Development of the perceptual narrowing process

Overall, the results of Study 1 and Study 2 speak for the domain-general hypothesis of the perceptual narrowing. More specifically, the results of Study 1 showed that 9-months old infants could discriminate between same-race faces, but not between other-race faces or non-native speech tones. This indicated that the infants seem to have lost their ability to discriminate among both faces and speech sounds to which they had little to no exposure by this age. Moreover, the infants' discrimination abilities for other-race faces and non-native speech tones were positively correlated, which further supports the hypothesis of domain-general mechanisms influencing perceptual narrowing in the perception of both faces and speech. Study 2 extended these results by demonstrating longitudinally that while 6-month-old infants could discriminate among non-native speech contrasts, same-races faces, and other-race faces, the same infants at the age of 9 months could discriminate only among the same-race faces. These results therefore demonstrate that not only does perceptual narrowing significantly influence infants' perception of other-race faces and non-native speech by 9 months of age, but that the window for the onset of these developments seems to be rather narrow. However, a lack of a significant correlation between the infants' novelty preferences for other-race faces and non-native speech at 9 months in Study 2 lies is in contrast to the results of Study 1. This suggests that the influence of any hypothetical shared domain-general mechanisms might be relatively weak in comparison to the natural variation between individuals.

The parallels we found in the development of perceptual narrowing in faces and speech between the ages of 6 and 9 months also agree with previous findings from cross-sectional studies of perceptual narrowing in the domains of face (Kelly et al., 2007; Kelly et al., 2009) and speech perception (Götz et al., 2018). Furthermore, our results extend the findings from previous studies that showed temporal synchronicity between perceptual narrowing in face and speech perception across different groups of infants (Götz et al., 2018; Kelly et al., 2007; Kelly et al., 2009; Xiao et al., 2018), by longitudinally demonstrating that this temporal synchronicity occurs within the same individuals. Thus, the findings of Study 1 and Study 2 add evidence to the hypothesis that the developmental processes driving perceptual narrowing for faces and speech may share some underlying mechanisms (Pascalis et al., 2014).

6.2. Statistical learning as a perceptual narrowing mechanism

The results of Study 3 show that 12-month-old infants' processing of other-race faces depends on the statistical distribution of frequencies with which those faces are encountered. Infants who were exposed to a unimodal frequency distribution of other-race faces during familiarization (where they saw faces closer to the midpoint of the morphed continuum the most frequently), could not discriminate between the two endpoint faces during testing. On the other hand, infants who were exposed to a bimodal distribution of other-race faces during familiarization (where they saw faces closer to the endpoints of the morphed continuum the most frequently), could discriminate between the endpoint test faces. Our findings thus demonstrate that the manipulation of statistical distribution information can re-shape infants' other-race face perception ability and counteract the typical effects of perceptual narrowing.

These results support the findings of previous studies in other sensory domains indicating that the statistical distribution of encountering specific stimuli can modulate infants' perception of non-native speech contrasts (Yoshida et al., 2010) and sounds (Maye et al., 2002; Pelucchi, et al. 2009). Thus, statistical learning appears to be involved in perceptual narrowing in both face perception and auditory perception, making it a likely candidate for the role of a multi-domain mechanism as posited by the domain-general theory of perceptual narrowing (Pascalis et al., 2014).

6.3. Gaze patterns

Study 4 showed that 9-month-old Caucasian infants used different looking patterns when being habituated to same- and other-race faces: Infants looked significantly longer at the eyes of same-race faces than at the eyes of other-race faces. The infants also showed a clear ORE, being able to discriminate between same-race faces, but not between other-race faces. Most interestingly, the infants' ability to discriminate between same-race faces was significantly correlated with their fixation time towards the eyes of same-race faces during habituation. These results therefore suggest that even as early as the visual encoding stage, perceptual narrowing seems to play a role in infants' perception of rarely encountered stimuli, and that such differences in visual encoding seem to be related to the ORE.

6.4. Implications and future directions

Taken together, the four studies presented here highlighted several fascinating aspects of perceptual narrowing, which in turn suggest a number of intriguing possibilities for future research. One particularly interesting direction for future research would be to further explore the possibility of counteracting the effects of perceptual narrowing. Since the results of Study 3 indicate that it is indeed possible to restore infants' sensitivity for other-race faces after the onset of perceptual narrowing, an obvious follow up question is for how long can this restored sensitivity be retained? It would additionally be worthwhile to test whether this type of sensitivity manipulation can also work in older participants, since it is possible that the malleability of such statistical learning mechanisms may diminish with increasing age. Therefore, a valuable follow up experiment to carry out would involve repeating our frequency exposure manipulation with older children, as well as an additional follow-up testing session some time after the initial familiarization in order to test for the retention of any sensitivity improvements.

Another avenue of research to explore would be to test whether the cross-domain nature of perceptual narrowing (as suggested by Studies 1 and 2) can be harnessed to improve the effectiveness of the frequency-manipulation approach to re-sensitization we used in Study 3. For example, could audiovisual stimuli, such as speaking faces, be more effective in re-sensitizing participants to other-race faces or non-native speech than either faces or speech stimuli alone?

Finally, the results of Study 4 suggest that gaze behavior may play a crucial role in the reduction of sensitivity towards other-race faces in the course of perceptual narrowing. Therefore, an obvious question to ask is whether it is possible to influence this gaze behavior such that infants would use similar gaze patterns for examining both same-race and other-race faces. For instance, it may be possible to train infants to look more at the eyes of other-race faces (as they do for same-race faces), by exposing them to only the eye region of these faces. If successful, such an experimental approach would allow us to either prove or disprove the hypothetical causal relationship where gaze patterns influence the infants' face discrimination abilities. If this causal relationship would be confirmed, such results would also suggest that gaze-training could be a useful strategy for counteracting the ORE.

6.5. Conclusions

In summary, the present studies added to our understanding of perceptual narrowing in the domains of speech and face perception, and provided valuable insights regarding the possible mechanisms which may drive this process. Our findings support the hypothesis that shared domain-general mechanisms may drive perceptual narrowing in the domains of speech and face perception. Moreover, our data suggest that statistical learning could be a mechanism which drives perceptual narrowing in both of these domains. Finally, we also found that gaze behavior seems to be involved in the manifestation of perceptual narrowing for face perception.

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II - PUBLICATIONS

8. Overview of Publications

1) Krasotkina, A., Götz, A., Höhle, B., & Schwarzer, G. (2018) Perceptual Narrowing in Speech and Face Recognition: Evidence for Intra-individual Cross-Domain Relations. *Frontiers in psychology*, 9:1711.
2) Krasotkina, A., Götz, A., Höhle, B., & Schwarzer, G. (2021b). Perceptual narrowing in face-and speech-perception domains in infancy: A longitudinal approach. *Infant Behavior and Development*, *64*, 101607.
3) Krasotkina, A., Götz, A., Höhle, B., & Schwarzer, G. (2021a). Bimodal familiarization re-sensitizes 12-month-old infants to other-race faces. *Infant Behavior and Development* 62:101502.
4) Krasotkina, A., Götz, A., Höhle, B., & Schwarzer, G. (2020). Infants' Gaze Patterns for Same-Race and Other-Race Faces, and the Other-Race Effect. *Brain Sciences. 10*(6):331.

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BRIEF RESEARCH REPORT
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Check for updates

Perceptual Narrowing in Speech and Face Recognition: Evidence for Intra-individual Cross-Domain Relations

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During the first year of life, infants undergo perceptual narrowing in the domains of speech and face perception. This is typically characterized by improvements in infants' abilities in discriminating among stimuli of familiar types, such as native speech tones and same-race faces. Simultaneously, infants begin to decline in their ability to discriminate among stimuli of types with which they have little experience, such as non-native tones and other-race faces. The similarity in time-frames during which perceptual narrowing seems to occur in the domains of speech and face perception has led some researchers to hypothesize that the perceptual narrowing in these domains could be driven by shared domain-general processes. To explore this hypothesis, we tested 53 Caucasian 9-month-old infants from monolingual German households on their ability to discriminate among non-native Cantonese speech tones, as well among same-race German faces and other-race Chinese faces. We tested the infants using an infant-controlled habituation-dishabituation paradigm, with infants' preferences for looking at novel stimuli versus the habituated stimuli (dishabituation scores) acting as indicators of discrimination ability. As expected for their age, infants were able to discriminate between same-race faces, but not between other-race faces or non-native speech tones. Most interestingly, we found that infants' dishabituation scores for the non-native speech tones and other-race faces showed significant positive correlations, while the dishabituation scores for non-native speech tones and same-race faces did not. These results therefore support the hypothesis that shared domain-general mechanisms may drive perceptual narrowing in the domains of speech and face perception.

Keywords: perceptual narrowing, perceptual reorganization, other-race effect, face perception, speech perception, habituation

INTRODUCTION

The first year of an infant's life is characterized by a fast attunement of perceptual mechanisms to the specific sensory inputs that infants encounter in their daily life. This process, known as perceptual narrowing, leads to a decline in the ability to discriminate or recognize stimuli that are not present or not relevant in the infant's environment. So far, perceptual narrowing has been observed for visual as well as acoustic perception. In speech, very young infants can discriminate all kinds of speech sound contrasts but this sensitivity declines for many non-native sound contrasts within the first year of life (e.g., Werker and Tees, 1984; Höhle et al., 2009) and increases for native contrasts (e.g., Kuhl et al., 2006). Such perceptual narrowing may arise for vowels (around 6 months; e.g., Polka and Werker, 1994), consonants (around 10–12 months, e.g., Werker and Tees, 1984), and prosodic properties like lexical tone contrasts (between 6 and 9 months: e.g., Mattock and Burnham, 2006; Yeung et al., 2013; Götz et al., 2018) or word stress (Höhle et al., 2009).

Similar patterns have emerged in research on infants' face perception. For instance, the face-sensitive N170 signal showed different properties for upright and inverted faces in adults, but similar properties for both orientations in infants (de Haan et al., 2002). Regarding the other-race effect, while Caucasian 3-month-olds discriminated between faces within four ethnic groups, Caucasian 6-month-olds discriminated faces within only two, and Caucasian 9-month-olds only discriminated Caucasian faces (Kelly et al., 2007). Similar results were also found for Chinese infants (Kelly et al., 2009). Experience with faces of other races seems to slow or modify perceptual fine-tuning toward faces of one's own race (Heron-Delaney et al., 2011; Spangler et al., 2013). Thus, with increasing age, specific experience with face categories leads infants to fine-tune their face-processing system to those faces that are most relevant in their environment (Schwarzer, 2014).

The similarities between the perceptual narrowing processes in speech and face perception have led to the suggestion that these domains share some underlying developmental mechanisms (Maurer and Werker, 2014). However, research examining interactions between these domains in perceptual narrowing has started to appear only recently. For instance, Minar and Lewkowicz (2017) found that 10- to 12-month-old Caucasian infants could still discriminate Asian faces when the faces articulated the vowel /a/ but not when the articulating faces were presented silently or with a non-speech sound superimposed on the speech sound.

The present study investigated relations between perceptual narrowing in these two domains by testing the effects of perceptual narrowing in both domains in Caucasian monolingual infants: We tested 9-month-old German learning children on their ability to discriminate same-race and other-race faces, as well as non-native Cantonese tone contrasts in separate experiments using an infant-controlled habituation-dishabituation paradigm.

METHODS

Participants

Fifty-three healthy, full-term Caucasian infants of German origin (M = 287, 92; range: 274–302 days, 24 girls and 29 boys) took part in our study. All infants were from monolingual German-speaking (without local dialects) households, with at least one parent in every household reporting some university-level education. Infants had no direct contact with persons of Asian descent according to a questionnaire administered to their parents. Thirteen additional infants were excluded from the final sample because of fussiness (N = 5), insufficient quality of eye-tracking calibration (N = 6), or technical problems during the experiment (N = 2). Infants were randomly assigned to either Group A or Group B. Group A participated in the face task in which other-race faces were used and in the non-native speech task (N = 27). Group B participated in the face task in which same-race faces were used and in the non-native speech task (N = 26). The order of the face and speech tasks was counterbalanced in both groups.

Our study was conducted in accordance with the German Psychological Society (DGPs) research ethics guidelines. The experimental procedures and informed consent protocols were approved by the Offices of Research Ethics at the Universities of Giessen and Potsdam. Written informed consent was obtained from all parents of the infant participants prior to their participation in experiments.

Stimuli

Speech Stimuli

Non-native speech stimuli consisted of Cantonese CV syllables (/tɕʰi/) with mid-level (tone 33) or high-rising (tone 25) tone variants taken from the study by Yeung et al. (2013). For each tone, four distinct tokens were used. The duration of each individual tone was 40 ms. For each trial, each tone was presented repeatedly with 1 s intervals between repetitions at a volume of 75 dB for the duration of the trial. A previous study had shown perceptual narrowing for exactly these stimuli in German infants between 6 and 9 months (see Götz et al., 2018 for more details).

Face Stimuli

Face stimuli consisted of colored photographs of six other-race Asian (Chinese origin) and six same-race Caucasian (German origin) women, on a white background. All faces were presented in three poses: frontal, ¾ to left, and ¾ to right. On each photo the women looked straight at the camera with the hair, neck, and shoulders being visible. We edited the photos in Photoshop CS3 to make them matched in head size, and also made the skin-tone, eyes, head, and lip-color as similar as possible. Each photo was presented in the middle of the screen, appearing as 12.5 cm (10.98° visual angle) wide and 16.5 cm (14.47° visual angle) tall. Faces were paired within each ethnicity according to similarity ratings collected in a pilot experiment. A follow-up pilot experiment confirmed the occurrence of the ORE in 9-month-old infants using these face pairs.

Procedure

Parents were informed about the general purpose of the study and the experimental procedure, but were blind to the hypotheses. Parents gave written consent for their child's participation. During the experiment infants sat on their parent's lap at a distance of approximately 65 cm from the 23.8″ display with a resolution of 1920 pixels × 1080 pixels, and an integrated Tobii tx300 eye-tracker with a sampling rate of 300 Hz. Parents were instructed to close their eyes and stay silent during the experiment. Each testing started with a 5-point infant calibration procedure. The calibration was repeated until it was successful for

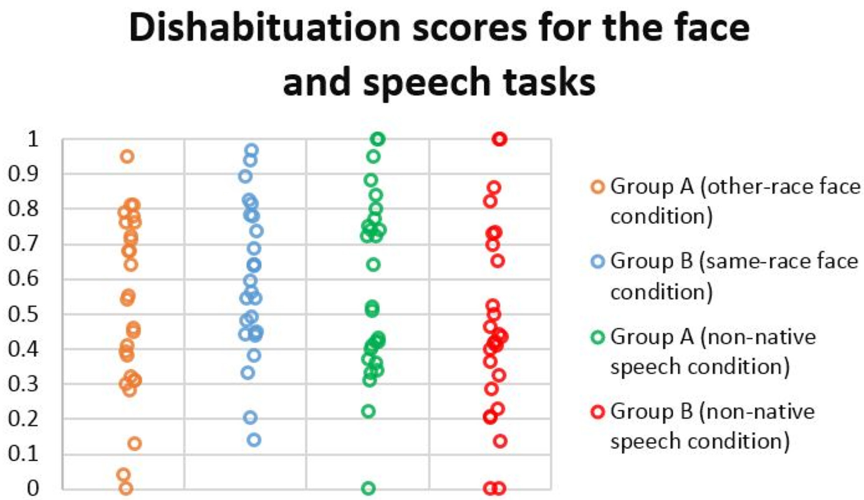

FIGURE 1 | Dishabituation scores for the face and speech tasks.

all five points for up to four maximum attempts. The data from infants who failed the calibration procedure were excluded from the final sample.

