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# Development of Non-Native Vowel Discrimination: Improvement Without Exposure

**ABSTRACT:** *The present study tested Japanese 4.5- and 10-month old infants' ability to discriminate three German vowel pairs, none of which are contrastive in Japanese, using a visual habituation–dishabituation paradigm. Japanese adults' discrimination of the same pairs was also tested. The results revealed that Japanese 4.5-month old infants discriminated the German /bu:k/-/by:k/ contrast, but they showed no evidence of discriminating the /bi:k/-/be:k/ or /bu:k/-/bo:k/ contrasts. Japanese 10-month old infants, on the other hand, discriminated the German /bi:k/-/be:k/ contrast, while they showed no evidence of discriminating the /bu:k/-/by:k/ or /bu:k/-/bo:k/ contrasts. Japanese adults, in contrast, were highly accurate in their discrimination of all of the pairs. The results indicate that discrimination of non-native contrasts is not always easy even for young infants, and that their ability to discriminate non-native contrasts can improve with age even when they receive no exposure to a language in which the given contrast is phonemic.* © 2013 Wiley Periodicals, Inc. Dev Psychobiol 56: 192–209, 2014.

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## INTRODUCTION

During the past several decades, research on infant speech perception has demonstrated that the ability of infants to discriminate speech segments undergoes a significant shift during their first year of life, from a general sensitivity toward a broad range of contrasts to a selective sensitivity toward their native language (e.g., Kuhl, 2004; Saffran, Werker, & Werner, 2006; Werker & Yeung, 2005, for review). It appears that infants start out with the sensitivity to discriminate the majority of phonemic contrasts, including contrasts not used in their native languages (Eimas, Siqueland, Jusczyk, & Vigorito, 1971; Kuhl et al., 2006; Polka & Werker, 1994; Tsushima et al., 1994; Werker, Gilbert, Humphrey, & Tees, 1981). The ability to discriminate non-native speech sounds begins to decline by 6 months for vowels, and by 10 or 12 months for consonants

(Best & McRoberts, 2003; Kuhl, Williams, Lacerda, Stevens, & Lindblom, 1992; Polka & Werker, 1994; Tsushima et al., 1994; Werker & Tees, 1984), while the ability to discriminate native speech sounds is maintained. This pattern of development is sometimes called perceptual narrowing. A similar pattern of development has been observed in other domains such as face discrimination and musical rhythm recognition. As it seems to be the dominant pattern of infants' phonological development, much research has been devoted to uncovering the mechanisms underlying such development.

Further research has revealed additional developmental patterns. First, a number of studies has reported that infants' experience with a particular language can actually enhance (or facilitate) their ability to discriminate some contrasts. This pattern has been reported for the contrast between voiced and voiceless stop consonants in Spanish (Eilers, Wilson, & Moore, 1979; Lasky, Syrdal-Lasky, & Klein, 1975); alveolar versus dental contrasts (/d/ vs. /ð/) in English (compared to French infants) (Polka, Colantonio, & Sundara, 2001; Sundara, Polka, & Genesee, 2006); affricate-fricative contrasts in Mandarin (Tsao, Liu, & Kuhl, 2006); a nasal alveloar-velar contrast (/n/ vs. /ng/) (Narayan,

2006); and the contrast between liquid /r/ versus /l/ in English (Kuhl, Tsao, Liu, Zhang, & de Boer, 2001; Kuhl et al., 2006). Recently it has been shown that duration-based phonemic contrasts in Japanese such as vowel duration contrasts (/a/ vs. /a:/) and singleton-geminate consonant contrasts (/t/ vs. /tt/) also become enhanced with age and exposure (Sato, Sogabe, & Mazuka, 2010a; Sato, Kato, & Mazuka, 2012).

Second, it has also been shown that infants' sensitivity to particular phonemic contrasts can sometimes be maintained without exposure. For example, 12- to 14-month old English learning infants who had never been exposed to Zulu click contrasts were found to discriminate them. English speaking adults were also able to discriminate these contrasts (Best, McRoberts, & Sithole, 1988).

Figure 1 schematically summarizes these developmental paths (although the actual developmental patterns are more complex and nuanced). Eventually, infants become capable of discriminating phonemic contrasts that are present in their ambient language. Thus, there are only two possible paths (solid lines); infants can either discriminate the contrasts to begin with and continue discriminating them (1: experience-contingent maintenance), or show poor discrimination at a younger age, but become capable of discriminating them as they grow (2: enhancement). There are more variations for non-native contrasts (dotted lines). Infants can discriminate them at a younger age and lose them later (3: decline), or continue discriminating them (4: experience-independent maintenance), as in Zulu click contrasts by English infants. Some non-native contrasts may never be discriminated by infants, as the /d/ versus /ð/ contrast by French infants (5: non-discrimination). As discussed further below, there is another possible path; poor discrimination initially but good discrimina-
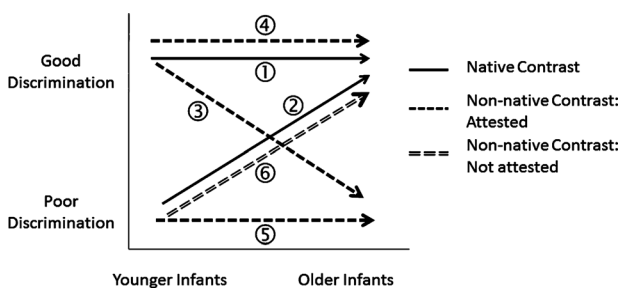
tion at an older age (6: improvement without exposure). To date, however, this pattern has not been experimentally affirmed.

To account for this variability in developmental paths, two issues need to be addressed. The first is why some phonemic contrasts are initially difficult for infants, despite the majority being easy. To account for this issue, the acoustic nature of the stimuli themselves, as well as their distributional properties, have been discussed. As for the acoustic nature of the stimuli, Burnham (1986) proposed that whether the acoustic salience of the contrast is robust or fragile might determine its ease of discrimination. Best et al. proposed a Perceptual Assimilation Model (PAM, Best, 1994; Best & McRoberts, 2003), where not only the acoustic salience but also the articulatory nature of the contrasts play a pivotal role. PAM predicts that two segments that involve different articulators or different articulatory gestures are more easily discriminated than those with the same articulator or articulatory gesture. Polka and Bohn (2003, 2011) proposed a Natural Referent Vowel (NRV) framework suggesting that vowels that are peripheral in the vowel space act as natural referent vowels. The model predicts asymmetrical discrimination of vowels when one of the vowels occupies a more extreme position in the vowel space than the other. Discrimination should be easier when infants are first habituated with a less extreme vowel, then tested with an extreme one than vice versa. As the acoustic factors in all above models are inherent to the segments themselves, they could constrain infants' initial perception of speech segments even without experience of language-specific distributional information.

Regarding the distributional properties of segments, it has been argued that how often and how widely distributed the target phoneme occurs in a language can be an important contributor to ease of discrimination. For example, Polka et al. (2001) and Sundara et al. (2006) suggested that a restricted distribution of /ð/ (given that /ð/ occurs primarily in determiners such as "the" in English) may make the dental contrast /d/-/ð/ not very salient for young infants. For some contrasts, such as the long/short vowel contrast in Japanese, the imbalance of frequency of occurrence (over 90% of Japanese vowels are short vowels) could make discrimination difficult for young infants (Mugitani et al., 2009; Sato et al., 2010a). In addition, the complexity of isolating relevant acoustic cues that are embedded in natural speech could add to the difficulty. For example, Bion, Miyazawa, Kikuchi, and Mazuka (2013) found that the actual duration of long/short vowels in Japanese was not easily isolated from other durational variations in natural speech (e.g., final lengthening, slow speech rate, pragmatic emphasis). Note, however,



**FIGURE 1** Schematic description of various paths for the development of native and non-native phonemic contrasts. For native contrasts, ① experience-contingent maintenance and ② enhancement are possible paths. For non-native contrasts, ③ decline, ④ experience-independent maintenance, ⑤ non-discrimination, and ⑥ improvement without exposure are possible. The last pattern has not been affirmed experimentally with infants.

that such distributional cues need to be extracted from the input by infants, presupposing that infants are capable of detecting and keeping track of segment distributions. This makes these types of distributional cues more likely to be relevant for older infants. It is also important to note that a low frequency of occurrence, on its own, cannot be the reason why some contrasts are difficult to discriminate, since infants are capable of discriminating many contrasts that never occur in their native language.

