Infants use disambiguation to learn new voices

Abstract

The ability to identify individuals by voice is a fundamental communicative ability. However, little is known about the expectations that infants hold when learning the voices of unfamiliar people. Here, the voice-learning skills of 4- and 8-month-old infants (N=53) were tested using a preferential looking task that involved audio-visual stimuli of their mothers and other unfamiliar women. Findings reveal that the expectation that novel voices map on to novel faces emerges as early as 4 months of age, and that infants can retain learning of face-voice pairings via disambiguation by 8 months of age. This study provides new insights about voice learning in infancy, and the mechanisms by which infants integrate the visual and auditory features of individuals around them.

Keywords: voice identification, infancy, disambiguation, eye-tracking

Word count: 3999

1. Introduction

Infants receive abundant exposure to faces and voices from birth (Bergelson et al., 2019; Sugden, Mohamed-Ali, & Moulson, 2013). These face-to-face and turn-taking contexts drive cognitive and social learning (e.g., Bloom, Russell, & Wassenberg, 1987). A key skill infants need for efficient communication is the ability to recognize the voices of individuals around them. How and when do infants learn which voice goes with which individual? In the current study, we examined the emergence of a learning bias that infants may bring to the task of voice identification: namely, the expectation that novel voices map on to novel faces.

First, consider the low-level perceptual skills that are needed to form face-voice pairings: infants must be sensitive to facial and vocal differences between individuals. There is strong behavioral and neurological evidence that infants enter the world with attentional biases for both faces (Johnson, Dziurawiec, Ellis & Morton, 1990) and speech (Vouloumanos & Werker, 2007; Pena et al., 2003). Experience allows infants to further tune their perceptual capacities for processing facial and vocal features (Maurer & Werker, 2014).

Indeed, infants are sensitive to *facial* features of individuals (see Sugden & Marquis, 2017 for a review). Within a few hours from birth, infants already show recognition of their mother's face (Bushnell, 2001). In their first year of life, infants preferentially look towards familiar face types, such as female faces and faces of their mother's race (Kelly, Quinn, Slater, Lee, Ge, & Pascalis, 2007; Quinn, Yahr, Kuhn, Slater & Pascalis, 2002). Their ability to discriminate between unfamiliar faces appears very early on, even when the faces are presented via static photographs (de Haan, Johnson, Maurer, & Perrett, 2001). Moreover, infants' ability to discriminate faces gradually becomes more sophisticated through the first year of life (de Haan, Johnson & Halit, 2003).

Prior work has also shown that humans are sensitive to *vocal* properties from early on. Fetuses and newborns show physiological and behavioral changes in response to hearing their mother's voice versus an unfamiliar woman's voice (DeCasper & Fifer, 1980; Voegtline, Costigan, Pater & DiPietro, 2013). Further, neuroimaging studies reveal differential neural responses when listening to a familiar versus an unfamiliar voice (Naoi et al., 2012; Saito, Fukuhara, Aoyama & Toshima, 2009). Beyond sensitivity to voice identity, young infants also recognize various indexical aspects of speech: they can differentiate between male and female voices (Miller, 1983) and between speech sounds from an adult and from another infant (Polka, Masapollo, & Ménard, 2014).

Matching *facial* and *vocal* features presents an additional cognitive step, but research suggests that infants are quite adept at detecting and collating these two types of information. For example, infants are sensitive to the temporal congruency between lip movements and speech sounds by 2-months of age (Dodd, 1979), and can already match these features on the basis of phonetic information (Patterson & Werker, 2003). Impressively, behavioral work shows that 4-month-old infants will look towards their mother's face when listening to a recording of her voice (Spelke & Owsley, 1979), suggesting that their face-voice representations extend beyond audio-visual congruency.