We used an infant-controlled habituation-dishabituation procedure for both the speech and face tasks. Within both habituation and test trials, stimuli were presented until infants looked away from the screen for 2 s, or until a maximum trial length of 40 s was reached. The average looking time during the first three habituation trials served as the baseline for the habituation criterion. The habituation phase continued in sets of three trials, until the average looking time for a set of three trials decreased to below 50% of the average from the first three trials. The habituation phase continued until either this habituation criterion was reached, or until a total of 18 habituation trials had been presented. Infants who failed to habituate (n = 7) were exclude from the final sample.

After habituation, infants proceeded to the test phase, where they were sequentially presented with the habituated stimulus and a novel stimulus of the same type, with each infant being randomly assigned to see the habituated stimulus either first or second. E-Prime version 2.0 (Psychology Software Tools, Pittsburgh, PA, United States) was used for stimuli presentation.

Speech Task

During the speech task infants were habituated to one of the two tones. A silent rotating animation of a colorful circle presented on the screen was used as an attention getter between trials. During test trials, the infants heard repetitions of the habituated tone, and the second (novel) tone in a sequential random order in order to eliminate order effects. A checkerboard pattern was presented on the screen whenever infants heard the tones during both habituation and test trials.

Face Task

During the face task, infants were habituated to photos of one person in three different poses, alternating in random order in sequences of three. To direct infants' attention to the screen, a neutral audio signal was played as an attention getter before the start of each habituation trial. During the test trials, the previously habituated and a novel face of the corresponding condition were shown sequentially (in the frontal pose) in random order.

Data Analysis

Dishabituation scores for each infant in the speech and face tasks (**Figure 1**) were calculated by dividing the fixation time toward the novel stimulus by the sum of the fixation times toward the novel and habituated stimuli during test trials. Based on previous eye-tracking research with infants (Liu et al., 2011; Wheeler et al., 2011; Xiao et al., 2014) we defined fixations by a minimum duration of 100 ms within a 30 pixel radius. Tobii Pro Studio was used to analyze the eye-tracking data. The fixation times used for these calculations came from the area of interest covering the whole head in the case of the face task, and the entire checkerboard screen in the case of the sound task. Dishabituation scores above 0.5 indicated a preference for the novel stimulus, and dishabituation scores below 0.5 indicated a preference for the habituated stimulus. One sample t-tests were used to test the dishabituation scores against chance level.

Finally, to determine whether there was a relation between infants' dishabituation scores in the speech and face condition, we calculated the Pearson correlations between the dishabituation scores in the speech and face tasks for each group of infants.

RESULTS

The t-tests in the face tasks revealed that only the infants in the same-race face condition (Group B) showed a significant dishabituation score (mean dishabituation score = 0.591, SD = 0.214; t_{25} = 2.181, p = 0.039; d_z = 0.43), while the infants in the other-race face condition (Group A) did not (mean dishabituation score = 0.517, SD = 0.255; t_{26} = 0.347, p = 0.732;

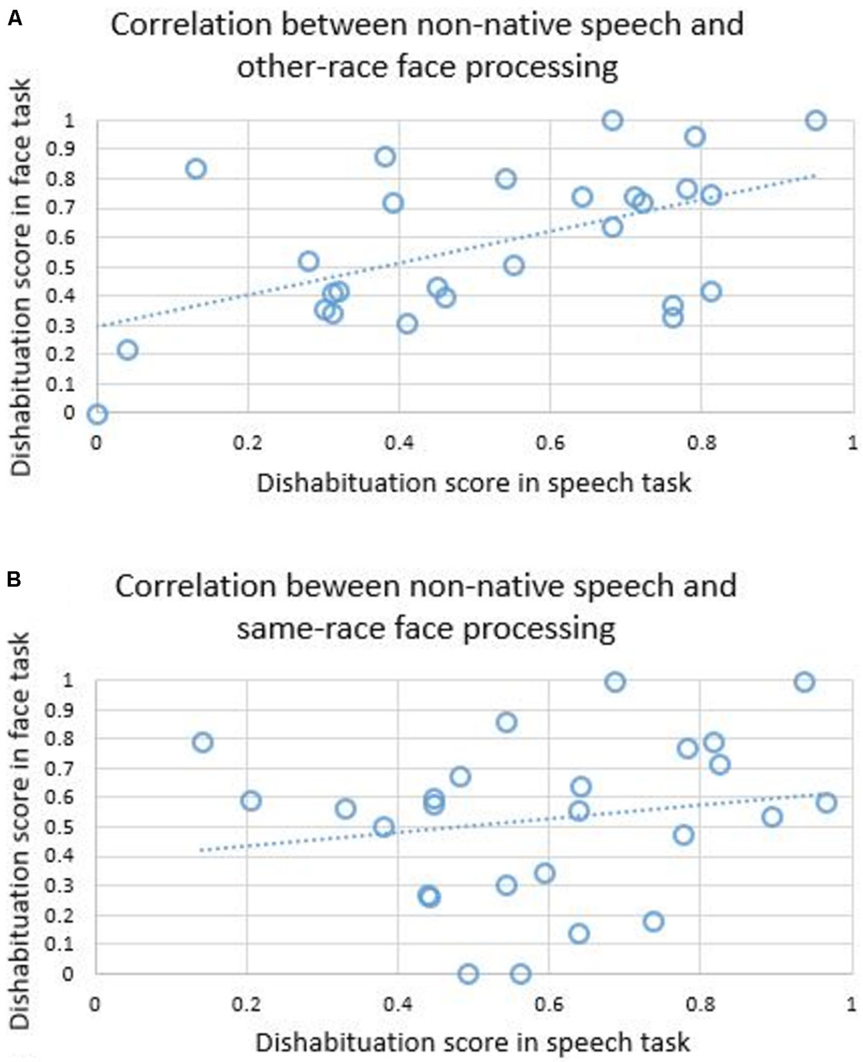

FIGURE 2 | Correlations between dishabituation scores in the non-native speech and other-race face task **(A)**, and between dishabituation scores in the non-native speech and same-race face task **(B)**.

d_z = 0.03). In the speech task, we did not find a significant dishabituation score in either Group A (mean dishabituation score = 0.577, *SD* = 0.259; t_{26} = 1.551, *p* = 0.133; d_z = 0.3), or Group B (mean dishabituation score = 0.529, *SD* = 0.276; t_{25} = 0.538, *p* = 0.596; d_z = 0.11).

Next, we tested the Pearson correlations (**Figure 2**) between the speech- and face-related dishabituation scores of each infant separately for Group A and Group B. Infants in Group A showed a highly significant correlation between the dishabituation scores in the speech and face tasks [$R(25) = 0.536$, $p = 0.004$], while the infants in Group B did not [$R(24) = 0.182$, $p = 0.374$].

DISCUSSION

Agreeing with previous research, our results confirmed that 9-month-old monolingual infants were not able to discriminate between non-native tones (Mattock and Burnham, 2006; Yeung et al., 2013; Götz et al., 2018), or between other-race faces to which they had no prior exposure (Kelly et al., 2007, 2009).

Most interestingly, our results showed that the dishabituation scores of infants for non-native tones and other-race faces were highly correlated, while the dishabituation scores for non-native tones and same-race faces showed no correlation. The positive correlation between the ability to discriminate between non-native tones and other-race faces indicates that infants who are weak in discriminating other-race faces are also weak in discriminating non-native speech and vice versa. Most importantly for the interpretation of this effect, no correlation was found between the discrimination of non-native tones and same-race faces, which indicates that the correlation between the dishabituation scores for non-native tones and other-race faces is not merely an effect of general tasks requirements (e.g., attention, memory, or habituation speed). Our results therefore support the hypothesis that the developmental trajectories of perceptual narrowing in speech and faces share some underlying mechanisms that drive these processes and can affect the speed and/or the outcome of these processes across both domains within an individual. It could well be that these domain-general processes are involved in applying statistical learning to the stimuli surrounding infants, allowing for the specialization of their perceptual systems to the stimuli classes which appear most often (Maurer and Werker, 2014). The precise neural organization of these mechanisms would therefore be an important target for future research.

AUTHOR CONTRIBUTIONS

AK contributed to the design of the work, acquisition and analysis of the data, and drafting of the manuscript. AG contributed to the design of the work and revising of the manuscript. BH contributed to the design of the work, drafting and revising of the manuscript. GS contributed to the design of the work, analysis of the data, and revising of the manuscript. All authors approved the final version and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Perceptual narrowing in face- and speech-perception domains in infancy: A longitudinal approach

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ABSTRACT

During the first year of life, infants undergo a process known as perceptual narrowing, which reduces their sensitivity to classes of stimuli which the infants do not encounter in their environment. It has been proposed that perceptual narrowing for faces and speech may be driven by shared domain-general processes. To investigate this theory, our study longitudinally tested 50 German Caucasian infants with respect to these domains first at 6 months of age followed by a second testing at 9 months of age. We used an infant-controlled habituation-dishabituation paradigm to test the infants' ability to discriminate among other-race Asian faces and non-native Cantonese speech tones, as well as same-race Caucasian faces as a control. We found that while at 6 months of age infants could discriminate among all stimuli, by 9 months of age they could no longer discriminate among other-race faces or non-native tones. However, infants could discriminate among same-race stimuli both at 6 and at 9 months of age. These results demonstrate that the same infants undergo perceptual narrowing for both other-race faces and non-native speech tones between the ages of 6 and 9 months. This parallel development of perceptual narrowing occurring in both the face and speech perception modalities over the same period of time lends support to the domain-general theory of perceptual narrowing in face and speech perception.

1. Introduction

Starting from birth, infants are surrounded by an incredible amount of distinctive stimuli. Usually, infants are exposed to some types of stimuli more often than to others. For example, infants are usually exposed to same-race faces more frequently than to other-race faces. Similarly, infants are typically exposed to their native language more frequently than to non-native languages. This asymmetry in the frequency with which infants are exposed to various stimuli has long-reaching consequences. Around the second half of the first year of life, infants start to show a diminished sensitivity to infrequently encountered stimuli as they increase in sensitivity for more frequently encountered stimuli. This process of attunement of sensitivity to stimuli depending on the frequency of occurrence is known as *perceptual narrowing*.

Perceptual narrowing occurs in different modalities such as speech perception (Pons, Lewkowicz, Soto-Faraco, & Sebastián-Gallés, 2009), human and animal face perception (Kelly et al., 2009; Kelly et al., 2007; Simpson, Suomi, & Paukner, 2016), intersensory perception (Lewkowicz & Ghazanfar, 2006), sign language (Baker, Golinkoff, & Petitto, 2006), and even music perception (Hannon &

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Trehub, 2005a, 2005b; for a review, see Maurer & Werker, 2014). Interestingly, there are similarities in the timeframe of the onset of perceptual narrowing in speech (Maurer & Werker, 2014; Pons et al., 2009) and face perception (e.g., Pascalis, de Haan, & Nelson, 2002, 2005), which will be discussed in greater detail below.

Perceptual narrowing in the speech domain occurs during the second half of the first year of life with some variation for different language components. Infants start to show a decrease in sensitivity for non-native vowels at around 6 months, (Polka & Werker, 1994), to consonants at around 10–12 months, (Werker & Tees, 1984), to word stress at 10 months of age (Bijeljac-Babic, Serres, Höhle, & Nazzi, 2012), and to lexical tone contrasts between 6 and 9 months (Götz, Yeung, Krasotkina, Schwarzer, & Höhle, 2018; Mattock & Burnham, 2006; Yeung, Chen, & Werker, 2013). Thus, infants initially seem to have a broadly tuned speech-processing system that is similarly sensitive to stimuli which appear with varying levels of frequency in the infant's environment. This system then becomes be attuned to the infants' native language over the course of the second part of the first year of life due to the high frequency with which the infant is exposed to that language.

Around the same time, the infant's face-processing system becomes similarly attuned to faces which they encounter more frequently. The face-processing system of 3-month-old Caucasian infants is broadly tuned to all numerous of human faces, which allows them to successfully discriminate between Caucasian, Asian, African, and middle Eastern faces (Kelly et al., 2007). By the age of 6 months, Caucasian infants have been shown to only be capable of discrimination among Caucasian and Chinese faces (Kelly et al., 2007). At 9 months of age, infants have been shown to be capable of discrimination only between same-race faces (Kelly et al., 2007). This indicates that by 9 months, the face-processing system is already attuned to same-race faces. Similar results have also been demonstrated in Asian infants (Kelly et al., 2009). Thus, we can see that there is converging evidence form multiple studies which demonstrate a decrease in sensitivity for other-race faces at the age of 9 months (Kelly et al., 2007; Kelly et al., 2009; Krasotkina, Götz, Höhle, & Schwarzer, 2020; Spangler et al., 2013).

Researchers have already suggested that speech and face perception may share some underlying developmental (Maurer & Werker, 2014) and neural mechanisms (Belin, Bestelmeyer, Latinus, & Watson, 2011). Along with the sharing of some neural structures between face and speech perception such as the superior temporal sulcus (Pascalis et al., 2014), interdomain correlations and the similarities in the timing of perceptual narrowing in these two domains have led to the suggestion of an underlying domain-general principle or mechanism driving this development (Hadley, Rost, Fava, & Scott, 2014; Pascalis et al., 2014; Scott, Pascalis, & Nelson, 2007). For instance, Krasotkina, Götz, Höhle, and Schwarzer (2018)) found that infants' abilities in discriminating other-race faces were correlated with their discrimination abilities for non-native speech. In this study, infants who showed lower novelty preferences for other-race faces also showed lower novelty preferences for non-native speech. In another study, Xiao et al. (2018) also found that perceptual narrowing in face and speech perception were related in separate groups of 9- and 12-month old Japanese infants. However, thus far there have been no studies which longitudinally investigated how infants' abilities in discriminating other-race faces and non-native language change within the same infants. In fact, the authors of the above-mentioned study themselves suggested a longitudinal approach as a potential direction to expand the scope of their findings. Such longitudinal evidence of decreasing abilities for discriminating other-race faces and non-native language in the same infants could provide additional evidence towards the domain-general hypothesis described above.