The second, more complex question is what drives change (improvement or decline) for some contrasts, while others remain unchanged. Various hypotheses have been offered to explain how exposure might (or not) impact infants' initial perceptual sensitivities. Kuhl et al.'s (1992, 2008) Native Language Magnet model (NLM) accounts for patterns 1 (experience-contingent maintenance), 2 (enhancement), and 3 (decline). It proposes that infants' distributional learning of acoustic properties produces a bias in their perception such that a native language category prototype begins to act like a perceptual magnet. Thus, the perception of native contrasts is maintained or sharpened while the perception of non-native contrasts becomes more difficult. The PAM model offers concrete predictions as to how the segmental categories of the native language will lead to different levels of difficulty in perceiving non-native contrasts (Best, 1994; Best & McRoberts, 2003), accounting for patterns 3 (decline) and 4 (experience-independent maintenance). It predicts that the difficulty of discriminating non-native contrasts depends on how listeners assimilate non-native contrasts into their native phonemic inventory. That is, non-native contrasts that can be assimilated into two distinct categories in the native language should be easily discriminable, while contrasts that are assimilated into a single category should be difficult. Contrasts that are assimilated into a single category, but differ in their perceived degree of similarity to the native category should be intermediately difficult to discriminate. Tees and Werker (1984) proposed that infants' exposure to different allophonic variations in their native language could contribute to variability in the difficulty of discriminating non-native contrasts, thus accounting for patterns 3 (decline) and 4 (experience-independent maintenance). The potential contribution of infants' developing cognitive skills has also been considered in the same context. For example, improvement in infants' inhibitory control has been examined as contributing to pattern 3, the decline of discrimination in non-native contrasts, which enables infants to ignore or suppress irelevant variation in speech in the native language (Conboy, Sommerville, & Kuhl, 2008; Diamond, Werker, & Lalonde, 1994; Lalonde & Werker, 1995).

For the discrimination of duration-based phonemic contrasts in Japanese, Sato et al. (2012) offered one possibility for how developing cognitive skills could impact phoneme discrimination abilities.[1] Sato et al. (2010a) found that Japanese 4.5-month olds showed no evidence of discriminating duration-based long/short vowel contrasts (/mana/ vs. /ma:na/), while 10-month olds did. Similarly, infants showed no evidence of discrimination for duration-based singleton-geminate stop contrasts (/pata/ vs. /patta/) at 4.5 months of age, while they demonstrated evidence of discriminating them at 10 months of age (Sato et al., 2012). Previous studies of infants' abilities to discriminate auditory duration contrasts have indicated that infants' abilities to perceive duration differences are ratio-based (Van-Marle & Wynn, 2006), and that the precision of discrimination improves between 6 and 12 months of age (Brannon, Suanda, & Libertus, 2007). Infants at 6 months of age are capable of discriminating 1-to-2 ratios of durational differences, but not 2-to-3 ratios. By 12 months, they become capable of discriminating 2-to-3 ratios as well. In Sato et al. (2010a, 2012), the syllables containing short and long vowel/consonants were approximately 200 ms versus 300 ms. If infants were trying to discriminate syllables that differ minimally in duration, the ratio would have been 2-to-3, which is beyond the discrimination threshold for younger infants. Thus, the developmental changes in infants' ability to detect auditory duration could have been a factor contributing to infants' developing perception of duration-based phonemic contrasts.

Crucially, it is difficult to assess the possibility that factors beyond native language exposure could account for improvement in phoneme perception by only testing contrasts that are either discriminated to begin with, and/or that are native and thus show enhancement based on exposure. Indeed, a critical limitation of the existing literature is that only a handful of studies thus far have reported cases in which infants showed no evidence of discriminating a contrast initially, and even fewer studies have followed up on infants' later discrimination ability in case the contrast was a non-native one. Given this asymmetry in available data, it is critical to accumulate more data points on non-native phoneme discrimination, especially those cases in which initial discrimination is difficult. Adding such data points will lead to a more complete picture of developing phoneme discrimination.

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[1] In addition, Sato et al. (2012) discussed a number of additional factors that could have contributed to the development of duration-based phonemic contrasts.

In order to contribute such data, the present article assesses the developmental changes in Japanese infants' discrimination of three pairs of non-native German vowel contrasts. These three pairs differed in a number of ways from Japanese vowels as described further below, and they were potentially difficult for Japanese infants to discriminate.

## THE PRESENT STUDY

The present study tests Japanese infants' abilities to discriminate three German vowel contrasts at 4.5 and 9 months of age (Experiment 1 and 2), using the modified visual habituation method (Werker, Cohen, Lloyd, Casasola, & Stager, 1998). In Experiment 3, a group of Japanese adults were tested as a control, on their ability to discriminate the same vowels, using an ABX paradigm. In the following sections, we will first discuss the characteristics of stimuli used for the study, followed by predictions for 4.5- and 9-month old infants from various models discussed above.

### Stimuli

German vowels were chosen for two reasons. First, as shown in Figure 2, German has at least 15 monophthong vowels, as compared to 5 in Japanese. This gave us flexibility in choosing pairs that differed in difficulty. Second, a previous study with English-learning infants tested one of the German vowel pairs (Polka & Werker, 1994), and can be used as a reference for comparison to the present study.

All vowels were placed in the context of [b_k]. This design was modified from Polka and Werker (1994), who used a [d_t] context. In Japanese, /d/ and /t/ occur before /a, e, o/ but not before /i/ or /u/. This constraint could bias Japanese listeners' judgment of vowel identities. Thus, we chose [b_k] instead, which

could occur with all five vowels of Japanese.[2] Three pairs of contrasts, /bu:k/-/by:k/, /bi:k/-/be:k/, and /bu:k/-/bo:k/ were used as stimuli. All vowels tested in the present study are tense vowels[3] in order to avoid a potential influence of vowel duration variation across the pairs, which would be relevant for infants learning Japanese, a language in which vowel duration is phonemic (Sato et al., 2010a).

The vowels used in the infant experiments are marked with red filled circles in the vowel space in Figure 2. All vowels are tense, close or close-mid vowels. German /e:/ and /i:/ are not rounded, while /u:/, /y:/, /o:/ are rounded. Note that even though the same IPA symbols are used to represent /i/, /u/, /e/, and /o/ in Japanese and German vowels, they differ in a number of ways as described further below. None of the German vowel pairs tested in this study are contrastive in Japanese. Acoustic measurements of stimuli are summarized in Table 1. Note that F2 and F3 are considered to reflect lip rounding.

The first pair was the front versus back vowel contrast in close back tense rounded /bu:k/ versus close front tense rounded /by:k/. This contrast was discriminated by English learning infants at 4 months of age, but not later (Polka and Werker, 1994). /y:/ is a vowel that does not occur in Japanese. Japanese /u:/ is typically transcribed with the same IPA symbol as the German /u:/, but it is actually an unrounded vowel better characterized as /ɯ:/. The second contrast was a contrast of vowel openness (close vs. close-mid) in close front tense unrounded /bi:k/ versus close-mid front tense unrounded /be:k/. Although Japanese /i:/ and /e:/ are transcribed with the same IPA symbol as German /i:/ and /e:/, their phonetic realization differs from German. On the one hand, German /e:/ and /i:/ are articulated with stronger lip spreading than their Japanese counterparts. On the other hand, German /e:/ is
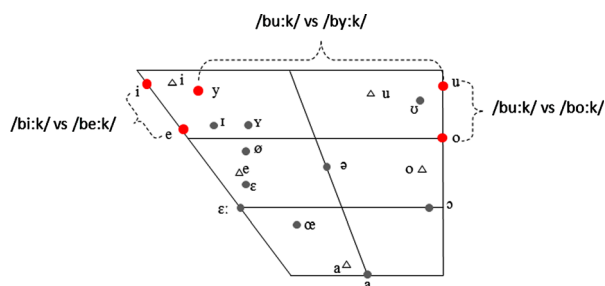


**FIGURE 2** Relative positions of German and Japanese monophthong vowels in a vowel space. Filled circles represent German vowels, and triangles represent Japanese vowels. German vowels used in Experiment 1 and 2 are marked by red filled circles.