To date, little is known about the expectations or biases that infants carry when learning the voices of unfamiliar speakers. One potential bias that infants could use is the expectation that novel voices map on to novel faces. Certainly, one-to-one mapping is not a new idea – rather, this bias is often discussed in the context of word learning to explain how children limit the scope of plausible referents. For example, in the presence of familiar and unfamiliar objects (e.g., a cup and a garlic press, respectively), children are more likely to associate a novel word, such as 'zav', with

the unfamiliar object (i.e., the garlic press; Markman & Wachtel, 1988). Similar variations of this heuristic have been explored across different domains (e.g., Childers & Tomasello, 2003), and even in other species (Kaminski, Call, & Fischer, 2004), suggesting that it is an accessible and effective cognitive tool for early learning. Indeed, this is a justifiable heuristic for voice learning given that infants typically interact with unfamiliar people in the context of a caregiver, such as their mother. Thus, it may be the case that infants will exhibit the disambiguation effect of mapping novel voices on to novel faces.

One study has directly examined whether children exhibit disambiguation in voice learning (Moher, Feigenson, & Halberda, 2010). In this study, 4- and 5-year-old children were introduced to unfamiliar speakers. During critical trials, children saw a picture of a newly-familiar face (of whose voice they recently learned) alongside a novel face. Results showed that children mapped a novel voice to the novel face. Impressively, children showed a disambiguation response to the novel face even after just a single exposure to the newly-familiar face-voice pairing.

In the current study, we examined whether this one-to-one bias for voice-face pairings is present in early infancy. Specifically, we examined whether infants would map novel voices to novel faces, and whether infants could retain learning of these face-voice pairings. As an ambitious first step, we first tested infants at 4 months of age via a preferential looking task, given evidence that infants can already discriminate a change in face-voice pairing at this age (Bahrick, Hernandez-Reif & Flom, 2005).

2. Experiment 1

2.1. Methods

Participants

We recruited 27 four-month-old infants (Mean age = 122 days; Age range = 107 – 134; 17 girls, 10 boys). An additional 12 infants were tested but excluded from the final sample because of fussiness (5), technical error due to eye tracking (6) or not meeting language criteria (1). All infants were exposed to English at least 90% of the time, per parent reports. Infants had a range of ethnic backgrounds (European: 17; East and Southeast Asian: 4; Multiracial: 6).

Mother information

There were 27 participating mothers (Mean age = 34 years; Age range = 30 – 41). Of the participating mothers, 18 were of European descent, 7 were of East and Southeast Asian descent, 1 was of African descent, and 1 was multiracial. All mothers learned English from birth and spoke English regularly with their infants.

Stimuli

Each participant was shown unique audiovisual stimuli from their mother and two unfamiliar women. The two unfamiliar women were the mothers of the two infants who had just participated; thus, each infant saw a different pair of unfamiliar speakers. This methodological step was taken so that vocal and facial familiarity across all audio and visual stimuli would be random. For our first two participants, we used stimuli of two unfamiliar women from pilot testing.

Prior to the study itself, we took a photo of the infant's mother. To maintain visual consistency across the different speakers, participating mothers were asked to wear a white laboratory coat and a white scarf. Further, they were asked to maintain a neutral face for the photograph.

We also audio recorded the mothers speaking two passages presented on a computer screen. They were asked to produce the sentences as if they were speaking to their own child. To provide mothers with practice, they were first asked to naturally produce the passages twice. Then, to

control for speech rate, mothers were asked to follow the tempo of words being presented on the computer screen (as if doing karaoke). Mothers were asked to repeat the passage for the introductory phase twice in this manner – one of which was chosen for the study. They were also asked to repeat the passage for the disambiguation and test phases six times – four of which were chosen for the study.

All infants stayed in the waiting area with a research assistant while the mother completed this stimuli-creation process; thus, participating infants did not see their mothers wearing the white lab coat and scarf, nor did they hear their mothers speaking the sentences, prior to the experiment. This process took approximately 5 minutes.

Procedure

The study was conducted in a dimly lit, sound-attenuated room. Infants were seated on their parent's lap, approximately 60 cm away from the television and eye-tracking system (Tobii X60 eye tracker). Loudspeakers were placed behind the monitor. Prior to the study, infants' eye movements were calibrated through the eye tracker via a 5-point infant calibration routine.