2. Current study

The goal of the present study was therefore to longitudinally investigate whether perceptual narrowing in face and speech perception occurs simultaneously in the same infants. With this goal in mind, our study took a longitudinal approach to testing infants' discrimination abilities for other-race faces and non-native speech stimuli. We tested our infants both at 6 months of age, when perceptual narrowing has been reported to begin, and later at 9 months, when perceptual narrowing should already be clearly manifested. In order to measure the infants' discrimination abilities for faces and speech stimuli, we used a standard infant-controlled habituation-dishabituation paradigm. To minimize the number of testing sessions per appointment (to avoid infant fatigue) and the number of testing appointments each infant needed to attend (to minimize the drop-out rate), infants were divided into two groups. Infants in group A were tested on their discrimination of other-race Asian faces and non-native speech stimuli in order to answer our main question of whether the same infants would show parallel perceptual narrowing effects for both types of stimuli. For speech stimuli, we used rising and mid-level Cantonese lexical tone contrasts instantiated on a CV-syllable. Götz et al. (2018) already demonstrated that German-learning 6-month-olds can discriminate these Cantonese stimuli while 9-month-olds cannot, indicating the typical trajectory of perceptual narrowing for speech across these ages. Because German has no lexical tones in its native phonological inventory, no native contrast was used in our speech experiments.

Infants in Group B were tested using the same non-native speech stimuli as well as same-race faces as a control group, in order to investigate whether a decrease in discriminating faces between 6 and 9 months would be limited to the other-race faces, as would be expected under the perceptual narrowing theory.

We hypothesized that 6-month-old infants would be able to discriminate among all stimulus types. At 9 months, we hypothesized that infants should no longer be able to discriminate among other-race faces and non-native speech, but should still be able to discriminate among same-race faces in our control group. If this were to be the case, such findings would provide additional evidence in support of a domain-general theory of perceptual narrowing in face and speech perception (Pascalis et al., 2014). Additionally, if domain-general mechanisms exert a strong influence on perceptual narrowing in these domains, then that should be reflected in a similarly strong correlation between the discrimination abilities of infants for other-race faces and non-native speech stimuli after the onset of perceptual narrowing at 9 months.

3. Methods

3.1. Participants

67 healthy, full-term Caucasian infants of German origin were recruited for our study. All infants were from monolingual German-speaking households and had no directed contact with persons of Asian descent according to their parents. We excluded 11 6-month-old infants from our study because of failure to complete the session due to fussiness (n = 8) or inability to calibrate (n = 3) in at least one of the appointments. An additional 6 infants were excluded at 9 months of age because of inability to attend any of the testing appointments (n = 4), incomplete sessions due to fussiness (n = 1), or inability to calibrate (n = 1). Thus, for our analyses we used only the data from infants who successfully participated in all four appointments, which comprised 50 infants (23 girls, 27 boys; age at 6 months: M = 203,04 days, range 184–209; age at 9 months M = 287,02, range 274–300).

Additionally, all infants were tested for normal cognitive development at the age of 12 months using the Bayley Scales of Infant Development III (Bayley, 2006). During this follow-up test, the parents also filled out the ELFRA questionnaire of language development (Grimm & Doil, 2006). All infants scored within the normal range in both assessments.

3.2. Stimuli

3.2.1. Face stimuli

Our face stimuli consisted of photographs of 6 Caucasian women for the same-race condition and 6 Asian women for the other-race condition. These photographs were the same as those used by Krasotkina et al. (2020), who found perceptual narrowing effects for these stimuli in 9-month-old Caucasian infants. The women were depicted looking directly at the camera while smiling with the hair, neck, and shoulders being visible. We used photographs of each woman in three poses: frontal, ¾ to the right, and ¾ to the left. For the testing phase of our experiment, each photograph was paired with another one from same condition based on previous similarity ratings by adults (see Krasotkina et al., 2020 for additional details). Pairings with similar scores in terms of similarity ratings were selected for the present experiment to ensure a similar degree of difficulty in distinguishing the faces in each pair across conditions. Examples of stimuli are presented in Fig. 1.

3.2.2. Speech stimuli

Our speech stimuli consisted of Cantonese CV syllables (/tɕhi/) with mid-level (tone 33) or high-rising (tone 25) tone variants taken from the study by Yeung et al. (2013). For each tone, the auditory stimulus consisted of a sequence of four distinct tokens with a 1 s interval between them. These sequences were repeated up to a maximum stimulus duration of 40 s. The volume was kept to a constant level of 75 dB. As mentioned above, a previous study has already confirmed the occurrence of perceptual narrowing for these stimuli in German infants between 6 and 9 months of age (Götz et al., 2018).

Fig. 1. Examples of other-race (above) and same-race (below) faces used in the habituation and test trials in the face task.

3.3. Procedure

Upon arrival parents gave written consent for their child's participation and were informed about the study procedure, but stayed blind to the hypotheses. During the experiment the infant sat on their parent's lap approximately 65 cm away from a 23.8″ display with a resolution of 1920 pixels × 1080 pixels, and an integrated Tobii tx300 eye-tracker with a sampling rate of 300 Hz. To avoid the parents' reaction interfering with the infants' looking behavior, parents were instructed to close their eyes or to wear opaque sun glasses and to sit relaxed and still during the experiment.

At the start of the experiment, we used a 5-point (4 corners and the middle of the screen) infant calibration procedure. We repeated the calibration procedure either until it was successful for all 5 points, or up to a maximum of 5 attempts (the data from infants who were not calibrated successfully were excluded from the data analysis).

Infants were randomly assigned to two groups. Infants in group A participated in the other-race face task and non-native sound task at both 6 and 9 months (N = 25). Infants in group B participated in the same-race face and non-native sound tasks at both 6 and 9 months (N = 25). The order of the face and sound tasks was counterbalanced in both groups, and were conducted one week apart.

An infant-controlled habituation-dishabituation procedure was used for both the sound and face tasks based on previous studies which used a similar approach (Kelly et al., 2007, 2009; Krasotkina et al., 2018; Spangler et al., 2013). The visual and the auditory stimuli were presented for as long as the infant looked at the screen during both the habituation and the test phase. A trial would end if the infant looked away from the screen for at least 2 s or after reaching the maximum trial duration of 40 s. After each trial, an attention getter was shown to redirect the infant's attention to the screen. The average looking time during the first three habituation trials served as the baseline for the habituation criterion. We considered infants as being habituated when the average looking time for three consecutive habituation trials (after the third habituation trial) was less than 50 % of the baseline from the first three habituation trials. The test phase started either after the infant had reached the habituation criterion or after a maximum of 18 habituation trials had been presented. During the test trials, infants were presented with the habituated stimulus and a novel stimulus of the same type in sequential order, for a total of two test trials in total. Half of the infants in each group were presented with the novel stimulus first and the habituated stimulus second, while the other half were presented with these stimuli in the reverse order. E-Prime version 2.0 (Psychology Software Tools, Pittsburgh, PA, United States) was used for stimuli presentation.

3.3.1. Face task

In the face task infants saw the photographs of two women. In the other-race conditions both faces were Asian faces, and in the same-race condition both faces were Caucasian faces. To avoid memory effects, infants were presented with different faces from the same condition at 6 and 9 months. During each trial, a single photograph was presented in the middle of the screen, appearing as 12.5 cm (10.98° visual angle) wide and 16.5 cm (14.47° visual angle) tall at a viewing distance of 65 cm. All the photographs presented across the habituation trials showed the same face but in three different positions: frontal, turned ¾ right, and turned ¾ left. After each trial, a neutral audio signal was played to redirect infant's attention to the screen. During the test phase, the photographs of the habituated face and the novel face showed the face in the frontal position.

3.3.2. Speech task

During habituation, infants heard one of the two tone sequences: either the mid-level tone sequence, or the high-rising tone sequence. Infants who were habituated to the high-rising tone at 6 months were habituated to the mid-level tone at 9 months and vice versa. The same habituation criteria and trials numbers were used as in the face task (see above), but with a checkerboard pattern being displayed as a visual stimulus on the display while the tones were played. A colorful rotating pattern was presented on the screen between the trials to recapture the infant's attention. During two test trials, the novel and habituated tones were presented in sequential order, as with the face stimuli.

3.4. Data analysis

Tobii Pro Studio was used to obtain the eye-tracking data. We filtered the eye-tracking data similarly to the procedure used in previous eye-tracking studies with infants (Liu et al., 2011; Wheeler et al., 2011; Xiao, Quinn, Pascalis, & Lee, 2014). Fixations were defined as a minimum looking duration of 100 ms within a 30 pixel radius. For the face task, we created an area of interest (AOI) covering the whole head of the person shown on the photographs. For the sound task, the entire screen area displaying the checkerboard was defined as the AOI. The total time of infants' fixations within these AOIs (total fixation time) was used for the calculation of novelty preferences. Novelty preferences were calculated by dividing the total fixation time for the novel stimulus by the sum of the total fixation times toward the novel and habituated stimuli during test trials.

One sample t-tests were used to test the novelty preferences against chance level for the face and sound tasks for both groups separately at 6 and 9 months. Next, we calculated repeated measures ANOVAs for each group separately, using task type (face task, sound task) and age (6 months, 9 months) as within-subject factors. Finally, we also calculated the Pearson correlation between the novelty preferences for other-race faces and non-native speech for group A at 9 months of age to determine the degree to which the similarity between the outcomes of the perceptual narrowing process for both types of stimuli varied between participants.

4. Results

4.1. Habituation

To ensure that infants in the two groups did not differ with respect to the number of trials seen during habituation, we conducted 2 separate repeated-measures ANOVAs, one for each age group (6 months, 9 months). For both ANOVAs, we used group (group A, group B) as a between-subjects factor and task type (face task, sound task) as a within-subject factor. We found no significant effect of group or task type at 6 months (p = .198, p = .092, respectively), indicating that infants in both groups saw similar numbers of habituation trials in both the face (group A: M = 8.16 vs. group B: M = 9.12) and the speech task (group A: M = 9.48; group B: M = 7.92). Similar results were found in 9-month-old infants with no significant effects of group or task (p = .394 p = .698, respectively), indicating that infants in both groups saw a similar number of habituation trials in both the face (group A: M = 7.92; group B M = 8.04) and the speech task (group A: M = 7.80; group B: M = 7.20).

4.2. Novelty preferences

4.2.1. Face task

To determine whether infants showed perceptual narrowing in their perception of other-race Asian faces, we examined their looking preferences towards the novel and habituated Asian faces during the test trials. We then performed the same analysis for the same-race Caucasian face condition. We first compared the novelty preferences (looking time during novel trial divided by the sum of the looking time during the novel trial and looking time during the habituated trial) of the infants at 6 and 9 months against chance-level (0.5) using a one-sample *t*-test. The *t*-tests for the face task revealed that at the age of 6 months infants in both groups showed novelty preference scores significantly above chance-level (mean novelty preference for other-race faces = 0.61, $SD = 0.15$; $t_{24} = 3.734$, $p = .001$, $d = 1.524$; mean novelty preference for same-race faces = 0.62, $SD = 0.20$; $t_{24} = 3.065$, $p = .000$ $d = 1.251$; see Fig. 2). However, at the age of 9 months only infants in the same-race condition (group B) showed novelty preferences significantly above chance-level (mean novelty preference for the same-race faces = 0.66, $SD = 0.18$; $t_{24} = 4.811$, $p = .000$, $d = 1.964$), while infants in other-race condition (group A) showed novelty-preferences that did not significantly differ from chance-level (mean novelty preference for other-race faces = 0.48, $SD = 0.17$; $t(24) = -.699$, $p = .491$, $d = -0.285$; see Fig. 3). These results indicate that at 6 months, infants are able to discriminate between the novel and habituated faces in both the same-race and other-race conditions. However, by 9 months of age, these infants could no longer effectively differentiate between novel and habituated other-race faces, but could still differentiate between the novel and habituated same-race faces.

4.2.2. Speech task

To determine whether the infants in our study underwent perceptual narrowing for the non-native speech contrasts, we examined their looking preferences for the trials where they heard the novel non-native tone versus the habituated non-native tone across both groups. We again conducted one-sample *t*-tests for the infants in each group at 6 and 9 months as described earlier to compare the infants' novelty preferences against chance-level (0.5). Results revealed that at the age of 6 months, infants in group A showed novelty preferences significantly higher than chance-level (mean novelty preference = 0.64, $SD = 0.14$; $t_{24} = 4.957$, $p = .000$, $d = 0.9911$). Infants in group B also showed novelty preference higher than chance, although here the statistical test showed only a marginal

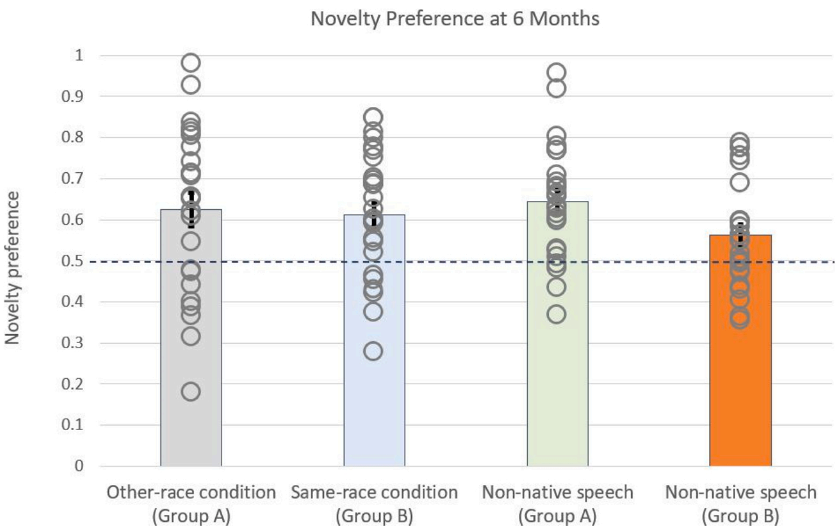

Fig. 2. Novelty preference scores for the other-race faces (n = 25 group A), same-race faces (n = 25, group B), and non-native speech in groups A and B (n = 25 in each group) at the age of 6 months.