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[2] At the phonological level, /k/ does not occur in a word-final position in Japanese, and one may argue that our stimuli that were presented in [bVk] form are illegal in Japanese. In Tokyo Japanese, however, high vowels such as /u/ and /i/ are almost always pronounced as devoiced vowels when they occur between two voiceless obstruents or following voiceless obstruents word finally (Vance, 1987). Thus, Japanese words such as /re:ki/ (cold air) and /ma:ku/ (mark) are produced with devoiced final vowels as [re:ki̥] and [ma:ku̥]. In fact, vowels are often completely deleted, and only the preceding consonants are articulated (Kitahara, 1999; Mimatsu et al., 1999), viz., [re:k] or [ma:k]. Therefore, for infants growing up hearing Tokyo Japanese, [bVk] is a word form that occurs regularly in their input.

[3] In many Germanic languages, including English, German, and Dutch, tense vowels are longer in duration than lax vowels. In English, for example, [i] in "beaf" is a tense vowel while [I] in "bit" is a lax vowel, and the former vowel is longer in duration than the latter.

**Table 1.    Acoustic Measurements (and Standard Deviations) of the Stimuli in Experiment 1–3, and the Relevant Results of Ito (2010), in Which Japanese Adults Were Asked to Write Down How Various German Vowels Sound Like in Japanese Scripts**

| Stimuli | F0 (Hz) | Duration (ms) | F1 (Hz) | F2 (Hz) | F3 (Hz) | Japanese Adults Heard As |
|---------|---------|---------------|---------|---------|---------|--------------------------|
| /bu:k/  | 245 (3.3) | 660 (37.5) | 390 (32.3) | 720 (43.3) | 2,990 (229.0) | /u:/ 57% |
|         |         |             |         |         |         | /o:/ 32% |
| /by:k/  | 244 (4.3) | 630 (41.9) | 350 (18.7) | 1,870 (76.6) | 2,210 (214.6) | /u:/ 72% |
| /bi:k/  | 224 (4.1) | 655 (28.2) | 270 (17.7) | 2,620 (55.7) | 3,610 (180.2) | /i:/ 98% |
| /be:k/  | 225 (3.9) | 625 (68.7) | 360 (32.6) | 2,550 (73.2) | 3,340 (32.2) | /i:/ 94% |
| /bo:k/  | 245 (2.8) | 656 (34.0) | 470 (11.9) | 750 (22.9) | 3,000 (137.2) | /o:/ 96% |

also articulated at a higher position. As can be seen in Figure 2, the distance between German /i:/ and /e:/ is much closer than that of Japanese /i:/ and /e:/.

The third contrast was also a contrast of vowel openness (close vs. close-mid) between close back tense rounded /bu:k/ versus close-mid back tense rounded /bo:k/. Although Japanese /o:/ is also transcribed with the same IPA symbol as German /o:/, it is produced with much less lip rounding. German /o:/ is also articulated at a higher position than Japanese /o:/.

Compared to /bu:k/-/by:k/, which is a front–back contrast, /bi:k/-/be:k/ and /bu:k/-/bo:k/, which are both close versus close-mid vowel height contrasts, are closer to each other in the vowel space. The predictions for these contrasts are discussed below.

## Predictions

Let us first examine the predictions for younger infants. The perceptual narrowing account in its original form of decline and maintenance predicts that all three contrasts should be discriminated by younger Japanese infants. If the results of Polka and Werker (1994) with English learning infants are replicated with Japanese infants, younger Japanese infants should discriminate the /bu:k/-/by:k/ pair. According to the PAM model, the /bu:k/-/by:k/ contrast should be easier to discriminate than the other two, since it is articulated at the front and back of the mouth, which is further apart than the close versus close-mid contrasts in the other two pairs. In addition, PAM also predicts that while younger infants are sensitive to detecting simple differences between single articulatory gestures, older infants are able to note "how gestures are combined into native constellation" (Best & McRoberts, 2003, p. 194). Recall that German /u:/, /o:/ and /y:/ are rounded vowels, while /i:/ and /e:/ are not. The fact that /bu:k/-/by:k/ and /bu:k/-/bo:k/ involve the combination of lip rounding in addition to a backness or height distinction, while /bi:k/-/be:k/ is a simple vowel height contrast may lead infants to respond differently to these contrasts.

In the NRV framework, asymmetrical discrimination is predicted for all of the vowel contrasts. For the first contrast, infants who are habituated with /by:k/, then tested with /bu:k/ (/by:k/-> /bu:k/) should perform better than infants tested in the reverse order. Similarly, /be:k/-> /bi:k/ should be easier than the reverse order (Pons, Albareda-Castellot, & Sevastián-Gallés, 2012). Although /u:/ versus /o:/ is not one of the contrasts that has been reported in Polka and Bohn (2011), /bo:k/ ->/bu:k/ should be easier than the reverse order since /u:/ is one of the corner vowels, and is more extreme than /o:/.

For older infants, different factors are predicted to matter. If all three contrasts are treated as non-native, the perceptual narrowing account predicts that older infants should have difficulty discriminating all of them, as was the case for the /by:k/-/bu:k/ pair in Polka and Werker (1994).

The PAM model predicts that the difficulty of older infants' discrimination of non-native contrasts depends on how the non-native contrasts are assimilated into native categories. Results of Ito (2010) can be used to estimate how Japanese adults assimilate German vowels into Japanese vowel categories. She conducted a survey asking 50 Japanese college students to write down in Japanese kana (syllabary) what various German words sound like. She found that the participants transcribed German /i:/ and /e:/ as Japanese /i:/ 98% and 94% of the time respectively, suggesting that both German vowels are assimilated into a single Japanese vowel /i:/. Ito also found that German /u:/ was transcribed either as Japanese /u:/ (57%) or Japanese /o:/ (32%), while German /y:/ was transcribed mostly as Japanese /u:/ (72%). This means that German /u:/ and /y:/ were transcribed into the same Japanese /u:/ at least 57% of the time. Lastly, German /o:/ was transcribed as Japanese /o:/ 96% of the time, meaning that German /o:/ and /u:/ were transcribed into the same Japanese vowel /o:/ at least 32% of the time.

These % overlap can be used as an approximation of the likelihood of the three pairs of German vowels to

be assimilated into a single native vowel category. The % overlap in how Japanese adults would transcribe respective pairs in Japanese is 94% for /bi:k/-/be:k/, 57% for /bu:k/-/by:k/, and 32% for /bu:k/-/bo:k/ (cf. Table 1). On the basis of these, the predictions of the PAM model are that the older Japanese infants should have the most difficulty in discriminating the /bi:k/-/be:k/ contrast, followed by the /bu:k/-/by:k/ contrast, and the /bu:k/-/bo:k/ contrast should be easiest.

Interestingly, Japanese adults transcribed rounded German /y:/ as a Japanese back vowel /u:/ 72% of the time, even though German /y:/ is a front vowel. German /u:/, in contrast, was transcribed as Japanese /u:/ only 57% of the time (transcribed as Japanese /o:/ 32% of the time). In all other cases, German back vowels were transcribed as Japanese back vowels, and German front vowels were transcribed as Japanese front vowels. It suggests that the roundedness of a vowel may be an important factor for the perception of non-native vowels for Japanese listeners.

## EXPERIMENT 1: 4.5-MONTH OLDS

In the first experiment, 4.5-month old Japanese infants were tested on their discrimination of three German vowel contrasts. This age group was chosen as previous studies on vowel discrimination development have shown that language specific vowel perception emerges by around 6 months of age (Kuhl et al., 1992; Polka & Werker, 1994).

## Methods

*Participants.* A total of 134 4.5-month old infants participated in this experiment. Forty-seven infants participated in the /bu:k/ versus /by:k/ condition. Data from 19 infants were not included in the analysis for reasons as follows: cried or were fussy (16), infants' behavior problems (3). The final sample consisted of 28 4.5-month olds (14 girls, mean age = 4.73 months, age range = 4.13–5.07 months).

Forty-one 4.5-month old infants participated in the /bi:k/ versus /be:k/ condition. Fourteen infants' data were not included in the analysis for the following reasons: cried or were fussy (11), technical difficulties (1), experimenter error (1), infants' behavior problems (1). The final sample consisted of 27 4.5-month olds (13 girls, mean age = 4.64 months, age range = 4.13–5.07 months).

Forty-six 4.5-month old infants participated in the /bu:k/ versus /bo:k/ condition. Data from 18 infants were not included in the analysis for the following reasons: cried or were fussy (14), experimenter error (1), parental interference (2), infants' behavior problems (1). The final sample consisted of 28 4.5-month olds (15 girls, mean age = 4.58 months, age range = 4.07–5.07 months).