The experiment consisted of three phases: an introductory phase, a learning phase, and a test phase (see Figure 1 for visual schematic). In the introductory phase, infants saw a still image of their mother on the center of the screen, and they heard their mother introducing the experiment. The purpose of this phase was to introduce the pairing of the still picture of their mother and the auditory stimuli. Indeed, previous word learning studies show that a referential familiarization phase boosts performance in a word learning task (Fennell & Waxman, 2010). Further, this phase allowed infants some time to acclimate seeing their mothers on the television screen.

In the learning phase, infants were presented with eight trials. Each trial featured the photographs of the mother and one unfamiliar speaker (henceforth referred to *unfamiliar speaker*

A), presented side-by-side on the screen. The presentation side of the speakers was counterbalanced throughout the experiment. The pair of faces first appeared in silence on the monitor for two seconds, so that infants' baseline preference for each face could be measured. Then, on each trial, they heard either their mother's voice or unfamiliar speaker A's voice saying: "*I'm over here! Look at my nose!*" Each trial lasted 9 seconds. The order in which voices were presented was based on randomized lists, with the rule that the same type of trial could not be presented more than twice in a row.

In the test phase, infants were tested on their recognition of the unfamiliar speaker A. In this phase, infants saw the photographs of *unfamiliar speaker A* as well as a novel unfamiliar speaker (henceforth referred to *unfamiliar speaker B*). On each trial, they heard either unfamiliar speaker A or B saying: "*I'm over here! Look at my nose!*". Similar to the learning phase, there were four repeating blocks of two trials each, for a total of eight trials, and the presentation side of the speakers was counterbalanced.

Data preparation

We analyzed infants' looking time across the length of the trial. We defined the area of interest as the rectangular photos on each side. We excluded gazes outside of these AOIs. In total, each infant contributed an average of 6.6 (SD = 2.1) out of 8 learning trials, and 5.3 (SD = 2.1) out of 8 test trials. In all primary analyses, the dependent variable was proportion looking time to the target face divided by total looking to the target and non-target faces. We preset three windows of analysis (WoA) during the trial (see Figure 1): baseline (0 – 2000 ms), WoA 1 (2360 – 4360 ms; 360 ms after the onset of the first utterance: *I'm over here!*), and WoA 2 (5360 – 7360 ms; 360 ms after the onset of the second utterance: *Look at my nose!*). Note that the beginning of WoA 1 and WoA 2 were offset by 360 ms, the time needed for infants to process speech sounds and initiate an

eye movement (Swingley, 2011). We used the eyetrackingR package (Dink & Ferguson, 2015) in R (R Development Core Team, 2017) to prepare and analyze the data.

2.2. Results

Looking patterns for learning phase

Figure 2a shows the continuous time-course of infants' looking behavior through the learning phase. Visual inspection of the figure suggests divergent looking behaviors during the first WoA. Specifically, infants looked proportionally more towards their mother's face while hearing their mother's voice, and they looked proportionally more towards the unfamiliar woman's voice while hearing the unfamiliar woman's voice.

Statistical analyses confirm these observations. First, we submitted infants' proportion looking to their Mother's face to a repeated-measures ANOVA with target voice (2: Mother, Unfamiliar speaker A) and period (2: Baseline, First WoA, Second WoA) as within-participants factors. There was a main effect of period [$F(2,52) = 6.27, p = .004, \eta_p^2 = .19$], and no main effect of target voice [$p = .22$]. Importantly, there was a significant interaction between these two factors [$F(2,52) = 3.13, p = .05, \eta_p^2 = .11$]. Therefore, we analyzed infants' looking patterns between each trial type at each period. Pairwise comparisons, using paired t-tests with Bonferroni adjusted p -value, confirm that infants' looking patterns differed for the first WoA [$p = .02$], but not at baseline or the second WoA [$ps > .25$] (see Figure 2b).