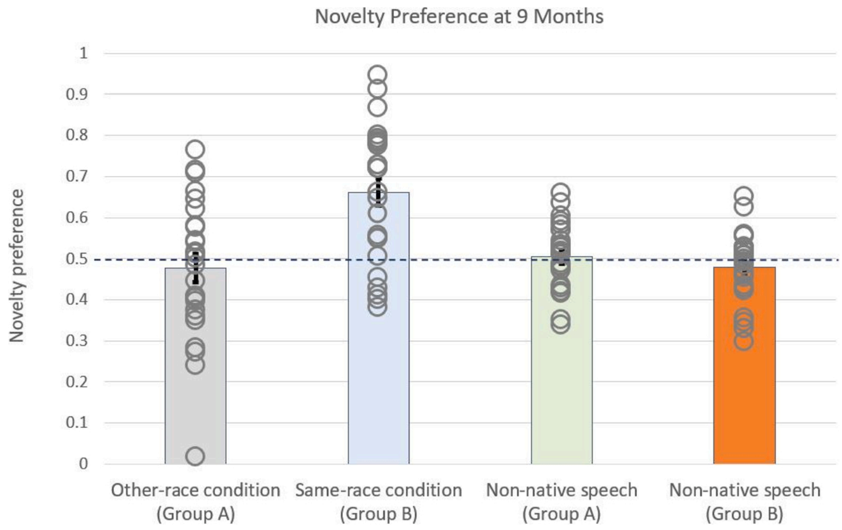

Fig. 3. Novelty preference scores for the other-race faces (n = 25 group A), same-race faces (n = 25, group B), and non-native speech in groups A and B (n = 25 in each group) at the age of 9 months.

significance (mean novelty preference = 0.55, $SD = 0.13$; $t_{24} = 1.983$, $p = .059$, $d = 0.3968$). This indicated that at 6 months infants seem to differentiate between the novel and habituated non-native speech tones (Fig. 2). By contrast, at 9 months of age the analysis indicated that the same infants no longer showed a novelty preference higher than chance-level in either group A (mean novelty preference = 0.50, $SD = 0.07$; $t_{24} = 0.232$, $p = .818$, $d = 0.0468$), or group B (mean novelty preference = 0.48, $SD = 0.10$; $t_{24} = -0.924$, $p = .365$, $d = -0.1848$). This indicated that by 9 months, the infants could no longer effectively differentiate between the novel and habituated non-native speech tones (Fig. 3).

4.3. Age dependent changes in novelty preferences

To analyze age-dependent changes in stimulus discrimination we conducted separate repeated-measures ANOVAs for group A and group B with novelty preference as the dependent variable, and with age (6 months, 9 months) and task type (face task, speech task) as within-subject factors.

4.3.1. Group A (other-race faces, non-native speech)

We found a significant main effect of age ($F(1, 24) = 19.701$, $p = 0.000$, $d = 1.281$), indicating that infants' novelty preferences for both types of stimuli significantly dropped between 6 months ($M = .634$, $SD = .023$) and 9 months of age ($M = .490$, $SD = .020$). We found no significant main effect of task type ($F(1, 24) = 1.001$, $p = .327$, $d = 0.289$), and no significant interaction between the two factors ($F(1,24) = .010$, $p = .922$, $d = 0.029$), indicating that novelty preferences decreased similarly for both the face and the speech stimuli.

4.3.2. Group B (same-race faces, non-native speech)

We found a significant main effect of task type ($F(1, 24) = 22.817$, $p = .000$, $d = 1.379$), indicating that infants' novelty preferences for faces ($M = .637$, $SD = .018$) differed significantly from their novelty preferences for speech ($M = .521$, $SD = .016$). We also found a

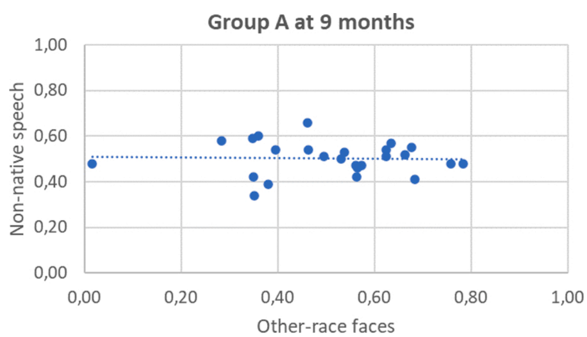

Fig. 4. Pearson correlations between infants' novelty preference scores for other-race faces and non-native speech stimuli (Group A) at 9 months.

significant interaction between age and task type, $F(1, 24) = 4.972$, $p = .0355$, $d = 0.644$). Post-hoc pairwise comparisons (with Bonferroni corrections for multiple comparisons) showed that while the infants' novelty preferences for same-race faces at 6 months ($M = .612$, $SD = .030$) and at 9 months ($M = .562$, SD = .020) did not differ significantly, their novelty preferences for non-native tones decreased significantly ($p = .012$) from the age of 6 months ($M = .662$, $SD = .034$) to 9 months ($M = .479$, $SD = .017$).

4.4. Correlations between novelty preferences

To further examine the relations between the discrimination of face and speech stimuli, we conducted separate Pearson correlation analyses on novelty preference scores for group A at 9 months. We did not find any significant correlation between the novelty preferences for other-race faces and non-native speech tones in Group A(r[25] = −0.027, 2-tailed Sig. p = .898), see Fig. 4.

5. Discussion

The present study was aimed at investigating the hypothesis that perceptual narrowing in face and speech perception may be driven by shared mechanisms. The main goal of our study was therefore to determine whether the same infants would show a similar decrease in their sensitivity towards both other-race faces and non-native speech. Crucially, we tested the same Caucasian infants longitudinally at 6 and 9 months of age on their ability to discriminate among Asian other-race faces and non-native Cantonese tones. An additional control group of Caucasian infants was tested at the same ages, but using same-race Caucasian faces, in order to verify that any decreases in sensitivity towards the other-race faces were indeed driven by perceptual narrowing.

Our results showed that at 6 months of age, Caucasian infants were able to discriminate amongst same-race Caucasian faces, other-race Asian faces, and non-native Cantonese lexical tones. However, by 9 months of age, the same infants were no longer able to discriminate among other-race faces and non-native speech stimuli. By contrast, the 9-month-old infants were still able to successfully discriminate among same-race faces. These results fit our hypothesis that between the ages of 6 and 9 months, infants would show a decrease in their ability to discriminate among other-race faces and non-native speech stimuli, while maintaining their ability to discriminate among same-race faces. Thus, our results replicate the previous findings made in cross-sectional studies of perceptual narrowing in the domains of face (Kelly et al., 2007, 2009; Krasotkina et al., 2018) and speech perception (Götz et al., 2018).

Our findings also fit the overall theory of perceptual narrowing which posits that over a specific critical period of time, infants undergo a decrease in sensitivity towards stimuli which are rarely or never encountered in their environment. As far as we know, our study is the first to investigate perceptual narrowing in face and speech perception longitudinally within the same infants rather across different groups of infants (Maurer & Werker, 2014). Therefore, the parallels that we found in the changes of infants' responses to other-race faces and the non-native speech contrasts between the ages of 6 and 9 months add some evidence in support of the hypothesis that perceptual narrowing in the domains of face and speech perception might occur as part of a domain-general process (Pascalis et al., 2014).

So far, it remains unclear exactly which underlying mechanisms may provide the link between perceptual narrowing of speech and face perception. Xiao et al. (2018) reasoned that mutual influences between speech and face processing may contribute to this link between perceptual narrowing in speech and face perception, since some studies have shown that pairing faces with speech may enhance infants' discrimination of faces as well as of speech sounds (Scott & Monesson, 2009; Teinonen, Aslin, Alku, & Csibra, 2008). Another possibility, as described earlier, is that a domain-general statistical learning process contributes to cross-domain similarities in the development of face and speech perception. We have recently shown that a distributional learning mechanism that has previously been shown to modulate infants' perception of non-native speech contrasts (Yoshida, Maye, & Werker, 2010) can also modulate infants' perception of other-race faces (Krasotkina, Götz, Höhle, & Schwarzer, 2021). This learning mechanism may drive perceptual reorganization based on the statistical patterns embedded within the frequency and distribution of stimuli that individuals encounter. More evidence for such a mechanism comes from Minar and Lewkowicz (2017), who found that 10- to 12-month-old Caucasian infants could still discriminate among other-race faces if the faces were combined with familiar speech stimuli, but not if the faces were accompanied by non-speech sounds. The authors suggest that such results are an indication that the statistical co-occurrence the faces and speech encountered by infants during early development is a crucial factor in the appearance of discrimination deficits typically associated with perceptual narrowing. A potentially useful direction for future studies regarding this hypothesis could be to further extend the research on parallels in perceptual reorganization to even more domains of stimuli which infants encounter in their surroundings (e.g., music Hannon & Trehub, 2005a, 2005b).

However, we were surprised that we did not find a significant correlation between the novelty preferences for other-race faces and non-native speech stimuli at 9 months. This lack of a significant correlation is in contrast to the results from a previous study which showed a significant positive correlation between the novelty scores for other-race faces and non-native speech stimuli in another group of 9-month-olds (Krasotkina et al., 2018) and the findings by the Xiao et al. (2018) who also report a correlation – though a negative one – between face and speech perception in 9-month-olds. The discrepancies between these results suggest that the influence of any hypothetical shared domain-general mechanisms might be relatively weak in comparison to the natural variation between individuals. Thus, additional future experiments with larger sample sizes are necessary to further clarify the exact nature and strength of these relationships.

Our study was limited by the inclusion of only Caucasian infants as a participant group, and only Caucasian and Asian faces, as well as Cantonese tones as stimuli. Previous studies have demonstrated that, at least in the domain of face perception, infants undergo changes in their sensitivity to various other-race faces at different rates (Kelly et al., 2007; Kelly et al., 2009; Krasotkina et al., 2020; Spangler et al., 2013). Therefore, future studies should carry out similar longitudinal studies on perceptual narrowing with participants from a variety of ethnic backgrounds, as well as faces from additional backgrounds and native and non-native speech stimuli with different acoustic properties. Another limiting aspect of carrying out the study only Caucasian German infants and using non-native tones as stimuli, is that the German language lacks tones while the majority of the world's languages do indeed features tones (Singh & Fu, 2016). It would therefore be important to test whether our findings concerning perceptual narrowing with respect to tone contrasts can be replicated in another group of infants whose native language does feature tones. Additionally, it would be useful to conduct more extended longitudinal studies to examine the further progress of perceptual narrowing, and perhaps even extend our current research into children old enough to provide responses, which would allow for the use of more precise and informative testing paradigms. Finally, future studies should be aware of potential intersensory training and carryover effects when testing infants at multiple ages, and aim for larger sample sizes in order to allow for the detection of even subtle relationships between the domains of face and speech perception.

In conclusion, our study longitudinally shows that German Caucasian infants undergo simultaneous perceptual narrowing in their perception of other-race Asian faces and non-native Cantonese tones between 6 and 9 months of age. These findings provide some evidence of temporal similarity in the appearance of perceptual narrowing in face- and speech-perception, which adds to the overall evidence in support of the theory of domain-general processes driving perceptual narrowing in these domains. However, the lack of correlation between the outcomes of these perceptual narrowing processes across individual infants suggests even if domain-general processes are involved, their influence appears to be relatively weak in comparison to the effects of natural variance between individual infants.

Author statement

Anna Krasotkina: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Validation; Roles/Writing - original draft; Writing - review & editing. **Antonia Götz:** Writing - review & editing. **Barbara Höhle:** Conceptualization; Funding acquisition; Supervision; Writing - review & editing. **Gudrun Schwarzer:** Conceptualization; Funding acquisition; Project administration; Resources; Software; Supervision; Writing - review & editing.

Declaration of Competing Interest

The authors report no declarations of interest.

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Full length article

Bimodal familiarization re-sensitizes 12-month-old infants to other-race faces

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ABSTRACT

Perceptual narrowing in the domain of face perception typically begins to reduce infants' sensitivity to differences distinguishing other-race faces from approximately 6 months of age. The present study investigated whether it is possible to re-sensitize Caucasian 12-month-old infants to other-race Asian faces through statistical learning by familiarizing them with different statistical distributions of these faces. The familiarization faces were created by generating a morphed continuum from one Asian face identity to another. In the unimodal condition, infants were familiarized with a frequency distribution wherein they saw the midpoint face of the morphed continuum the most frequently. In the bimodal condition, infants were familiarized with a frequency distribution wherein they saw faces closer to the endpoints of the morphed continuum the most frequently. After familiarization, infants were tested on their discrimination of the two original Asian faces. The infants' looking times during the test indicated that infants in the bimodal condition could discriminate between the two faces, while infants in the unimodal condition could not. These findings therefore suggest that 12-month-old Caucasian infants could be re-sensitized to Asian faces by familiarizing them with a bimodal frequency distribution of such faces.

1. Introduction

Starting from birth, infants are exposed to various types of stimuli, with some classes of stimuli being encountered more frequently than others. For example, with regard to human faces, infants are usually surrounded by faces which are for the most part of the same-race type (Sugden, Mohamed-Ali, & Moulson, 2014). Being more experienced with a specific type of stimulus attunes infants' discrimination abilities towards these stimuli at the expense of other – less frequently encountered types. This change in discrimination ability, known as perceptual narrowing, usually happens during the second half of the first year of life. While up to approximately 6 months of age, infants can discriminate between novel and familiar stimulus exemplars within many classes of stimuli, from the second half of the first year they maintain and improve their discrimination abilities only with regard to stimuli that they frequently encounter in their daily life. This developmental change has been observed in several domains such as speech perception (e.g., Höhle, Bijeljac-Babic, Herold, Weissenborn, & Nazzi, 2009; Werker & Tees, 1984), human face perception (e.g., Kelly et al., 2005, 2007), animal face perception (Simpson, Suomi, & Paukner, 2016), as well as audio-visual integration of face and speech information (Kubicek et al., 2014; Pons, Lewkowicz, Soto-Faraco, & Sebastián-Gallés, 2009).

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In particular, perceptual narrowing in the domain of face perception has been well documented in human infants during the first year of life. It has been observed that prior to 6 months of age, infants typically show similar levels of discrimination abilities for both same-race and various other-race faces. From 6 months of age, infants who live in mono-ethnic environments begin to show reduced discrimination of faces from some, though not all, other ethnicities. By 9 months of age, infants show reduced discrimination for faces from a broad variety of other ethnicities (Kelly et al., 2007, 2009; Krasotkina, Götz, Höhle, & Schwarzer, 2020). The concept of a multi-dimensional "face-space" provides a plausible framework for perceptual narrowing reducing the sensitivity of infants to faces belonging to classes which they rarely encounter (Slater et al., 2010; Valentine, Lewis, & Hills, 2016). Specifically, it has been proposed that while infants and younger children might initially make use of a larger number of dimensions within the face-space, this multidimensional space gradually loses those dimensions which are not useful for the perception of rarely encountered faces (Hills, Holland, & Lewis, 2010; Valentine et al., 2016).

However, there is reason to believe that the human face-space remains flexible and can accommodate new dimensions. For instance, there is evidence that around 9 months of age infants can be re-sensitized towards the faces of ethnicities which are uncommon in their environment through exposure to them. For example, Caucasian infants, who were exposed to books with Asian faces between the ages of 6–9 months, did not show the typical reduction in sensitivity for Asian faces at the age of 9 months (Heron-Delaney et al., 2011). Anzures et al. (2012) were also able to re-sensitize 8- to 10-month-old Caucasian infants to faces from other ethnicities. They exposed infants to a video of Asian women singing and using infant-directed speech over the course of 3 weeks, and found that the infants did not show a sensitivity reduction towards Asian faces after this training. However, beyond the simple need for exposure to other-race faces, not much is known about additional factors which may be important for re-sensitizing older infants to these faces after the infants have already undergone the typical reduction in sensitivity for these faces.