All infants who participated in this and other experiments reported in this paper were healthy full-term infants, born and raised in the Metropolitan Tokyo area in monolingual native Japanese speaking families. The study was approved by the ethics review committee of RIKEN, and parents of all participants gave written consent to participate in the study. Parents received a bookstore certificate for their participation.

*Stimuli.* Stimuli were recorded by a female native speaker of German (the third author). From the recordings, ten tokens were selected for each of the three contrasts. Acoustic measurements of the stimuli are summarized in Table 1, and sample stimuli are shown in Figure 3a. For the first contrast, ten tokens of /bu:k/ were randomly sequenced at a 1.5 s Inter Stimulus Interval (ISI) to create a 15 s sound file. Four sequences of these 15 s files were created for /bu:k/. Similarly, four sequences of 15 s files were created for /by:k/. Stimuli for the other two contrasts were created in the same way.

*Procedure.* The infants were tested using the modified visual habituation paradigm method (adopted from Experiment 4 in Stager & Werker, 1997). In this paradigm, infants are first habituated with one of the stimuli while looking at a non-descript visual display (e.g., checker board pattern), which is followed by 2 test trials in which the same stimuli with which they are habituated and the other pair of the stimuli are presented in a counter-balanced order.

The experiments were carried out in a sound attenuated room and controlled by software (Habit X, Cohen, Atkinson, & Chaput, 2000) on a Macintosh computer. The infant sat on the parent's lap facing a 19-inch monitor (FlexScan1767, EIZO). A speaker (GX-77M, ONKYO) was located behind the monitor, from which stimuli were presented at approximately 65 dB SPL. An experimenter monitored the infants' visual responses without audio feedback in an observation room through a video camera (VC-C50iR, Canon) and the responses were simultaneously recorded by a DV recorder (DVCAM DSR-11, SONY) for later video coding. The parent listened to music through headsets in order to mask the auditory stimuli presented to the infants.

In carrying out the experiment, we followed the procedure described in Werker et al. (1998). Infants were first presented with one of the vowel sequences (e.g., /bu:k/) repeatedly during a habituation phase. In the test phase, they were presented with the other
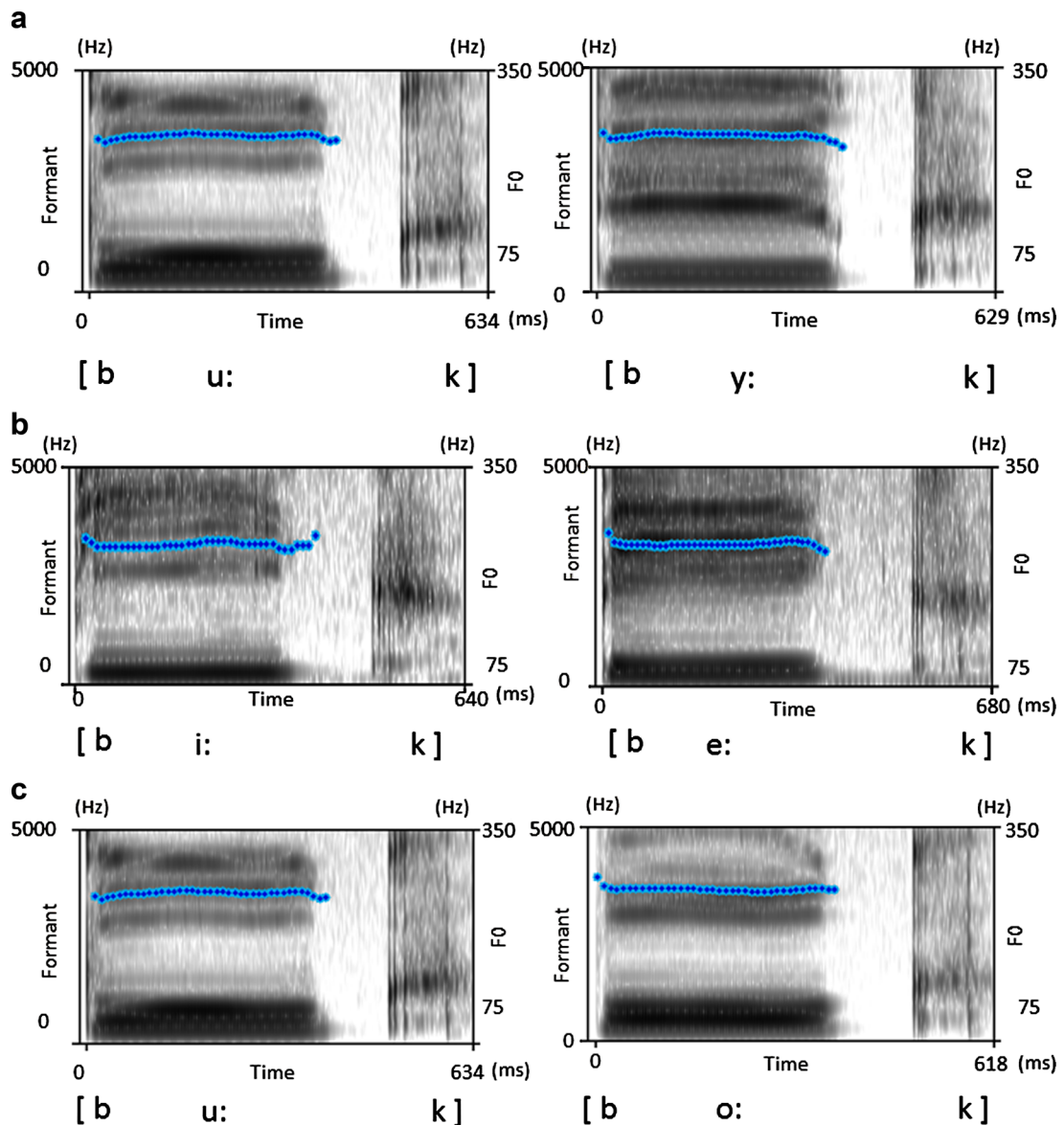
**FIGURE 3**  (a) Example of stimuli tokens /bi:k/ and /be:k/. Dotted line represents F0 of the segment. (b) Example of stimuli tokens /bu:k/ and /by:k/. (c) Example of stimuli tokens /bu:k/ and /bo:k/.

vowel of the pair (e.g., one of /by:k/ sequences) in a Switch trial and the vowel that was used in the habituation phase (/bu:k/) in a Same trial. During the habituation and test phase, infants were visually presented with a checkerboard with red and black squares on the monitor. Which stimuli they were habituated with, and whether they were first presented with the Switch trials (then followed by the Same trials) or the Same trials (then followed by the Switch trials) during the test phase was counter-balanced across infants. As a control for whether the infant was uninterested in the test stimuli, or had become fatigued, a novel animation (a brightly colored character that looks like a ladybug slowly moving across the monitor) with a novel auditory stimulus /panta/ was presented once as a pretest trial, before the habituation phase, and once as a post-test trial, at the conclusion of the test phase.

An attention getter appeared before each trial, which was a bright yellow character that looks like a rubber duck slowly moving along the edge of the monitor. The experimenter pressed a key to start a trial as soon as the infant looked at it. In each trial of the habituation phase, one of the four lists of either vowel stimuli was presented randomly with the visual stimulus (checker-

board). During the trials, the experimenter pressed down a key on a computer keyboard during the interval that the infant was looking at the monitor, and the time was recorded as looking time.

The criterion for ending the habituation phase was either when a maximum of 28 trials was completed or the infant's looking times declined to a preset criterion: the average looking time on the last four habituation trials reached less than 65% of that on the first four habituation trials. Infants who reached the end of the habituation phase proceeded to the test phase, during which they were presented with one Same and one Switch trial in a counter-balanced order. All infants were presented with both of these trials (unless the experiment had to be terminated due to infants' fussiness or some other reasons). Infants' looking times during the test trials were later hand-coded from the video frame by frame. Infants' looking times during the Switch trials were compared with those of the Same trials. Looking times during pre-test and post-test trials were calculated from online results.