To confirm that this pattern of results is robust (and not merely present due to a pre-selected WoA), we conducted a Growth Curve Analysis. One advantage of this analysis is that it does not have prior assumptions about when differences (if any) might emerge during the course of the trial (see Waxman et al., 2016 for an example). The model was fitted with trial-level looking data, with target voice (2: Mother, Unfamiliar speaker A), time (3: linear, cubic, and quartic growth

trajectories) and their interaction as fixed effects, and participants as random effects. There was a significant interaction between target voice and time, particularly the cubic time parameter [$\beta = 1.73$, $SE = 0.49$, $\chi(1) = 3.53$, $p < 0.001$], indicating that the looking patterns of infants differed significantly across the two trial types. To control further for false-alarms, we conducted a bootstrapped cluster-based permutation analysis (similar to Waxman et al., 2016). This analysis reveals that infants' attention diverged from 2100 ms to 3400 ms [$p < .001$]; no other 100-ms time bins reached statistical significance.

Looking patterns for test phase

Visual inspection of Figure 2b suggests no differences in looking behaviors across the two trial types. Specifically, infants did not appear to look proportionally differently at the two faces – regardless of the voice they heard. To confirm these observations, we conducted a repeated-measures ANOVA, with target voice and period as within-subject factors. There was a main effect of both target voice and period [$p < .05$]; but crucially, there was no significant interaction between the two factors [$F(2,28) = .69$, $p = .51$, $\eta_p^2 = .03$]. Pre-planned pairwise comparisons reveal no significant differences in looking behavior between the two trial types for baseline and the first and second WoA [$ps > .29$]. A growth curve analysis confirms no significant interaction between the two factors [$ps > .25$].

3. Experiment 2

In Experiment 1, infants looked longer towards their mother's face when hearing her voice, indicating that this paradigm is well-suited for assessing voice recognition in infants. Impressively, infants showed disambiguation during the learning phase: they looked proportionally longer at an unfamiliar woman's face upon hearing an unfamiliar voice. Nonetheless, the 4-month-old infants did not show retention of the novel face-voice pairing, indicating that younger infants have

difficulty learning the voices of unfamiliar individuals via disambiguation. To assess whether slightly older infants might be able to use disambiguation to learn new face-voice pairings, we conducted the same experiment with 8-month-old infants.

3.1. Methods

Participants

We recruited 26 eight-month-old infants (Mean age = 237 days; Age range = 225 – 250; 12 girls, 14 boys). An additional 17 infants were tested but excluded from the final sample because of fussiness (7), technical error (2), lack of eye-tracking data (6), not meeting language criteria (1), or not meeting participant criteria (i.e. premature infant; 1). Per parent reports, all infants were exposed to English at least 90% of the time. This group of infants also had a range of ethnic backgrounds (European: 18; East and Southeast Asian: 2; Multiracial: 6).

Mother information

There were 24 participating mothers (Mean age = 34 years; Age range = 28 – 38). Of the participating mothers, 19 were of European descent, 6 were of East and Southeast Asian descent, and 1 was multiracial. All mothers reported learning English from birth and speaking English regularly with their infants.

Stimuli

The process of recording stimuli was identical to Experiment 1.

Procedure

The procedure was identical to Experiment 1.

Data preparation

On average, each infant contributed 6.1 (SD = 2.4) out of 8 learning trials, and 4.3 (SD = 2.0) out of 8 test trials.

3.2. Results

Looking patterns for learning phase

Figure 3A shows the continuous time-course of 8-month-old infants' looking behavior through the learning phase. Visual inspection of the figure suggests divergent looking behaviors during portions of the first WoA. That is, upon hearing their mother's voice, infants looked proportionally more towards their mother's face. Similarly, when hearing unfamiliar speaker A's voice, infants looked proportionally more towards speaker A's voice.