One possible approach to re-sensitize older infants to differences between other-race faces is to provide them with the opportunity to use statistical learning as they are familiarized to such stimuli. Statistical learning theory (for a review, see Aslin & Newport, 2012) proposes that infants have a remarkable ability to detect statistical information in stimulus sequences from birth (Bulf, Johnson, & Valenza, 2011), which is considered to be a crucial element of human information processing (e.g., Gomez et al., 2017). This theory relies on observations that infants are sensitive to clusters of similarity between objects, and can form object categories centered on those clusters (e.g., Younger, 1985). It is important to point out that although infants can also form categories based on more explicit information, such as verbal labels (e.g. Plunkett, Hu, & Cohen, 2008), statistical learning does not actually require any explicit labels, and posits that infants can also implicitly learn the statistical patterns in the sets of objects which they are exposed to.

Statistical learning as it applies to the present topic can be illustrated by considering an example with a single dimension which represents the variability of exemplars belonging to a particular class of objects. Statistical learning can allow infants to learn to distinguish those exemplars by using their position along that dimension. In other words, if two exemplars of stimuli differ along some particular sensory dimension, infants can learn to rely on this dimension in order to distinguish between these stimuli. The effectiveness of this learning process naturally depends on the distribution of the exemplars along this dimension. Research on statistical learning has focused on two highly contrasting distributions of stimuli, a bimodal and a unimodal distribution (Maye, Werker, & Gerken, 2002; Yoshida, Pons, Maye, & Werker, 2010). A bimodal distribution, with exemplars most commonly falling into two clusters at the opposite ends of the dimension (e.g. very widely set eyes vs. very closely set eyes) appears to more easily sensitize infants to this dimension. By contrast, a unimodal distribution with exemplars forming one single cluster, seems to make it more difficult for infants to learn to use this dimension for discriminating among stimuli of this class. Evidence for this type of statistical learning, has been found in domains such as speech-, object-, and face-perception (Altvater-Mackensen, Jessen, & Grossmann, 2017; Junge, van Rooijen, & Raijmakers, 2018; Maye et al., 2002; Yoshida et al., 2010).

In the domain of speech perception there is evidence that infants' discrimination of speech sounds can be modified by auditory exposure to speech that is highly controlled for distributional properties. For example, Maye et al. (2002) exposed 6- to 8-month-old infants to a continuum made of speech sounds that differed in voicing. Infants who were exposed to a bimodal distribution of speech sounds from this voicing continuum (sounds which were nearer to the two endpoints of the voicing continuum were presented more frequently) could discriminate between sounds from the end points of this continuum afterwards. By contrast, infants who were exposed to a unimodal distribution from the same voicing continuum (sounds which were nearer to the middle of the voicing continuum were presented more often) could not discriminate the sounds from the endpoints afterwards. Changes in sensitivity to sound differences using distributional properties were also demonstrated in another study (Yoshida et al., 2010) that examined 10-month-old infants who were already undergoing a reduction in sensitivity for non-native sound contrasts due to perceptual narrowing. The authors were able to re-sensitize infants from an English-speaking environment to a sound contrast from Hindi which is not present in the English language by exposing them to a bimodal distribution of these sounds during familiarization. By contrast, infants exposed to a unimodal distribution did not show re-sensitization. These findings demonstrate that manipulating distributional properties of stimuli can re-sensitize infants to rarely encountered stimuli classes even after they undergo perceptual narrowing.

In the visual domain, another study with 10-month-old infants likewise showed differences in the ability of infants to construct visual object categories depending on whether they were familiarized to objects using a unimodal or a bimodal frequency distribution (Junge et al., 2018). In this study, infants were familiarized with either a unimodal or a bimodal distribution of exemplars from a morphed continuum created using 2 unfamiliar objects. After familiarization, infants were exposed to test trials consisting of exemplar objects from the continuum in alternating and non-alternating orders. Alternating trial pairs showed different objects from the continuum one after the other, while non-alternating trial pairs showed a repetition of the same object. Infants in the bimodal condition preferred to look at the alternating test trials, most likely as a result of constructing two object categories after the familiarization procedure, which allowed them to perceive the two objects as different. On the other hand, infants in the unimodal condition did not demonstrate any looking differences between the alternating and non-alternating test trials. This indicated that they were unable to differentiate between the objects, possibly because they constructed a single large category comprising objects from the whole continuum.

There is also evidence that distributional properties in the input can have a similar effect on infants' discrimination abilities for faces. Altvater-Mackensen et al. (2017) measured event-related potentials as they familiarized and tested 6.5-month-old infants using a procedure that we adapted for the present study. Infants were first familiarized with either a bimodal or unimodal distribution from a morphed continuum constructed from two same-race faces. They presented a total of 159 faces during familiarization to allow infants to experience these different frequency distributions. After familiarization, all infants were tested using the same procedure. In each test trial, two faces that could be either identical (match trials) or different (mismatch trials) were shown consecutively, similarly to the alternating and non-alternating trial orders used by Junge et al. (2018) as described above. Most importantly, the test faces consisted of faces at or close to the endpoints of the face continuum. The results showed that the infants could discriminate between the test faces only if they were exposed to a bimodal distribution during familiarization. On the other hand, infants exposed to a unimodal distribution did not show any evidence of discriminating between the test faces.

1.1. Current study

The current study aimed to investigate whether the effects of perceptual narrowing in the domain of face perception could be altered in infants by manipulating the distributional properties of familiarization well after infants start to undergo the perceptual narrowing process in this domain, which typically begins at 6 months of age. To investigate this question, we exposed Caucasian infants to other-race Asian faces using a bimodal frequency distribution of face morphs compared to a unimodal distribution. We chose 12-month-old infants as our age group to ensure that they were old enough to show the typical reduction in their sensitivity for other-race faces by this age (Kelly et al., 2007, 2009).

In our study, we measured infants' fixation times using an approach adapted from Altvater-Mackensen et al. (2017), as described above. This approach made it easier to compare our findings with those of other studies which examined the possibility of re-sensitizing infants to other-race faces via their fixation times (Anzures et al., 2012; Heron-Delaney et al., 2011). In our adapted approach, we familiarized 12-month-old Caucasian children with a continuum of morphed other-race (Asian) female faces using either a unimodal or a bimodal distribution. After familiarization, we tested the infants on their ability to discriminate between the two endpoint other-race faces of the continuum.

Based on the results of Altvater-Mackensen et al. (2017), we hypothesized that infants in the unimodal familiarization condition would form a single other-race face identity category based on the distribution of the morphed exemplars they saw. These infants should therefore be unable to discriminate between the two endpoint other-race faces of the continuum in the test phase. By contrast,

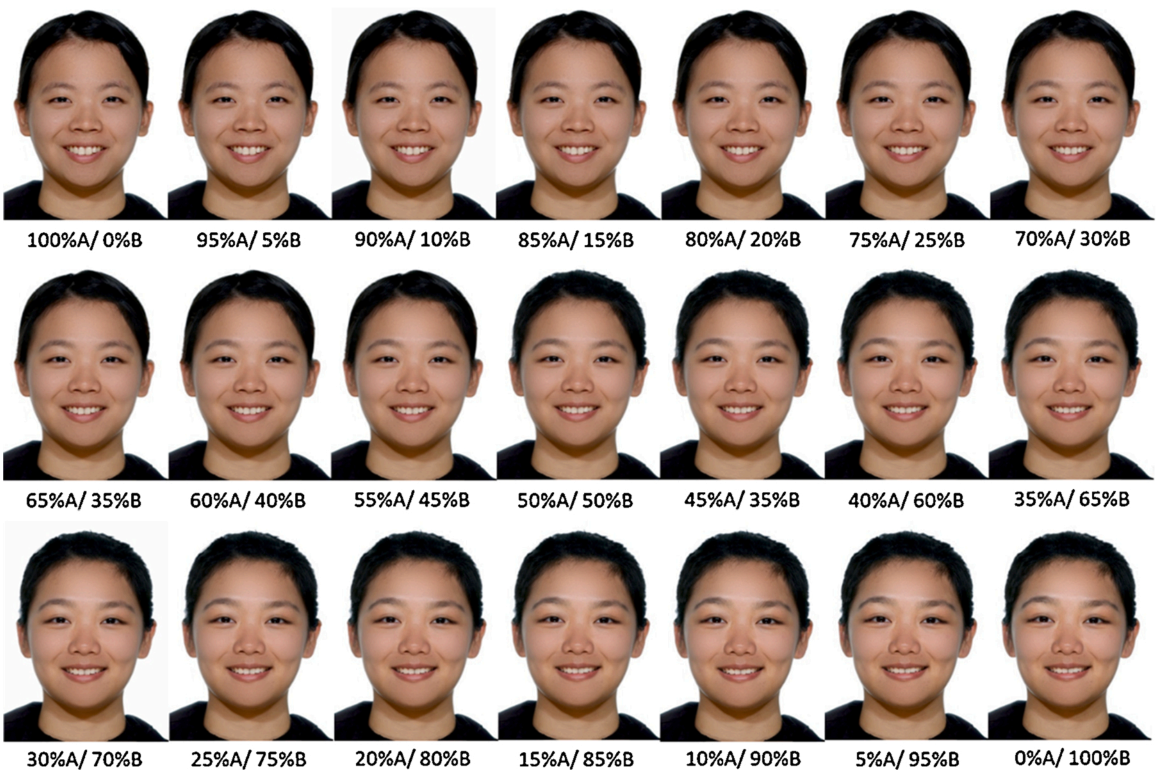

Fig. 1. Morphing sequence from Face A to Face B.

we hypothesized that children in the bimodal group would form two separate other-race face identity categories which would help them to successfully discriminate between the two endpoint other-race faces during testing.

2. Method

2.1. Participants

We collected data from 55 12-month-old Caucasian infants from monolingual German households. The infants were randomly assigned to either the unimodal or bimodal condition. None of the infants had direct regular contact with persons of Asian descent according to their parents' reports. Fifteen infants were excluded from the final sample because of fussiness (n = 1), failure to calibrate (n = 4), technical problems during the experiment (n = 2), or failure to reach the familiarization criteria of looking at the faces in a least 80 % of the familiarization trials (n = 8). The final sample thus consisted of 40 infants (age range: 365–394 days, 17 female), with 20 infants in each condition. The present study was conducted in accordance with the German Psychological Society (DGPs) Research Ethics Guidelines. Experimental procedures were approved by the Office of Research Ethics at the University of Giessen.

2.2. Stimuli

In our study, we used FantaMorph version 5.4.8 to create morphed faces from color photographs of two Asian women (Face A and Face B). These two photos were previously used to demonstrate a sensitivity reduction for other-race faces in 9 months old infants in a study by Krasotkina, Götz, Höhle, and Schwarzer (2018). The resulting morphed continuum gradually changed from Face A (100 % Face A/ 0 % Face B) to Face B (0 % Face A/ 100 % Face B) in 5 % steps in a sequence of 21 faces (Fig. 1). These 21 faces were used as stimuli in the present study. All stimuli appeared as 14.5 cm x 21 cm in size on the screen. All 21 faces of the continuum including the endpoints were used in the familiarization phase of the experiment. The test phase included only the endpoint faces.

2.3. Procedure, apparatus, and design

Parents received a description of the experimental purpose but stayed blind to the hypotheses. All parents then gave written consent for their child's participation in our study. Children sat on their parent's lap approximately 60 cm from a computer display with a screen resolution of 1920 × 1080 pixels, and an integrated Tobii tx300 eye tracker with a 300 Hz sampling rate. Parents were instructed to close their eyes and not to communicate with their children during the experiment.

We used an infant-specific 5-point calibration procedure with an animated attention-getter which popped up at the 4 corners and the middle of the screen. We repeated the calibration procedure until it was successful for all 5 points according to the eye-tracking software calibration report. Children who failed to calibrate were excluded from the final sample (n = 4). The experiment started immediately after the calibration procedure was completed.

We used the same frequency distribution schema as described by Altvater-Mackensen et al. (2017) (see Fig. 2 for face frequency distributions for both conditions). Infants in the unimodal condition were presented with the 50 %A/ 50 %B morph face most frequently (15 times), whereas children in the bimodal condition saw the 25 %A/ 75 %B and 75 %A/ 25 %B morphs most frequently (15 times each). Infants in both conditions saw the endpoint faces the same amount of times (3 times each).

The faces in each condition were shown in random order with the restriction that the same face would not appear in two consecutive trials. It is important to note, that infants in both conditions saw the same amount of familiarization faces (159) and the

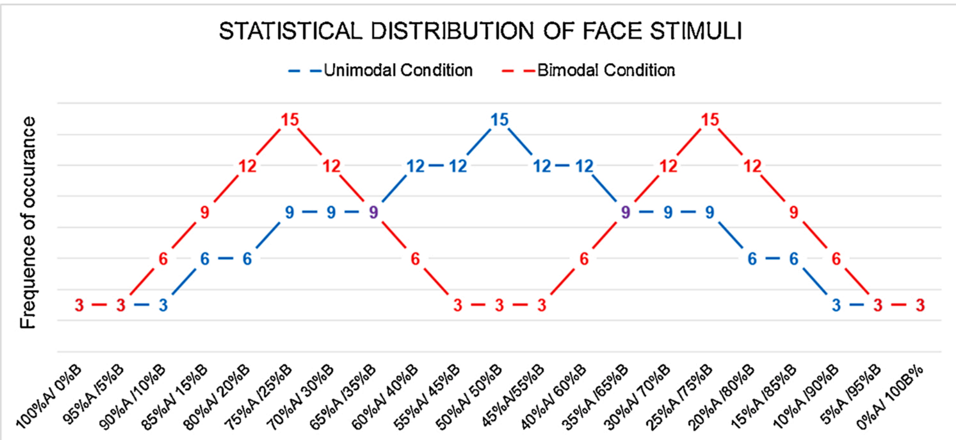

Fig. 2. Frequency distribution of morphed face stimuli in the unimodal (blue) and bimodal (red) familiarization conditions (adapted from Altvater-Mackensen et al., 2017). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

same amount of the endpoints faces (100 %A/ 0 %B and 0 %A/ 100 %B). Each face was presented for 750 ms (at the center of the screen), followed by a blank screen for 350 ms. The presentation duration was brief in order to accommodate the high number of faces shown during the familiarization trials without fatiguing the infants. The entire duration of the familiarization phase including the pauses between the trials was 174.55 s.