## Results and Discussion

Figure 4 shows the average looking times for Same and Switch trials for each contrast in Experiment 1. The looking time data were submitted to a repeated-measures analysis of variance with Vowel Type (/bu:k/-/by:k/, /bi:k/-/be:k/, or /bu:k/-/bo:k/) and Direction (if the habituation stimulus was less peripheral than test, or vice versa, for example, /bu:k/-> /by:k/ or /by:k/-> /bu:k/) as between-subject factors and Trial Type (Same vs. Switch) as a within-subject factor. The results revealed that neither the main effect of Vowel



**FIGURE 4** Mean looking times (with standard error bars) during the same and switch trials (see procedure) for the /bu:k/-/by:k/, /bi:k/-/be:k/, and /bu:k/-/bo:k/ contrasts with 4.5-month old groups (Experiment 1). A significant difference in looking times between Same and Switch conditions was found only in the /bu:k/-/by:k/ contrast.

Type, $F(2, 77) = 1.799$, $p = .172$, $\eta^2 = .045$, or Direction, $F(1, 77) = 2.457$, $p = .121$, $\eta^2 = .031$, were significant while Trial Type was significant, $F(1, 77) = 6.650$, $p = .012$, $\eta^2 = .079$. None of the interactions were significant; Trial Type × Direction, $F(1, 77) = .145$, $p = .704$, $\eta^2 = .002$; Trial Type × Vowel Type, $F(2, 77) = .644$, $p = .528$, $\eta^2 = .016$; Trial Type × Direction × Vowel Type, $F(2, 77) = .405$, $p = .669$, $\eta^2 = .010$; Trial Type × Direction × Vowel Type, $F(2, 77) = .923$, $p = .402$, $\eta^2 = .023$.

Although the main effect of Trial Type was significant, the interaction between Vowel Type and Trial Type was not significant. The present experiment was designed a priori to test whether Japanese 4.5-month old infants are able to discriminate any of the three vowel contrasts. Thus, planned contrasts (with Bonferroni corrections for multiple comparisons) were estimated to test a priori comparisons for Vowel Type. It showed that for /bu:k/-/by:k/ contrast, 4.5-month old infants looked significantly longer during the Switch trials than the Same trials: $F(1, 77) = 5.069$, $p = .027$, $\eta^2 = .062$, 95% CI for the looking time difference between Same and Switch trials [.125, 2.045]. In contrast, their looking times during Switch trials were not longer than Same trials for the /bi:k/-/be:k/ contrast, $F(1, 77) = .391$, $p = .534$, $\eta^2 = .005$, 95% CI of the difference [−.671, 1.285]; nor for the /bu:k/-/bo:k/ contrast, $F(1, 77) = 2.457$, $p = .121$, $\eta^2 = .031$, 95% CI of the difference [−.204, 1.715].

Although Direction was not significant either as a main effect or in any of the interactions, planned contrasts were estimated to test whether there was a directional asymmetry in any of the Vowel Types (Bonferroni corrections were applied to control for multiple comparisons). The results are summarized in Table 2. It revealed that in the /bu:k/-/by:k/ contrast, infants who were tested in /bu:k/-> /by:k/ order showed a longer looking time to the Switch than to the Same trial ($p = .039$), but not the infants tested in the /by:k/-> /bu:k/ order ($p = .283$). No asymmetry was found for the /bi:k/-be:k/ contrast. For the /bu:k/-/bo:k/ contrast, infants tested in the order /bo:k/-> /bu:k/ showed a marginally longer looking time to the Switch than to the Same trial ($p = .054$), while infants tested in the reverse order did not ($p = .795$).

To confirm that the lack of a significant effect in two of the three vowel contrasts in 4.5-month olds was not due to fatigue, or that infants became uninterested in the experiment, we compared the looking time of pretest to posttest trials for each Vowel Type in paired *t*-test. If infants were fatigued after the experiment, or had lost interest in the experiment itself, they were not likely to pay as much attention to the visual stimuli during the posttest trials as during the pretest trials.
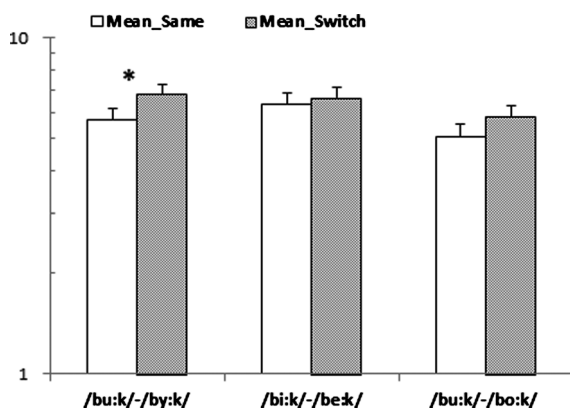
**Table 2.  Summary of Results for Directional Asymmetry in Experiment 1 and 2**

| Habituation → Switch | | Habituation → Switch Trial | | | Habituation → Switch | | | |
|---|---|---|---|---|---|---|---|---|
| **Experiment 1: 4.5-month olds** | | | | | | | | |
| /by:k/ → /bu:k/ | $Msa = 5.542$, $Msw = 6.279$ | /be:k/ → /bi:k/ | $F_{(1, 77)} = 1.170$, $p = .283$, $\eta^2 = .015$, 95% CI [−.620, 2.094] | $Msa = 7.061$, $Msw = 7.278$ | /bo:k/ → /bu:k/ | $F_{(1, 77)} = .094$, $p = .760$, $\eta^2 = .001$, 95% CI [−1.191, 1.625] | $Msa = 4.644$, $Msw = 5.976$ | $F_{(1, 77)} = 3.824$, $p = .054$, $\eta^2 = .047$, 95% CI [−.024, 2.690] |
| /bu:k/ → /by:k/ | $Msa = 5.868$, $Msw = 7.301$ | /bi:k/ → /be:k/ | $F_{(1, 77)} = 4.420$, $p = .039$, $\eta^2 = .054$, 95% CI [.076, 2.790] | $Msa = 5.658$, $Msw = 6.055$ | /bu:k/ → /bo:k/ | $F_{(1, 77)} = .340$, $p = .562$, $\eta^2 = .004$, 95% CI [−.960, 1.754] | $Msa = 5.491$, $Msw = 5.669$ | $F_{(1, 77)} = .068$, $p = .795$, $\eta^2 = .001$, 95% CI [−1.179, 1.535] |
| **Experiment 2: 10-month olds** | | | | | | | | |
| /by:k/ → /bu:k/ | $Msa = 7.796$, $Msw = 8.347$ | /be:k/ → /bi:k/ | $F_{(1, 80)} = .349$, $p = .556$, $\eta^2 = .004$, 95% CI [−1.306, 2.409] | $Msa = 6.845$, $Msw = 8.008$ | /bo:k/ → /bu:k/ | $F_{(1, 80)} = 1.552$, $p = .216$, $\eta^2 = .019$, 95% CI [−.695, 3.021] | $Msa = 7.048$, $Msw = 8.050$ | $F_{(1, 80)} = 1.235$, $p = .270$, $\eta^2 = .015$, 95% CI [−.793, 2.797] |
| /bu:k/ → /by:k/ | $Msa = 6.833$, $Msw = 7.596$ | /bi:k/ → /be:k/ | $F_{(1, 80)} = .668$, $p = .416$, $\eta^2 = .008$, 95% CI [−1.095, 2.621] | $Msa = 6.261$, $Msw = 8.869$ | /bu:k/ → /bo:k/ | $F_{(1, 80)} = 7.805$, $p = .007$, $\eta^2 = .089$, 95% CI [.750, 4.466] | $Msa = 6.683$, $Msw = 6.543$ | $F_{(1, 80)} = .024$, $p = .877$, $\eta^2 = .000$, 95% CI [−1.935, 1.655] |

sa, same LT; sw, switch LT.

For each contrast, average looking time for the Same and Switch trials were compared in planned contrasts, with Bonferroni correction for multiple comparisons. For each age group, the top half of the table shows the results for infants who were habituated with a vowel and tested on a one, and the bottom half shows those who were tested in reverse order. For 4.5-month olds, NRV framework predicts that the infants in the top half of the table should perform better than those in the bottom half. No clear predictions can be drawn for 10-month olds.