To confirm these observations, we submitted infants' proportion looking to their Mother's face to a repeated-measures ANOVA with target voice and period as within-participants factors. There was a significant main effect of target voice and period [$p < .05$], but no interaction between these two factors [$F(2,24) = 2.70, p = .09, \eta_p^2 = .18$]. Nevertheless, pre-planned pairwise comparisons indicate that infants' looking patterns differed for the first WoA [$p = .048$], but not at baseline or the second WoA [$p > .70$] (see Figure 3b).

A growth curve analysis confirms this pattern of results. As before, the model was fitted with trial-level looking data, with target voice, time, and their interaction as fixed effects, and participants as random effects. Particularly, there was a significant interaction between target voice and the quadratic time parameter [$\beta = -.36, SE = .11, \chi(1) = -3.13, p = 0.002$]. These results confirm that the looking patterns of infants differed significantly across the two trial types. Note, however, that a cluster-based permutation analysis does not reveal any divergent looking patterns in any 100-ms bin across the two trial types.

Looking patterns for test phase

Visual inspection of Figure 3B suggests divergent looking behaviors during the test phase, specifically in portions of the first WoA and portions after the second WoA. Infants appeared to

look proportionally more at the target unfamiliar person during their respective trials, indicating that they were able to retain the novel face-voice pairing from the learning phase.

A repeated-measures ANOVA confirms these observations. There was a significant main effect of period [$F(2,38) = 11.45, p < .001, \eta_p^2 = .48$], but not of trial type [$p = .51$]. Crucially, there was a significant interaction between target voice and period [$F(2,38) = 3.52, p = .04, \eta_p^2 = .16$]. Indeed, pairwise comparisons show that infants had significantly different looking patterns during the first WoA [$p = .01$], but not during baseline or the second WoA [$ps > .09$] (see Figure 3d).

Using growth curve analysis, we confirmed these patterns of results. Particularly, a model fitted with trial-level looking data revealed a significant interaction between target voice and the linear time parameter [$\beta = .51, SE = 0.10, \chi(1) = 5.06, p < 0.001$], confirming that infants had significantly different looking patterns across the two trial types. Further, a cluster-based permutation analysis revealed divergent looking patterns between 7200 ms and 7900 ms [$p = .05$] across the two trial types.

4. General Discussion

Our results support and extend previous findings in several meaningful ways. First, consistent with previous literature, our results show that infants' familiarity with the *facial* and *vocal* features of their mother is robust from early on. Prior work has suggested that behavioral responses to highly familiar individuals are attenuated when their faces are presented via a static photograph (de Haan & Nelson, 1997), or when audio recordings are elicited in a way that obscures temporal information, such as speaking rate (Vongpaisal, Trehub, Schellenburg, van Lieshout & Papsin, 2010). Against these odds, 4- and 8-month-old infants in the present study looked toward a static photograph of their mother upon hearing an audio recording of her voice. Consistent with

prior work (Spelke & Owsley, 1979), this association emerged even in the absence of audio-visual congruency that is typical in live interactions.

Second, infants' looking patterns are consistent with the *disambiguation effect* for learning voices – that is, the tendency to map novel voices on to novel faces. The patterns found here are not merely a novelty preference, as both 4- and 8-month-old infants looked proportionally more toward the novel face upon hearing a novel voice, compared to when they heard their mother's voice. Although it is not clear from the initial learning phase alone whether infants were choosing the novel face as a referent for the novel voice, the pattern of findings indicate at the very least that infants will look towards a different referent than their mother's face when hearing a novel voice.

Finally, our findings reveal that these disambiguation patterns led to learning, at least for 8-month-old infants. Specifically, 8-month-old, but not 4-month-old, infants looked proportionally more toward the newly-familiar talker (i.e., Unfamiliar A) during the test phase, compared to when they heard a novel talker (i.e., Unfamiliar B). Impressively, these infants were able to map the novel voice to the novel face after a non-ostensive training phase and after just four repetitions of the novel face-voice association. Prior work has examined these disambiguation and learning effects of voice learning in preschoolers (Moher et al., 2010), and the current study reveals that even young infants exhibit this behavior.