The test phase started immediately after the familiarization phase. Test phases were identical for both familiarization conditions and contained 4 trials. Each test trial began with an animated attention-getter (a bouncing ball). As soon as the infant fixated the attention-getter, it was replaced by a prime face (face A or B) shown for 750 ms at the center of the screen, immediately followed by a blank screen for 350 ms, and then immediately followed by one of the test faces (face A or B) at the center of the screen. To reduce the risk of infants losing interest before viewing all test trials, each test face was shown on the screen only for as long as the infant continued to look at it (the trial ended once infants looked away from the test face for longer than 2 s), up to a maximum of 20 s. The mean duration for test trials was 7.4 s. For the test trials we used the endpoints faces (100 %A/ 0 %B and 0 %A/ 100 %B), as both prime and test faces resulting in match and mismatch test trials. In match trials the prime and test faces were identical (e. g. prime: 100 %A/ 0 %B, test: 100 %A/ 0 %B), while in mismatch trials the prime and test faces were different (e. g. prime: 100 %A/ 0 %B, test: 0 %A/ 100 %B). Each infant thus saw a total of 4 trials, consisting of the 4 possible order combinations of the prime and test face.

2.4. Data analysis

We used Tobii Pro Studio to analyze the gaze data. A single fixation was defined as a looking period of at least 100 ms within a maximum radius of 30 pixels based on previous analyses of eye tracking data from infants (e.g., Liu et al., 2011; Wheeler et al., 2011; Xiao, Quinn, Wheeler, Pascalis, & Lee, 2014). For fixation time measurements, we used the sum of the fixation durations for each trial for one single AOI which encompassed the entire head of the person in the photograph (with both internal and external face features included).

All infants included in the final sample saw at least 80 % of the familiarization faces (i.e. made at least one fixation toward the 80 % of faces shown during the familiarization phase). There was no significant difference between the average amount of faces infants saw in the unimodal condition ($M = 144.9$, $SD = 5.48$), and bimodal condition ($M = 148.25$, $SD = 6.09$). Additionally, we verified that the trials included in the analysis (i.e. where we recorded at least one fixation) did not deviate from the bimodal or unimodal distributions, depending on the condition. All infants included in the final sample showed at least one fixation toward the prime and the target in each test trial.

3. Results

To test whether infants discriminated between the two other-race Asian test faces after familiarization, we compared fixation times in the test phase for the test faces in match and mismatch trials in the unimodal and the bimodal conditions. There were no significant differences in fixation times for face A and face B. Therefore, we took the sum of the infants' fixation times for the 100 %A/ 0 %B target face and 0 %A/ 100 %B target face within each level of congruency and condition (see Fig. 3). Using these values, we conducted a repeated-measures ANOVA with congruency (match trial, mismatch trial) as a within-subject factor and condition (unimodal distribution, bimodal distribution) as a between-subjects factor. We found a significant main effect of congruency, $F(1,38) = 9.062$, $p = .005$, partial $\eta^2 = .23$, and a significant interaction between congruency and condition, $F(1,38) = 5.583$, $p = .023$, partial $\eta^2 = .14$. Planned pairwise comparisons showed that there was no significant difference in fixation times between match and mismatch trials in the unimodal condition, $F(1,38) = 0.210$, $p = .650$, partial $\eta^2 = .002$, match: 16.886 ± 1.898 s ($M \pm SE$), mismatch: 16.408 ± 1.983 s (Fig. 3, left). However, in the bimodal condition children showed significant differences in fixation times between match and mismatch

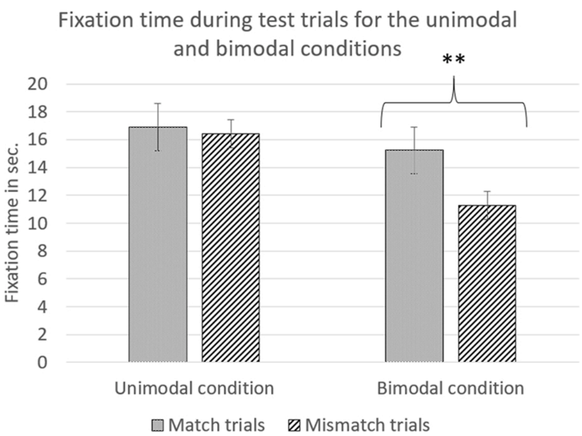

Fig. 3. Comparison of fixation times during the test trials by 12-month-old infants in the unimodal and bimodal conditions. Error bars represent standard error, ** indicates a level of significance of $p < .01$.

trials, $F(1,38) = 14.437$, $p = .001$, partial $\eta^2 = .632$, match: 15.230 ± 1.898 s, mismatch:11.260 ± 1,983 s (Fig. 3, right).

These results show that Caucasian infants' discrimination abilities for other-race faces were influenced by the frequency distribution with which different face exemplars were seen by the infants. After being exposed to a unimodal distribution of faces from a morphed continuum during familiarization, infants showed no differences in fixation times in match and mismatch trials. This suggests that they did not discriminate between the endpoint faces. However, infants who were exposed to a bimodal distribution of faces from the same morphed continuum during familiarization looked less at the test faces during the mismatch trials compared to the match trials. This indicates that infants could perceive the differences between the endpoint faces after being exposed to the bimodal distribution. Taking into account that infants in both conditions saw the endpoint faces with the same frequency during familiarization, these group differences could only have occurred due to the difference in the distribution of the presentation of the morphed faces during the familiarization phase.

4. Discussion

Our findings agree with previous reports that the statistical distribution of encountering specific stimuli influences the formation of categories in different modalities such as sounds (Maye et al., 2002; Pelucchi, Hay, & Saffran, 2009), object shapes (Junge et al., 2018), and face identities (Altvater-Mackensen et al., 2017). To our knowledge, our study is the first to investigate how statistical information affects infants' discrimination of other-race faces after the onset of the perceptual narrowing. Our results show that infants' processing of other-race faces can be modulated by the frequencies with which those faces are seen. Infants who were exposed to a unimodal frequency distribution of other-race faces during the familiarization trials did not show any fixation time differences when viewing match versus mismatch test trials. This indicates that the infants could not discriminate between the two endpoint faces. On the other hand, 12-month-old infants who were exposed to a bimodal distribution of other-race faces during familiarization, showed different fixation times in the corresponding match and mismatch trials, indicating that they were able to discriminate between the endpoint test faces. Our findings thus extend previous research by showing that experience with this kind of distributional information can modify infants' ability to discriminate other race-faces at an age at which they typically show a reduction in sensitivity for other-race faces due to perceptual narrowing.

These data support the findings of previous studies indicating that discrimination abilities of infants for faces from unfamiliar ethnicities are still flexible even after undergoing perceptual narrowing (Anzures et al., 2012; Heering et al., 2010). Our results add to these findings by showing that exposure to a bimodal distribution of such faces is particularly effective in improving discrimination for these faces even in infants as old as 12 months. While infants typically lose their sensitivity to differences between faces from unfamiliar ethnicities between 6 and 9 months of age (Kelly et al., 2007, 2009; Krasotkina et al., 2018, 2020), our study suggests that exposure to a sufficiently varied statistical distribution of face exemplars can allow infants to discriminate between such faces at 12 months. This suggests that even infants already undergoing perceptual narrowing in face processing can be re-sensitized to the patterns differentiating other-race faces if they are exposed to a sample of other-race faces containing a sufficiently high proportion of distinct face exemplars. In our study, we were able to observe this re-sensitization in the bimodal condition, in which the most frequently presented faces differed from each other to a much greater extent than the most frequently presented faces in the unimodal condition. Thus, in agreement with the findings of Altvater-Mackensen et al. (2017), our results provide further evidence that statistical learning is a mechanism that can shape the perception and discrimination of other-race faces even after the onset of perceptual narrowing during infancy. Furthermore, our findings together with those of Altvater-Mackensen et al. (2017), Junge et al. (2018), and Maye et al. (2002) indicate that the manipulation of statistical learning through the use of varying frequency distributions can re-shape infants' perception abilities across multiple domains and counteract the typical effects of perceptual narrowing.

Our results also contribute to a general understanding of the development of face perception based on statistical learning and category formation within the infants' face-space, by extending the findings of previous studies on infants' discrimination abilities for other-race faces (Kelly et al., 2007, 2009; Krasotkina et al., 2018; Spangler et al., 2013). In classical studies on infants' face discrimination, infants were usually habituated or familiarized to one (Kelly et al., 2007; Kelly et al., 2009) or several (Krasotkina et al., 2018; Spangler et al., 2013) pictures of a single face, and then tested on their ability to discriminate between the familiar faces and a novel face. A number of studies using this method have found that at the age of 9 months, infants cannot discriminate between novel and familiar other-race faces (Kelly et al., 2007, 2009; Krasotkina et al., 2018; Spangler et al., 2013). One possible explanation for these findings from the perspective of statistical learning is that through continuous exposure to the same other-race face during familiarization or habituation, infants who have undergone perceptual narrowing likely fail to identify the dimensions which can differentiate such faces, and form only a single other-race face identity category within their face-space. This could in turn make it difficult for them to attend to the crucial distinctions between the familiarized or habituated face and a novel face during testing. Our results seem to support this hypothesis by demonstrating that when infants are familiarized to a more varied bimodal distribution of other-race faces, they are able to discriminate among them. We hypothesize that this might occur as a result of infants becoming sensitized to the dimension underlying the continuum of morphed faces in the familiarization, and thus being able to form multiple separate other-race face identity categories within the face-space.

4.1. Limitations

In adapting our distribution-based experimental method from Altvater-Mackensen et al. (2017), we naturally had to limit ourselves to very brief presentations of static stimuli in order to maintain the infants' attention over such a large total number of trials. While this distributional approach allowed us to examine how infants use statistical learning, it cannot be denied that our brief presentation of still photographs might not be as visually rich compared to the some of the stimuli used in other studies such as books and videos (Anzures et al., 2012; Heering et al., 2010). It would thus be interesting to extend our methodological approach by exposing infants to similar stimuli, but with a longer presentation duration. If this could be accomplished while maintaining the infants' attention using some additional means, or using fewer trials, such an experiment could expand our understanding of the actual visual encoding process taking place. Another possible step for future studies would be to test even older infants and children in order to determine the limits of this approach in restoring sensitivity to other-race faces after the onset of perceptual narrowing in this domain.

4.2. Conclusions

Our findings extend previous research by showing that statistical learning can shape face discrimination abilities for other-race faces, and can allow infants to be re-sensitized to other-race faces even after a reduction in sensitivity due to perceptual narrowing. Infants who were familiarized using a bimodal morphed continuum distribution were able to discriminate between the two endpoint other-race faces during testing. On the other hand, infants in the unimodal condition were unable to discriminate between the two endpoint faces when tested. Our findings can therefore further our understanding of how infants use statistical regularities as they perceive the faces they are surrounded by, and what role such mechanisms could play as infants undergo perceptual narrowing in this domain.

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CRediT authorship contribution statement

Anna Krasotkina: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Writing - original draft, Writing - review & editing. **Antonia Götz:** Writing - review & editing. **Barbara Höhle:** Funding acquisition, Supervision, Writing - review & editing. **Gudrun Schwarzer:** Conceptualization, Funding acquisition, Project administration, Resources, Software, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors report no declarations of interest.

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Infants' Gaze Patterns for Same-Race and Other-Race Faces, and the Other-Race Effect

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Abstract: The other-race effect (ORE) can be described as difficulties in discriminating between faces of ethnicities other than one's own, and can already be observed at approximately 9 months of age. Recent studies also showed that infants visually explore same-and other-race faces differently. However, it is still unclear whether infants' looking behavior for same- and other-race faces is related to their face discrimination abilities. To investigate this question we conducted a habituation–dishabituation experiment to examine Caucasian 9-month-old infants' gaze behavior, and their discrimination of same- and other-race faces, using eye-tracking measurements. We found that infants looked longer at the eyes of same-race faces over the course of habituation, as compared to other-race faces. After habituation, infants demonstrated a clear other-race effect by successfully discriminating between same-race faces, but not other-race faces. Importantly, the infants' ability to discriminate between same-race faces significantly correlated with their fixation time towards the eyes of same-race faces during habituation. Thus, our findings suggest that for infants old enough to begin exhibiting the ORE, gaze behavior during habituation is related to their ability to differentiate among same-race faces, compared to other-race faces.

Keywords: eye-tracking; infancy; habituation; other-race effect; face discrimination

1. Introduction

The other race effect (ORE) begins to manifest during the first year of life, and is characterized by less efficient processing of faces from ethnicities that one does not have sufficient exposure to, when compared to faces from their own ethnicity (for a review, see [1]). Although recent studies showed that infants look at same- and other-race faces differently (e.g., [2–4], and see [5] for an overview) the role of infants' visual encoding of same- and other-race faces for face discrimination is still not fully understood. Therefore, the goal of our study was to investigate the extent to which infants' looking behavior while habituating to same- and other-race faces, is connected to their ability to discriminate among these faces.

During the first year of life there is a sensitive period when the face recognition system is exposed to inputs consisting of many exemplars of faces [6]. These inputs are thought to calibrate the face recognition system such that the infant begins to examine faces in an optimal way, for distinguishing faces matching the template of the initial calibrating sample. Given that infants have been shown to predominantly see same-race faces [7], this input might tune the face perception system towards the optimal perception of same-race faces. This hypothesis was supported by evidence that Caucasian [8], African [9], and Asian [10] 3-month-old infants who grew up in mono-ethical environments showed a looking preference for same-race faces when shown together with other-race faces. In terms of discrimination abilities, at 3 months of age, Caucasian and Asian infants did not yet exhibit differences in discrimination ability for same- and other-race faces, and only displayed a looking preference for the faces they were habituated to, regardless of race. However, by the age of 9 months, infants were able to discriminate only between same-race faces [11–13].

Regarding the mechanism behind this divergence of discrimination abilities, there is increasing evidence from eye-tracking studies that infants display different fixation patterns when looking at same- versus other-race faces (e.g., [2–4,14]). For example, when looking at same-race faces, 6- to 10-month-old Caucasian infants showed a higher proportion of fixation time for the eyes and showed a lower proportion of fixation time for the mouth, with increasing age. However, no such developmental changes were observed in the fixations for other-race faces [3]. Xiao and colleagues [14] found the same patterns in 6- and 9-month-old Caucasian infants. The same study also showed that at 9 months of age, infants looked significantly longer at the eyes of same-race compared to other races faces, and less at the mouth of same-race, as compared to other race faces. Thus, we already have an indication that infants might use different looking behaviors when viewing same-race and other-race faces.

It is important to note, however, that the above studies used passive viewing tasks to record infants' looking behavior but did not relate the looking behavior to discrimination abilities. Little is known about whether infants' looking behavior is connected with their discrimination performance for same-race and other-race faces. To the best of our knowledge, there are only two studies that investigated this question. Gaither and colleagues [15] investigated 3-month-old Caucasian and Asian infants' ability to discriminate among Caucasian and Asian faces, using a habituation–dishabituation procedure, combined with the recording of infants' gaze behavior. Consistent with previous studies [11,12], infants of both ethnicities showed comparable discrimination abilities for both face categories. Nevertheless, the authors revealed significant positive correlations between same-race novelty looking preference and more frequent transitions between the eye and mouth regions of own-race habituation stimuli for Caucasian and Asian infants. A recent study [16] extended this research by testing 6- and 9-month-old Asian infants. After familiarization to same- and other-race face stimuli, infants in both age groups showed a novelty looking preference in the same-race but not in the other-race condition. Infants also showed different looking patterns for the same- and other-race faces. Both 6- and 9-month old infants looked significantly longer at the nose and mouth of same-race faces than of other-race faces, during familiarization. Additionally, the amount of time infants looked at the eyes and nose of faces during a recognition test was positively correlated with the recognition performance during the test trials. Taken together, these data suggest that 3-month-old Caucasian and Asian infants, as well as Asian infants between 6 and 9 months of age look differently at same- and other-race faces, during familiarization or habituation, and that these differences in their looking patterns are connected with their face discrimination performance.