The results revealed that 4.5-month old infants who participated in /bu:k/-/by:k/ and /bu:k/-/bo:k/ contrasts did not have shorter looking times in post-test trials than pretest trials: for /bu:k/-/by:k/ ($M_{pre} = 14.55$ s, $M_{post} = 14.78$ s, $SD_{pre} = 1.04$ s, $SD_{post} = .43$ s), 95% CI of the difference [.162, .187], $t(27) = 1.03$, $p = .31$, $d = .29$; for /bu:k/-/bo:k/ ($M_{pre} = 14.24$ s, $M_{post} = 14.82$ s, $SD_{pre} = .79$ s, $SD_{post} = .45$s), 95% CI of the difference [.268, .289], $t(27) = 1.69$, $p = .10$, $d = .42$. Infants tested on the /bi:k/-/be:k/ contrast had a significantly longer looking time during the post-test trials than the pretest trials: ($M_{pre} = 14.37$s, $M_{post} = 14.91$s, $SD_{pre} = 1.17$ s, $SD_{post} = .11$ s), 95% CI of the difference [.527, .555], $t(26) = 2.39$, $p = .02$, $d = .65$. These results show that infants in the posttest trials were paying as much or more attention to the visual stimuli as in the pretest trials, suggesting that infants were neither fatigued nor lost interest in the experiments. Thus, we can reasonably conclude that the lack of significant looking time increase in the test trials in /bi:k/-/be:k/, or /bu:k/-/bo:k/ condition was not due to their fatigue or lack of interest in the experiment.

The results of Experiment 1 showed that Japanese 4.5-month old infants were able to discriminate the /bu:k/-/by:k/ contrast, as English learning infants did in Polka and Werker (1994). On the other hand, they did not show evidence of discrimination for the /bi:k/-/be:k/ or /bu:k/-/bo:k/ contrasts. As discussed above, this is not consistent with the prediction of perceptual narrowing that 4.5-month old should discriminate all three contrasts. The prediction of PAM that the /bu:k/-/by:k/ contrast should be easier than the other two was supported by the current results.

The results of this experiment were not consistent with the predictions of the NRV framework. Direction was not significant either as a main effect or in any of the interactions. When Direction was further analyzed, the /bu:k/-/by:k/ contrast was the only one that showed a significant asymmetry, but in the direction opposite from predictions.

## EXPERIMENT 2: 10-MONTH OLDS

To observe the developmental changes in Japanese infants' discrimination of German vowels, 10-month old Japanese infants were tested in the second experiment. Exactly the same stimuli and procedure were used as in Experiment 1.

## Method

***Participants.*** A total of 135 10-month old infants participated in this experiment. Forty-eight infants participated in the /bu:k/ versus /by:k/ condition. Data from 20 infants were not included in the analysis for the reasons as follows: cried or were fussy (13), technical difficulties (3), experimenter error (3), parental interference (1). The final sample consisted of 28 ten-month olds (14 girls, mean age = 10.27 months, age range = 9.67–10.67 months).

Forty-four 10-month old infants participated in the /bi:k/ versus /be:k/ condition. Sixteen infants' data were not included in the analysis for the following reasons: cried or were fussy (8), technical difficulties (3), experimenter error (2), parental interference (2), infants' behavior problems (1). The final sample consisted of 28 ten-month olds (15 girls, mean age = 10.19 months, age range = 9.67–10.60 months).

Forty-three 10-month old infants participated in the /bu:k/ versus /bo:k/ condition. Data from 13 infants were not included in the analysis for the following reasons: cried or were fussy (7), technical problems (2), experimenter error (2), infants' behavior problems (2). The final sample consisted of 30 ten-month olds (16 girls, mean age = 10.00 months, age range = 9.67–10.57 months).

***Stimuli.*** Stimuli for this experiment were the same as in Experiment 1.

***Procedure.*** The procedure for this experiment was the same as in Experiment 1.

## Results and Discussion

Figure 5 shows the average looking times for Same and Switch trials for each group in Experiment 2. As in Experiment 1, the results were submitted to a 2 (Direction) × 3 (Vowel Type) × 2 (Trial Type) repeated-measures ANOVA. Direction and Vowel Type were between-subject factors and Trial Type was a within-subject factor. The results revealed that while neither the main effect of Direction, $F(1, 80) = 1.182$, $p = .280$, $\eta^2 = .015$ nor Vowel Type were significant, $F(2, 80) = .322$, $p = .726$, $\eta^2 = .008$; the main effect of Trial Type was significant, $F(1, 80) = 6.745$, $p = .011$, $\eta^2 = .078$. None of the interactions were significant; Direction × Vowel Type, $F(2, 80) = .178$, $p = .837$, $\eta^2 = .004$; Trial Type × Direction, $F(1, 80) = 1.128$, $p = .291$, $\eta^2 = .014$; Trial Type × Vowel Type, $F(2, 80) = 1.431$, $p = .245$, $\eta^2 = .035$; Trial Type × Direction × Vowel Type, $F(2, 80) = .449$, $p = .640$, $\eta^2 = .011$.

Although interaction between Trial Type and Vowel Type was not significant, this experiment was designed a priori to test whether Japanese 10-month old infants are able to discriminate any of the three vowel
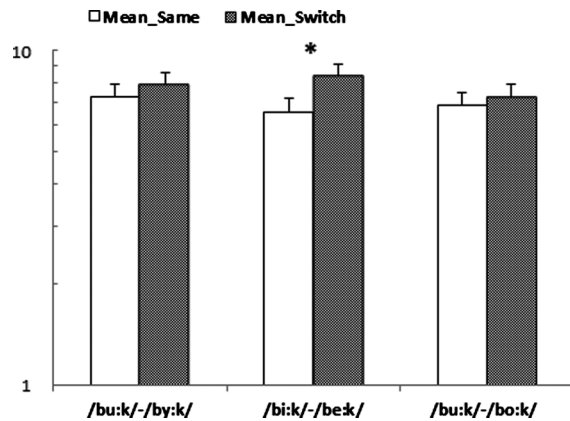
**FIGURE 5** Mean looking times (with standard error bars) during the same and switch trials (see procedure) for the /bu:k/-/by:k/, /bi:k/-/be:k/, and /bu:k/-/bo:k/ contrasts within the 10-month old groups (Experiment 2). A significant difference in looking times between Same and Switch conditions was found only in the /bi:k/-/be:k/ contrast.

contrasts. Thus, planned contrasts were estimated to compare looking times to Same and Switch trials for each Vowel Type a priori. The results showed that in the /bi:k/-/be:k/ condition, 10-month olds had significantly longer looking times in Switch than Same trials, but not in the other two conditions: for the /bu:k/-/by:k/ contrast, $F(1, 80) = .991$, $p = .322$, $\eta^2 = .012$, 95% CI of the difference $[-.656, 1.971]$; for the /bi:k/-/be:k/ contrast, $F(1, 80) = 8.159$, $p = .005$, $\eta^2 = .093$, 95% CI of the difference $[.572, 3.199]$; for the /bu:k/-/bo:k/ contrast, $F(1, 80) = .457$, $p = .501$, $\eta^2 = .006$, 95% CI of the difference $[-.838, 1.700]$.

Although Direction was not significant either as a main effect or in any of the interaction as in Experiment 1, planned contrasts were estimated to test whether there was a directional asymmetry in any of the Vowel Types (Bonferroni corrections were applied to control for multiple comparisons). The results are summarized in Table 2. It revealed that among the infants tested in the /bi:k/-/be:k/ contrast, infants tested in the /bi:k/-> /be:k/ order had significantly longer looking times to Switch than Same trials ($p = .007$), while infants in the reverse order did not. No asymmetry was found in the other two contrasts.

Again, we compared pre- and post-test trials of each Vowel Type by paired $t$-tests. They revealed that 10-month old infants in Experiment 2 did not have shorter looking times in post-test trials than pre-test trials for any vowel contrasts: for /bu:k/-/by:k/, ($M_{pre} = 14.18$ s, $M_{post} = 14.64$ s, $SD_{pre} = 1.23$ s, $SD_{post} = .77$ s), 95% CI of the difference $[.450, .483]$, $t(26) = 1.73$, $p = .10$, $d = .45$; for /bi:k/-/be:k/, ($M_{pre} = 13.81$ s, $M_{post} = 14.65$ s, $SD_{pre} = .82$ s, $SD_{post} = .48$ s), 95% CI of the difference

$[.440, .481]$, $t(27) = 1.73$, $p = .09$, $d = .71$; for /bu:k/-/bo:k/, ($M_{pre} = 14.43$ s, $M_{post} = 14.74$ s, $SD_{pre} = .79$ s, $SD_{post} = .45$ s), 95% CI of the difference $[.297, .323]$, $t(29) = 1.42$, $p = .17$, $d = .48$. The results show that the lack of significant looking time increase in the test trials for the /bu:k/-/by:k/ contrast or the /bu:k/-/bo:k/ contrast was not due to fatigue or lack of interest in the experiment.