What motivates infants to map novel voices to novel faces? In many ways, the arguments in this domain could parallel those found in the word learning literature (Markman, Wason & Hasen, 2003). One possibility is that infants are guided by a mutual exclusivity constraint whereby they assume that individuals are constrained by physiology to have one type of “voice”. Indeed, while there is variation in how each person sounds from moment-to-moment either due to what they are saying (e.g., Remez, Fellowes & Rubin, 1997) or due to other factors that affect vocal

quality (Lee, Keating & Kreiman, 2019), there is evidence that individuals encode the voices of others by forming a “prototype” of their voice (Latinus & Belin, 2011). As such, infants may hold a prototype of their mother’s voice and may avoid mapping any significant divergence from that prototype to their mother’s voice.

On the other hand, it is possible that infants will map a novel face to a novel person simply because they are motivated to learn the novel person’s voice. Indeed, infants are socially-motivated learners: they show more negative affect when interacting with an unresponsive adult (i.e., the still-face effect; Mesman, van Ijzendoorn & Bakermans-Kranenburg, 2009), suggesting that they expect social interactions with individuals. Findings from previous work (e.g., Brookes et al., 2001), as well as those of the current study, indicate that infants form audio-visual representations of individuals; thus, infants may search for a vocal representation for unfamiliar individuals for whom they do not have a vocal prototype. The current results do not favor one mechanism over another, and so invite future work to investigate the underlying mechanism of voice learning in infancy.

Beyond this mechanistic debate, the current study also highlights the early sophistication of voice processing. Prior work has shown that young infants are sensitive to vocal differences between individuals (Johnson, Westrek, Nazzi, & Cutler, 2011), but that robust performance in unfamiliar talker identification tasks does not emerge until 18-months (Fecher, Paquette-Smith & Johnson, 2019). Further, the use of disambiguation in voice learning had only been tested in 4- and 5-year-olds (Moher et al., 2010). The current findings reveal that 8-month-old infants can encode and retain learning of novel face-voice pairings. These findings shift our understanding of voice learning to a timeline far earlier than that typically found in word learning (i.e., ~24-months of age for disambiguation in word learning, and ~30-months of age for retention; Bion, Borovsky, &

Fernald, 2013), and thus provides support for the hypothesis that infants are cracking this important indexical code of the speech signal prior to the linguistic code (as described in Polka & Nazzi, 2019).

In summary, our study provides new insights about audio-visual matching and early voice processing. The findings show that even young infants can use one-to-one mapping biases to track and learn the voices of those around them. Future research examining the nature and limits of this capacity can advance understanding of speech and broader communicative development in typical and atypical children.

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Figure 1. Visual schematic of the three phases in the experiment: Introduction, Learning and Test. Note that photographs were used in the actual experiment, instead of drawings as visualized here. **M:** Mother; **A:** Unfamiliar Woman A; **B:** Unfamiliar Woman B; **WoA:** Window of Analysis.

Figure 2. Four-month-old infants' looking data for each phase (Learning phase: A1 and A2; Test phase: B1 and B2) presented in two ways: 1) A1 and B1 plots the time course of proportion looking, with the solid lines representing generalized additive model smoothing lines and the shaded regions representing 95% confidence intervals; 2) A2 and B2 plots proportion looking time to mother during the learning phase and to the unfamiliar woman A during the test phase, respectively, for baseline, WoA1 and WoA2.

Figure 3. Eight-month-old infants' looking data for each phase (Learning phase: A1 and A2; Test phase: B1 and B2) presented in two ways: 1) A1 and B1 plots the time course of proportion looking, with the solid lines representing generalized additive model smoothing lines and the shaded regions representing 95% confidence intervals; 2) A2 and B2 plots proportion looking time to mother during the learning phase and to the unfamiliar woman A during the test phase, respectively, for baseline, WoA1 and WoA2.