The aim of the current study was to extend the above approach to determine whether this link between gaze behavior and discrimination ability also appears in Caucasian infants old enough to begin exhibiting the ORE. We therefore investigated whether 9-month-old Caucasian infants' gaze behavior while habituating to same- and other-race faces is related to their discrimination of these faces. We tested only 9-month-old Caucasian infants because a previous study [16] revealed no age-related differences between 6- and 9-month old infants in the looking pattern for both same- and other-race faces, and the ORE was already observed at the age of 9 months in several studies [11–13]. As we wanted to replicate the previous findings regarding the ORE in infants, we used the same habituation–dishabituation procedure as [11–13]. This procedure allowed us to examine infants' gaze behavior while they encode same- and other-race faces during the habituation phase, and enabled us to subsequently test the discrimination of the habituated faces from a novel face. We were then able to test whether the patterns of infants' gaze behavior during habituation correlated with their discrimination abilities at test, in a similar manner to the study examining the gaze behavior and discrimination abilities of Asian infants [16].

Based on the finding of previous studies, we expected infants to show an ORE in terms of better discrimination of same-race faces, compared to other-race faces. We also anticipated Caucasian infants to use different looking patterns while habituating to same- and other-race faces. Based on the results of [4,14], we anticipated that infants might show differences in their fixation times towards the eyes, and perhaps the mouth of same-race faces, compared to other-race faces. Finally, we also expected to find a connection between infants' looking patterns during habituation and their face discrimination performance based on the findings of [15,16].

2. Materials and Methods

2.1. Participants

We collected data from 68 healthy, full-term, Caucasian 9-month-old infants (M = 292.42 days; range: 275–304 days, 31 female and 37 male). To avoid any possible carry-over effects from the exposure to faces of varying races within the experiment, each infant participated in either the same-race or other-race condition, as in prior studies [11–13]. Thirty-four infants participated in the same-race condition, and the other 34 infants participated in the other-race condition. The sample size was chosen based on a statistical power analysis that used effects sizes taken from a study by [13], which found the ORE in 9-month-old infants with a comparable sample size. An additional 16 participants were excluded from the final sample because of fussiness (n = 5), failing the habituation criteria (n = 8), or technical problems during the experiment (n = 3). Infants were recruited through the municipal administration office. None of the infants included in our analyses had direct contact with individuals of Asian descent (no Asian relatives or acquaintances), according to a questionnaire administered to their parents.

2.2. Stimuli

Based on the results of a preliminary study (see below), we selected colored photographs of 6 Caucasian (German origin) and 6 Asian (Chinese origin) women for use as stimuli. Each woman was presented in three poses: frontal-facing, turned $\frac{3}{4}$ to the left, and turned $\frac{3}{4}$ to the right. In every photo, the woman looked directly at the camera while smiling, with the hair, neck, and shoulders visible. Smiling faces were chosen over faces showing neutral expressions to make the stimuli more appealing to the infants, as neutral faces have been shown to appear as emotionally negative to children [17]. Examples of stimuli pairs are shown in Figure 1.

To select our stimuli, we conducted a preliminary study with 15 German and 14 Chinese adults to ensure that the pairs of faces from the same ethnicity that were used for the test phase were of comparable similarity for the two ethnicities. We took 15 pictures with faces from each ethnicity (15 German women for the Caucasian category, and 15 Chinese women for the Asian category), combined them into pairs within each ethnicity, and showed them to the German and Asian adults. Participants rated each pair of photographs twice using a scale from 1 (very similar) to 9 (very different). German subjects rated the Caucasian German faces, and the Chinese subjects rated the Chinese Asian faces.

The three most similar pairs from each ethnicity category were then selected as the stimuli for our main study—6 Caucasian faces in three pairs (with average similarity ratings of 4.69, 4.69, and 4.81), and 6 Asian faces in three pairs (with average similarity ratings of 4.59, 4.73, and 4.73).

Figure 1. Examples of other-race (above) and same-race (below) faces used in the habituation and test trials. We are authorized to use and publish the photographs of the person in the figures.

2.3. Procedure

Parents were informed regarding the study procedure and gave written consent for their child's participation. All parents were blind to the study hypotheses. Infants sat on their parent's lap approximately 60 cm from a computer monitor with a screen resolution of 1920 × 1080 pixels, and an integrated Tobii TX300 eye tracker with a data-sampling rate of 300 Hz. The nominal accuracy was given as 0.4°–0.5° at our lighting conditions (office-lighting), as per the TX300 manufacturer, and the nominal precision was given as 0.04°–0.06° using noise-reduction data filtering, although as shown by Hessels and Hooge [18], in practice such parameters could prove to be noticeably worse, especially when testing infants. See https://www.tobiipro.com/siteassets/tobii-pro/product-descriptions/tobii-pro-tx300-product-description.pdf for additional technical specifications of the Tobii TX300 system.

The parents were instructed to close their eyes and sit still during the experiment. In order to record infants' gaze behavior, we used a 5-points calibration procedure (4 corners and the middle of the screen). The calibration procedure was repeated until calibration was achieved successfully for all 5 points, up to a maximum of 4 attempts (the data from participants who failed the calibration procedure were excluded from data analysis).

Participants were randomly assigned to one of two conditions (Caucasian or Asian faces). Each picture was displayed 12.5 cm (11.89°) wide and 16.5 cm (15.66°) high on the screen. We used an infant-controlled habituation-dishabituation procedure with a maximum of 18 habituation trials. During habituation, pictures of a single face were shown sequentially, randomly alternating between the three possible poses (photos were presented in sequences of three, with each sequence containing all three poses in a random order). An acoustic attention-getter was played with the appearance of each picture. Pictures were presented until the infant looked away for 2 s, or until the maximum trial length of 40 s was reached. We considered that an infant was habituated when the mean looking time of the three last habituation trials was less than 50% of the mean of the first three habituation trials. The test phase started immediately after this habituation criterion was reached, or after the maximum of 18 habituation trials were presented. Those infants who saw all 18 habituation trials without having reached the habituation criterion were considered to not have been habituated, and were excluded from further analysis. In the test phase, the previously habituated face was shown in a randomly alternating order with another face from the same race category as the habituated face (from the originally selected pair of faces), with both faces presented frontally (one at a time) for a maximum duration of 40 s, for a total of two test trials. E-Prime version 2.0 (Psychology Software Tools, Pittsburgh, PA, USA) was used to control the stimulus presentation.

2.4. Data Analysis

The eye-tracking data were analyzed with the Tobii Pro Studio using the included ClearView fixation filter using the following setting. Fixations were defined with a minimum looking period of 100 ms, within a radius of 30 pixels (0.765°) for the consecutive samples, based on previous analyses of eye tracking data from infants ([2,4]). The nominal precision (0.04°–0.06°) given by the manufacturer for the TX300 was below 0.1°, which according to examples demonstrated by Holmqvist and colleagues [19] should be sufficient for the minimal loss of fixations detected. We created five Areas of Interest (AOIs)—whole-head, left eye, right eye (during analysis, we combined the left and right eyes together into a single AOI), nose, and mouth. Figure 2 shows an example of AOI positioning. The size of each AOI was the same for each picture, and the exact position was individually adjusted for each face. For each AOI within (each trial), we calculated total dwell time as the sum of the durations in seconds of all fixations made by each particular infant in that AOI. Mean total dwell time for each participant was then calculated as the average of total dwell times across all trials of the habituation phase of the experiment. Similar to the analysis used by Liu and colleagues [16], proportional total dwell times were computed by dividing the mean total dwell times of the individual AOI's (eyes, nose, mouth) by the mean total dwell time of the whole-head AOI.

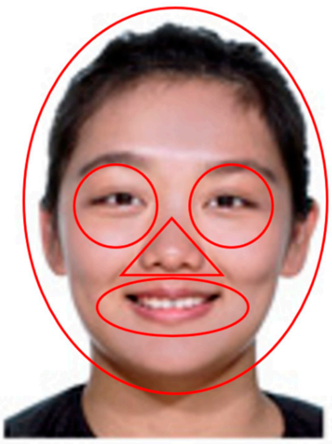

Figure 2. Illustration of areas of interest (AOIs) corresponding to the left eye (width: 104 pixels, 2.651°; height: 104 pixels, 2.651°), right eye (width: 104 pixels, 2.651°; height: 104 pixels, 2.651°), nose (width: 91 pixels, 2.320°; height: 55 pixels, 1.402°), mouth (width: 176 pixels, 4.485°; height: 87 pixels, 2.218°), and the whole-head (width: 399 pixels, 10.147°; height: 479 pixels, 12.167°). We are authorized to use and publish the photographs of the person in the figures.

Infant face discrimination was assessed via their novelty preference scores, which was defined as the total dwell time for the novel face (whole head AOI) as a proportion of the sum of the total dwell times for the novel and habituated faces at test. To look for connections between infants' gaze behavior during habituation and their discrimination ability at test, we computed correlations between infants' proportional total dwell times for the various AOIs during habituation, and their novelty preferences.

3. Results

3.1. Preliminary Analyses

To ensure that a similar level of eye-tracking data quality was obtained for both conditions, we conducted a one-way ANOVA on the percentages of the samples in which the eye-tracker successfully registered the position of the infants' gaze on the monitor, with stimulus-race condition (same-race, other-race) as a between subjects factor. We did not find a significant effect of stimulus-race condition, $F(1, 66) = 0.060$, $p = 0.807$, indicating a similar level of data capture quality in the same-race and other-race conditions ($M = 80.235\%$ vs. $M = 80.823\%$, respectively).

To ensure that the infants in the same-race and other-race conditions did not differ with respect to the number of trials seen during habituation and the total dwell time for the stimuli, we conducted two further one-way ANOVAs using stimulus-race condition (same-race, other-race) as a between subjects factor. The first ANOVA was conducted on the number of trials that the infants saw during habituation, and we found no significant effect of stimulus-race condition, $F(1, 66) = 0.636$, $p = 0.428$, indicating that the infants saw a similar number of habituation trials in the same-race and other-race conditions ($M = 8.12$ vs. $M = 8.71$, respectively). The second ANOVA was conducted on the total dwell times (in seconds) of the infants for the whole-head AOI during habituation. Again, we found no significant effect of stimulus-race condition, $F(1, 66) = 0.077$, $p = 0.782$, indicating that the infants showed a similar total dwell time for our face stimuli during habituation in the same-race and other-race conditions ($M = 67.16$ s vs. $M = 71.39$ s, respectively).

3.2. Face-Discrimination Performance

A one-way between subjects ANOVA was conducted to compare novelty preference scores (the whole-head AOI total dwell time for the novel face divided by the sum of the whole-head AOI total dwell times for the novel and habituated faces) for infants in the test trials for the same- and other-race face conditions. There was a significant difference between the novelty preference scores (Figure 3) in the two conditions, $F(1, 66) = 10.610$, $p = 0.002$, indicating a significantly higher average preference score in the same-race compared to the other-race condition. To investigate whether the novelty preference scores for same- and other-race faces were above chance, we used two post-hoc one-sample *t*-tests to compare the novelty preference scores against a chance-level novelty preference score of 0.50 for each condition. The results indicated that the infants' preference scores in the same-race condition were significantly above chance, ($M = 0.669$ s, $SD = 0.202$; $t(33) = 4.872$, $p < 0.001$), indicating that they were able to discriminate between the same-race faces. By contrast, the preference scores in the other-race condition ($M = 0.527$ s, $SD = 0.154$) were not significantly different from chance, $t(33) = 1.018$ $p = 0.316$, indicating that the infants could not discriminate between the other-race faces. This pattern of results clearly demonstrated the ORE.

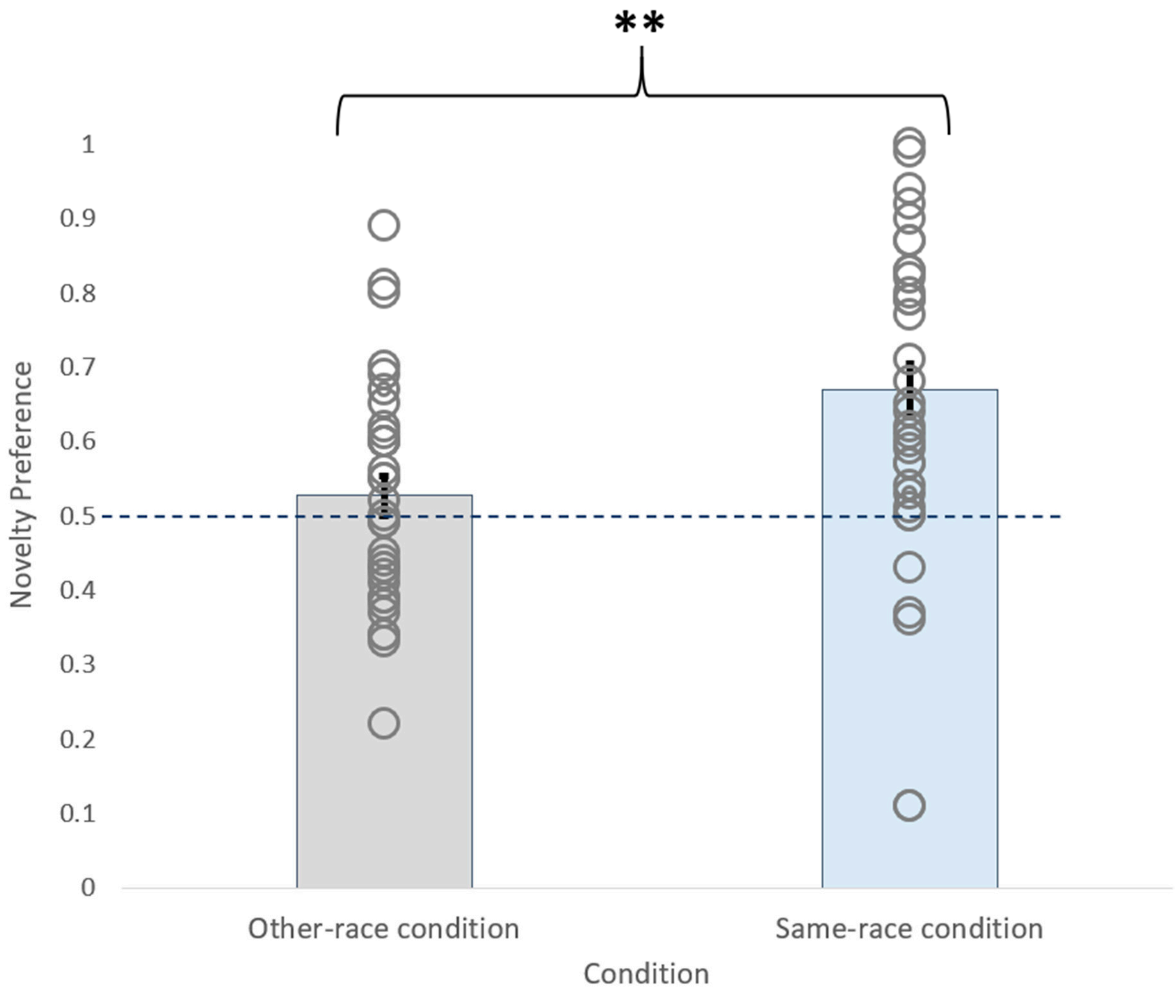

Figure 3. Novelty preference scores for the same-race and other-race conditions. Circles indicate the individual data points, and the dotted line indicates the expected chance-level novelty preference of 0.5. Error bars indicate standard error, and two stars indicate a significance level of $p < 0.01$.