The results of Experiment 2 revealed that 10-month old Japanese infants showed evidence of discrimination for the /bi:k/-/be:k/ contrast, while they showed no evidence of discrimination either for the /bu:k/-/by:k/ contrast or for the /bu:k/-/bo:k/ contrast. Together with the results from the 4.5-month olds, Japanese infants' responses to the /bu:k/-/by:k/ contrast replicate the results of Polka and Werker (1994) and are consistent with the original notion of perceptual narrowing, as well as predictions made by PAM and NLM. The lack of discrimination of the /bu:k/-/bo:k/ contrast at either age is not necessarily incompatible with model predictions, but it is a pattern that has rarely been reported. Finally, Japanese infants' discrimination of the /bik/-/be:k/ contrast improved, which would not be predicted by either model. In particular, the PAM model would have predicted /bi:k/-/be:k/ to be the most difficult contrast for older infants since both of the German vowels were assimilated into a single Japanese vowel category by adults.

## EXPERIMENT 3: ADULTS

In Experiment 1 and 2, 4.5- and 10-month old infants were tested on their discrimination of three German vowel contrasts. These results do not necessarily mean that Japanese adults would show the same pattern of results as 10-month old infants. As discussed above, Polka and Werker (1994), who found a declining pattern of discrimination for the German /bu:k/-/by:k/ contrasts in English learning infants, found that English adults were able to discriminate the same contrast reliably. In order to consider the developmental implication of Japanese infants' discrimination or lack of it for the three German vowel contrasts, it is necessary to test Japanese adults with the same contrasts as Japanese infants.

## Method

***Participants.*** Thirteen college students (7 female, age range 19–32) in the Tokyo area participated. They were all monolingual native speakers of Japanese.

***Stimuli.*** Stimuli for this experiment were the actual stimuli used for infants (10 tokens per vowel type). All

three types of stimuli (/bu:k/-/by:k/, /bi:k/- /be:k/, /bu:k/-/bo:k/) were presented to each participant.

***Procedure.*** Adults were tested in an ABX experiment. In order to approach the design of the infant experiment, stimuli of each contrast were tested in three separate blocks. We also included "same" trials, in which the two stimuli to be discriminated were different tokens of the same vowel category. We expected a chance level performance for these trials, assuming that participants treated vowels as coming from the same speech sound category. Responses to "different" trials were expected to be above chance if participants were able to discriminate the respective contrast.

Each participant was presented with 80 trials in each block, randomly drawing from the pool of possible token combinations. In each block, the first two tokens (A and B) were combinations of different tokens of the same vowel (e.g., 20 /be:k/-/be:k/, 20 /bi:k/-/bi:k/) in half of the trials, and combinations of different vowels (e.g., 20 /bi:k/- /be:k/, 20 /be:k/- /bi:k/) in the other half. For each of these four combinations of A and B, the third sound (X) was identical to A in 10 trials, and identical to B in the other 10 trials. The 80 trials in each block were randomized for each participant. Within each trial, participants heard three stimuli (A, B, X) in a row with an ISI of 300 ms, with the third stimulus being identical to either the first or the second stimulus. The participants were asked to choose whether the last of the three sounds (X) was the same as the first (A) or the second (B). They were told to guess when they were not sure.

## Results and Discussion

Japanese adults' performances on the ABX experiment were converted to $d'$, using the dprime.ABX function of the psyphy package (Knoblauch, 2012) in R (R Core Team, 2012). Summary of the results are shown in Table 3. In order to assess if participants were able to discriminate the vowel contrasts, we compared their responses to "same" trials to their responses to "different" trials. Separate repeated-measures analyses of variance were conducted for $d'$ and for the reaction times to correct responses. Vowel (/i:/-/e:/, /u:/-/o:/, /u:/-/y:/) and Contrast Type (same, different) were within-subject variables. For $d'$, there was a main effect of Contrast Type, $F(1, 12) = 274.09$, $p < .001$, such that trials with vowels from different categories yielded significantly higher $d'$ ($M = 3.39$, $SD = .42$) than trials with the same vowel ($M = .70$, $SD = 1.17$). For reaction times, again the main effect of Contrast Type, $F(1, 12) = 7.70$, $p = .017$, reached significance with a faster reaction time for trials with different ($M = 387.25$, $SD = 184.59$) than same ($M = 509.73$, $SD = 237.57$) vowels. These results demonstrate that participants were able to discriminate vowels from different categories for all vowel contrasts tested.

In order to assess if there were any differences in $d'$ scores between the vowel contrasts, a second type of analysis compared the responses to "different" trials only. A repeated-measures analysis of variance on $d'$ with the within-subject factor Vowel (/i:/-/e:/, /u:/-/o:/, /u:/-/y:/) yielded a main effect of Vowel, $F(1, 24) = 3.59$, $p = .043$. A post-hoc comparison (Bonferroni-corrected) showed that the difference between /u:/-/y:/ and /i:/-/e:/ was significant ($p = .048$) such that /u:/-/y:/ had higher $d'$ scores than /i:/-/e:/. There was no significant effect for reaction times, $F(2, 24) = .196$, $p = .823$.

Thus, Japanese adults are highly accurate in discriminating all three contrasts when tested on one contrast at a time. They do however show a tendency for an order (in order of ascending discrimination) /bi:k/-/be:k/ (92%, $d' = 3.23$) < /bu:k/-/bo:k/(94%, $d' = 3.41$) </bu:k/-/by:k/ (97%, $d' = 3.55$), as shown in Table 3. This means that Japanese adults are able to discriminate all three German vowel contrasts including those Japanese infants showed no evidence of discrimination for. This replicates the finding of Polka and Werker (1994) with English speaking adults. They found highly accurate discrimination of native and non-native vowels in adults, while infants showed changes related to stimulus nativeness between 6–8 and 10–12 months of

**Table 3.　Summary of ABX Experiments With Japanese Adults**

| N of sbj = 13 | | Stimuli | | % Correct (*SD*) | $d'$ (*SD*) |
|---|---|---|---|---|---|
| ABX | | | | | |
| N of trials per stimuli 80 | /bu:k/-/by:k/ | Same | | .576 (.109) | .47 (1.26) |
| | | Different | | .969 (.049) | 3.55 (.36) |
| | /bi:k/-be:k/ | Same | | .569 (.104) | .60 (1.13) |
| | | Different | | .921 (.059) | 3.23 (.43) |
| | /bu:k/-/bo:k/ | Same | | .610 (.117) | 1.01 (1.07) |
| | | Different | | .944 (.059) | 3.41 (.42) |

age. Thus, what we measure in infant discrimination tasks does not necessarily reflect adult ability to detect phonetic differences, an issue we will return to in the General Discussion.

## GENERAL DISCUSSION

In the present study, we conducted two experiments with Japanese infants to test how their ability to discriminate non-native German vowel contrasts changes during the first year of their lives. As a control, an additional experiment with Japanese adults was also carried out. Three German vowel contrasts – /bu:k/-/by:k/, /bi:k/-/be:k/, and /bu:k/-/bo:k/ – were tested using the visual habituation paradigm with 4.5- and 10-month old infants. The experiments revealed that Japanese infants' discrimination of the three German vowel contrasts developed in three different patterns. The 4.5-month old Japanese infants were able to discriminate the /bu:k/-/by:k/ contrast, while 10-month olds showed no evidence of discrimination. This is consistent with Polka and Werker's results with English learning infants (1994), manifesting an experience-contingent decline, that is, the third pattern in Figure 1. In contrast, 4.5-month old Japanese infants showed no evidence of discriminating the /bi:k/-/be:k/ contrast, but 10-month olds did, corresponding to the pattern of improvement without exposure, that is, the 6th pattern of development in Figure 1. Japanese infants showed no evidence of reliable discrimination for the /bu:k/-/bo:k/ pair either at 4.5- or 10-months of age, thus manifesting no discrimination, or the fifth pattern in Figure 1.

As discussed in the Introduction, it has been generally assumed that infants start out their life with an ability to discriminate most of the phonemic contrasts in the world's languages. It is the experience of being exposed to the language in which the relevant contrast is phonemic, or the lack of it, that is the primary driving force for changes in infants' discrimination abilities. The results of the present study provide data showing that perceptual narrowing is not sufficient to account for the variety of paths infants' phonological development can take.