3.3. Gaze Behavior

3.3.1. Proportional Total Dwell Time for Individual AOIs during the Habituation Phase

To analyze the gaze behavior of infants during habituation, we first calculated the proportional total dwell times for the eyes, nose, and mouth AOIs (in total for the entire habituation stage), as described earlier. Using those proportional total dwell times as the dependent measure, we conducted a repeated measures ANOVA with the AOI (eyes, nose, mouth) serving as a within-subject repeated measure factor, and the stimulus-race condition (same-race, other-race) as a between-subjects factor. Greenhouse–Geisser corrections were used due to a violation of sphericity. We detected a significant main effect of stimulus-race condition, $F(1, 66) = 21.255$, $p < 0.001$, as well as a significant main effect of AOI, $F(1.45, 95.685) = 20.055$, $p < 0.001$. Especially interesting for our study, the results also showed a significant interaction between AOI and the stimulus-race condition, $F(1.45, 95.685) = 3.630$, $p = 0.044$, which indicated that infants in the two conditions distributed their attention differently between the three AOIs.

To further analyze this interaction, we conducted three individual one-way ANOVAs on the proportional total dwell times for the eyes, nose, and mouth AOIs, with the stimulus-race serving as a between-subjects factor in a similar analysis procedure as that used by Liu and colleagues [16]. We found a significant difference between the stimulus-race conditions in the eyes AOI, $F(1, 66) = 10.698$, $p = 0.002$, with the infants showing a greater overall proportional total dwell times for the eyes in the same-race (*M* = 0.388, *SD* = 0.218) as compared to the other-race condition (*M* = 0.216, *SD* = 0.215). The remaining two ANOVAs on the proportional total dwell times for the mouth and nose AOIs did not show any significant differences between the stimulus-race conditions (Figure 4).

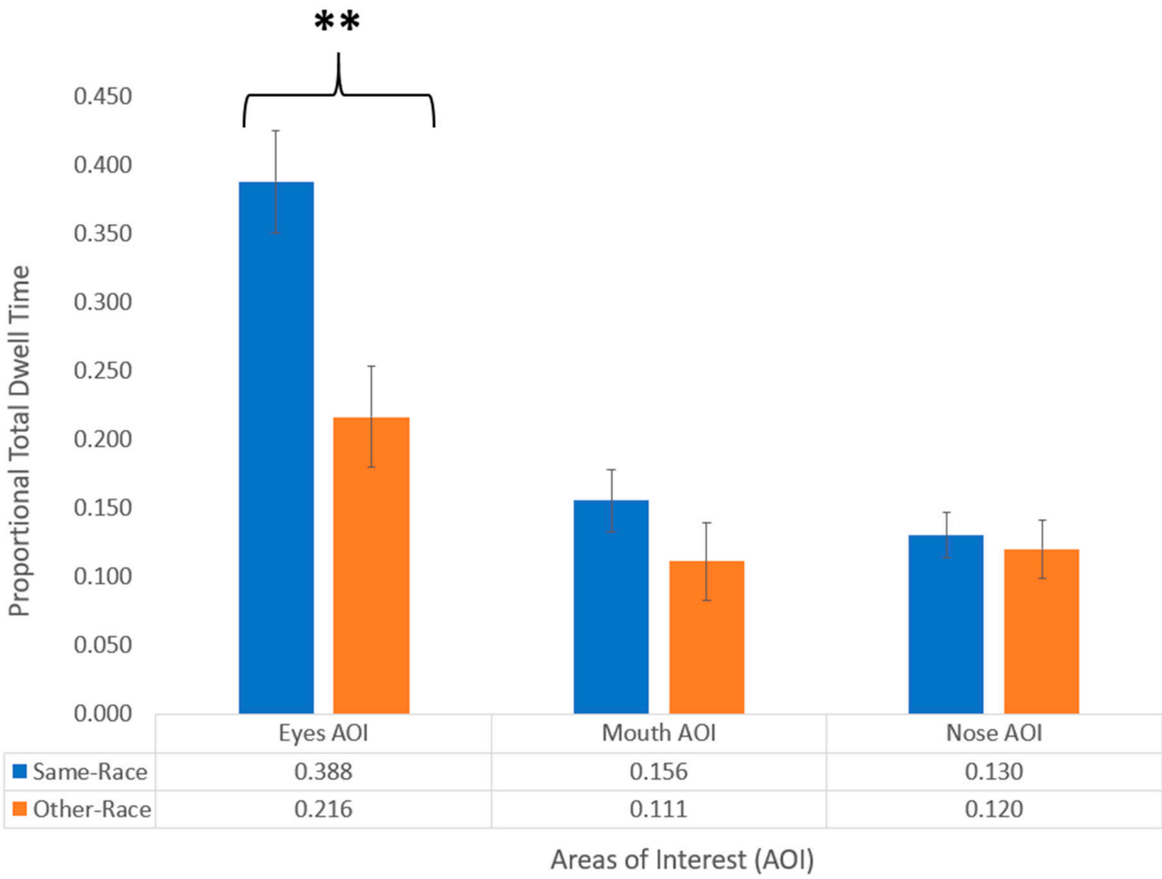

Figure 4. Proportional total dwell times for eyes, nose, and mouth AOIs during the habituation phase for the same-race and other-race conditions. Error bars indicate standard error, and the two stars indicate a significance level of $p < 0.01$.

3.3.2. Relations between Proportional Total Dwell Times during Habituation and Novelty Preferences

To examine the relationship between infants' looking patterns during habituation and their discrimination performance at test, we calculated Pearson correlations between the infants' novelty preference scores, and their proportional total dwell times for the eyes AOI during habituation. We found a significant difference between the same-race and other-race conditions, as per the ANOVA analysis described above (Figure 4). We found a significant positive correlation between infants' novelty preferences in the same-race condition during testing and their proportional total dwell times for the eyes AOI during habituation, r = 0.380, $p = 0.027$. Thus, the more the infants in the same-race condition looked at the eyes AOI during the habituation stage, the better they could discriminate between novel and familiar faces during the test phase (Figure 5). By contrast, infants in the other-race condition showed no significant correlation between their novelty preferences during testing and their proportional total dwell times towards the eyes AOI during habituation, r = 0.008, $p = 0.963$. Using a Fischer r-to-z transformation, we compared the above correlation coefficients from the same-race and other-race conditions, which showed the difference to be marginally significant, $p = 0.062$.

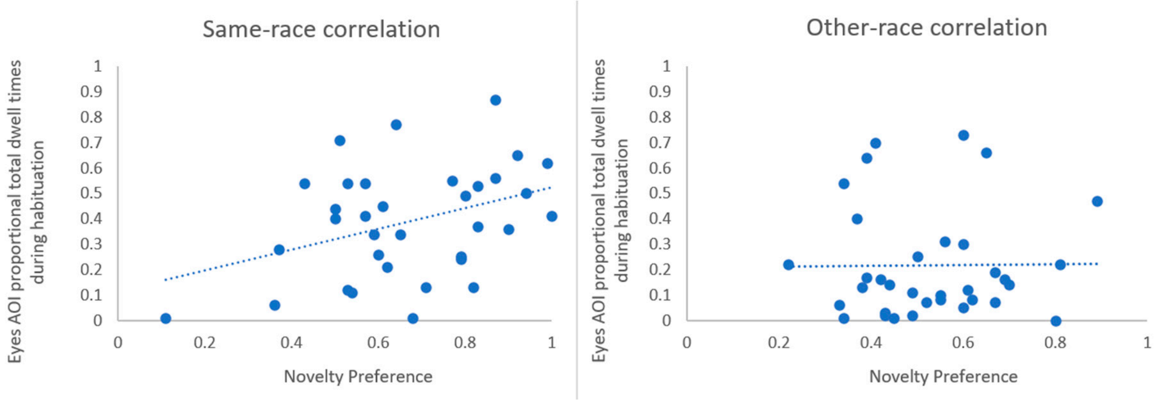

Figure 5. Correlation between infants' novelty preference scores during testing and their proportional total dwell times for the eyes AOI during habituation in the same-race condition (**left**) and the other-race condition (**right**).

4. Discussion

The aim of the present study was to investigate whether there are differences in the fixation patterns of 9-month-old Caucasian infants during habituation to same- and other-race faces, and whether these differences are connected to the ORE, i.e., better discrimination of same-race faces compared to other-race faces. Our results showed that the 9-month-old infants exhibited a clear ORE, as they showed a novelty preference in the Caucasian same-race condition, but not in the Asian other-race condition. Furthermore, our data showed that there are differences between the fixation patterns during habituation to Caucasian same-race faces versus Asian other-race faces. Infants showed greater proportional total dwell times (relative to the entire face) for the eye region of the same-race faces compared to other-race faces. Our findings also indicated that for the same-race faces, the proportion of time infants spend fixating the eyes AOI during habituation, significantly correlated with their discrimination abilities during testing. No such correlation was found for the other-race faces.

Our detection of the ORE in 9-month-olds confirmed results from numerous previous studies (e.g., [11–13,16]), showing that at the age of 9 months, infants begin to show a robust ORE if they have no direct contact with people from other ethnicities. Our findings also agreed with the results of previous eye-tracking studies on infants (e.g., [2–4,16]), showing that infants look differently at same- and other-race faces. In our study, Caucasian infants fixated significantly longer on the eyes of same-race faces than of the other-race faces, which agrees with the results of previous studies [3,4,14], where Caucasian infants also fixated more on the eyes of same-race faces than other-race faces. A preference for fixating on the eye area of more familiar face stimuli was previously observed in Caucasian infants as early as 3 months old. In one study [20], human infants fixated more on the eyes of human faces than on the eyes of monkey faces. A preference for looking at the eyes of same-race faces compared to other-race faces was also found in Caucasian adult participants [21–23]. However, unlike some studies such as [3,14], the infants in our study did not show significant differences in proportional total dwell times regarding the mouth region of same- and other-race faces. This difference between our results and those of the above studies could be explained by differences in stimulus materials. While [3,14] used videos of moving faces in their studies, we used pictures. The stillness of the faces in our study could have made them appear as less communicative, and thus attracted less attention towards the mouth, which is a key component in the perception of verbal communication.

Our results also agreed with previous infant studies that showed that there is a connection between infants' gaze behavior while encoding faces and their performance in recognizing faces (e.g., [15]). In our study, we found that longer proportional total dwell time on the eyes AOI during habituation corresponds with better face discrimination in testing in the same-race condition, but not in other-race conditions. These results are, to our knowledge, the first to demonstrate that the gaze patterns of

Caucasian infants old enough to exhibit the ORE are directly linked to their ability to discriminate between same-race and other-race faces. Thus, our findings suggest that the ORE at 9 months of age might at least partially stem from the lack of attention paid to the eye region of other-race faces by infants, and that infants might place less weight on the informative value of the eyes, with respect to the identity of other-race face during encoding, which could in turn lead to poorer other-race face discrimination.

One limitation of our study was the usage of still photographs rather than videos for face stimuli. An important step for future studies would be the production and usage of video stimuli, which would still conform to our requirements in terms of their visual parameters. Such video stimuli could add important new insights to the role of gaze patterns in the ORE, since such stimuli might offer additional useful visual cues for face discrimination. For example, a study by Xiao and colleagues [24] demonstrated that the recognition of moving faces seems to be more dependent on the quantity of infants' fixation shifts than that of static faces.

An additional point worth noting is that although we demonstrated a correlation between the infants' proportional total dwell times for the eyes during habituation and their discrimination ability, we cannot definitively prove causation. In order to prove that infants' dwell time for the eyes has an effect on face discrimination, future studies would need to manipulate the information that infants can gain from the eye region and measure the resulting discrimination performance. One possible way to achieve this would be, for example, to show the eye region with varying levels of blurring during habituation.

Another aspect of our experiment which bears further consideration was the use of smiling faces as opposed to neutral faces for stimuli. The ORE was already demonstrated in 9-month-old infants using smiling faces [17], and so we chose to use smiling faces as well, in order to make the stimuli appear more pleasant for the infants. However, emotional expressions were recently shown to play a role in the ability of infants to recognize other-race faces. For instance, Quinn and colleagues [25] demonstrated that infants old enough to exhibit the ORE were able to differentiate other-race faces better when they displayed emotions such as happiness or anger, than when they showed a neutral expression. While the infants in the present study still displayed the ORE, even for the happy faces, this could be a result of the face pairs in our experiments being selected to be as similar as possible, and thus, being more challenging to discriminate. Nevertheless, it would be important to expand our investigation to encompass other facial expressions, including neutral expressions, in future studies in order to fully understand the roles of perceptual narrowing and emotional expressions in the ORE.

It is also important to note that we only tested Caucasian infants in our study. Although it was demonstrated that the ORE appears in all races [8–12], it was also shown that children from different races look at faces by using different gaze patterns [2–4,16]. It would thus be interesting to extend our findings to further cultures to see whether and how the differences in looking patterns we found during habituation, and their relation to discrimination abilities, might differ across cultures. Likewise, it would also be interesting to see if the looking behaviors we observed in Caucasian infants were common across stimuli of additional ethnicities, since we only used Asian faces for our other-race face stimuli.

5. Conclusions

Our findings suggest a connection between the ORE and the gaze patterns that 9-month-old Caucasian infants use when examining same- and other-race faces. Our results showed that during habituation infants fixated significantly longer on the eye region of the same-race faces compared with the other-race faces, as a proportion of overall fixation time towards the stimuli. We then found a significant correlation between the infants' proportional total dwell time for the eyes of same-race faces during habituation and their discrimination of those faces during the test. By contrast, we found no such correlation for other-race faces. These findings offer novel evidence that directly links the gaze behavior of Caucasian infants during habituation to other-race effects during discrimination testing.

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