It should be noted, although there was a robust effect of Trial Type in ANOVAs (i.e., infants had a significantly longer looking time during Switch trials than Same trials overall) in both Experiment 1 and 2, we found no reliable interaction between Trial Type and Vowel Type. Planned contrasts revealed that it was only one of the three contrasts that was reliably discriminated in either age group. Although the use of planned contrasts was justified statistically, the lack of significant interaction may indicate that the effects are subtle.

## Do Young Infants Start Out With an Ability to Discriminate all Contrasts?

Japanese infants showed a decline pattern of development (pattern 3 in Fig. 1) for /bu:k/-/by:k/, replicating Polka and Werker (1994) with English learning infants. To the best of our knowledge, no previous study has tested Japanese learning infants' abilities to discriminate non-native vowel contrasts. But the results of this experiment demonstrate that Japanese infants are like infants learning other languages with regard to some vowel contrasts, and that our experimental set-up allowed us to replicate findings from the previous literature.

In contrast, Japanese 4.5-month olds did not show evidence of discriminating /bi:k/-/be:k/ or /bu:k/-/bo:k/ reliably. Taken together, we can hardly say that non-native German vowel contrasts are easily discriminated by younger Japanese infants. Given the results of the /bu:k/-/by:k/ contrast, it is not the case that Japanese 4.5-month olds are simply lacking the ability to discriminate any non-native vowel contrasts. Yet, the results of the present study challenge the first assumption of the original perceptual narrowing account.

If it is not the case that infants do start out with an ability to discriminate all contrasts, it becomes necessary to investigate the factors that may contribute to the differences. As discussed in the Introduction, several factors have been proposed. Acoustic salience of the contrast, for example, may be an important factor (Burnham, 1986). Among the three German vowel contrasts, /u:/ and /y:/ is a front-back contrast that is further separated in the vowel space than the other two contrasts. The results of the present study may be interpreted as consistent with this prediction. PAM (Best, 1994; Best & McRoberts, 2003) offers the more concrete prediction that /bu:k/-/by:k/ should be easier to discriminate since they are articulated at positions that are further apart from each other than the other two contrasts, which was consistent with the current study. These findings indicate that the difficulty of vowel discrimination is likely to be constrained by the acoustic and/or articulatory nature of the segments.

The results of the present study were, however, not consistent with the predictions of the NRV model (Polka & Bohn, 2003, 2011). The 4.5-month olds infants were predicted to show an easier discrimination for the /by:k/-> /bu:k/, /be:k/ ->/bi:k/, and /bo:k/ ->/bu:k/ directions compared to the reverse orders. Yet, the results of either the overall ANOVA or the results of planned contrasts for individual contrasts showed no evidence that is consistent with the prediction of this model. We need to be cautious in interpreting the negative results here, since the number

of infants tested in each direction was relatively small in the present study (cf., Pons et al., 2012). Yet, the results of the present study are consistent with previous Japanese studies. In Sato et al. (2010a), they found no directional asymmetries when Japanese 4.5-month old infants were tested on their discrimination of native vowel quality contrasts /a/ versus /i/. They also did not find an asymmetry for the vowel duration contrast /a/ versus /aː/. As discussed in Pons et al. (2012) and Polka and Bohn (2011), Mugitani et al. (2009) reported a directional asymmetry for Japanese infants' discrimination of vowel duration. Yet, the asymmetry was found only with older infants (18-month olds), and not with the 10-month old group, which was the youngest group they tested. Considering that NRV is assumed to provide initial biases for infants' perception of vowels, the fact that none of the three studies that tested Japanese infants' discrimination of vowel contrasts found evidence of directional asymmetries in the youngest group (present study, Mugitani et al., 2009; Sato et al., 2010a) suggests that NRV may not bias Japanese infants' initial discrimination of vowel contrasts in the same way as previously hypothesized.

## Does Exposure to the Native Language Account for Changes in Infants' Discrimination Abilities?

The present study found that Japanese infants' discrimination of three German vowel contrasts develops in three different trajectories, demonstrating that perceptual narrowing might not be sufficient to account for the various ways in which infants' ability to discriminate phonemic contrasts can develop. In particular, the improved discrimination for the /biːk/-/beːk/ contrast requires serious consideration. 4.5-month old infants showed no evidence of discrimination, but became able to discriminate reliably by 10 months of age. This is remarkable considering that Japanese is not a language in which this contrast is phonemic. To the best of our knowledge, this is the first time this pattern of development (sixth pattern in Fig. 1) was documented experimentally.

According to the perceptual narrowing account, infants' exposure to the language in which the relevant contrast is phonemic, or the lack of it, is the primary driving force for changes in infants' discrimination abilities. As discussed above, the models that predict a decline or no change in discrimination for non-native vowels (NRV, NLM) did not predict all results of the current study, as the /biːk/-/beːk/ contrast showed enhancement of discrimination without exposure. PAM does allow discrimination of non-native contrasts depending on how non-native categories are assimilated into native categories (Best, 1994; Best & McRoberts,

2003). As discussed in detail above, PAM predicted that, for Japanese 10-months olds, the discrimination of /biːk/-/beːk/ should be most difficult, followed by /buːk/-/byːk/, then /buːk/-/boːk/. The results of the present study were not consistent with this prediction.

Taken together, none of the existing models seem to be able to account for the Japanese 10-month old infants' discrimination of German /biːk/-/beːk/, but not the other two contrasts. How, then, can we account for the improvement without exposure pattern in Japanese infants' discrimination of the German /biːk/-/beːk/ vowel contrast? We speculate that it may be necessary to consider a combination of factors simultaneously; articulatory complexity of the contrast, the developmental changes in infants' ability to pay attention to finer acoustic/articulatory differences and to the combination of articulatory gestures, in addition to learning specific properties of Japanese native vowel categories.

As discussed in the prediction section, the PAM model predicts that while younger infants are sensitive to detecting simple differences between single articulatory gestures, older infants become capable of detecting "how gestures are combined into native constellation" (Best & McRoberts, 2003, p. 194). Recall that German /uː/, /oː/ and /yː/are rounded vowels, while /iː/ and /eː/ are not. In contrast, none of the Japanese vowels are rounded. In Ito (2010), Japanese adults were found to transcribe a rounded front German vowel /yː/ as a Japanese back vowel /uː/ frequently, not as a front vowel. It suggests that the roundedness of a vowel has a strong effect on how a Japanese native speaker hears a non-native vowel. If Japanese infants' vowel perception has become attuned to unrounded vowels by 10 months, this may be the reason why 10-month olds could discriminate only the /biːk/-/beːk/ contrast. If one ignores the rounded-unrounded distinction, the front versus back contrast of /buːk/-/byːk/ is furthest apart from each other in the vowel space (Fig. 2). 4.5-month old Japanese infants might be able to pay attention to simple differences in articulatory gestures, such as front versus back, or vowel height, but not yet to a combination of front–back distinction and roundedness or vowel height with roundedness. Thus, /uː/ and /yː/ ought to be an easier contrast to discriminate than other more subtle contrasts. By 10 months of age, infants might be able pay attention to more complex combinations of articulatory gestures or subtle acoustic cues. Since Japanese vowels are not rounded in general, their perception is now biased against roundedness, resulting in non-discrimination of rounded vowels.

This ability to pay attention to more complex combinations of articulatory gestures, or to extract better fine acoustic detail, might interact with other advances in infants' development such as better control

of attention, increased memory capacity, or higher processing speed. Clearly, the results of the present study alone are not sufficient to support such a complex speculation. Yet, it offers an indication that perceptual narrowing is too simplistic to capture the very complex nature of infants' developmental changes in their ability to discriminate phonemic contrasts.

Thus far, we have proceeded with the assumption that the three German contrasts are non-native for Japanese infants. Yet, the non-native status of the vowel pairs tested does not mean that Japanese infants were not exposed to vowel tokens that are similar to German vowels. For the unrounded German vowel contrast /i:/ and /e:/, in particular, it is very likely that the distribution of vowel tokens Japanese adults would produce overlap with those of German /i:/ and /e:/. Thus, the possibility exists that Japanese infants treated the experimental stimuli as instances of native vowels. In this case, despite the phonetic differences, exposure to native vowel tokens similar to German /i:/ or /e:/ might help with discrimination of non-native vowels. In this case, both PAM and NLM make predictions consistent with the present results, namely enhancement of native vowel perception.

## What Does Infant Discrimination Performance Tell us About Perceptual Narrowing?

Although in parts not consistent with models of infant speech perception, our results provide evidence that 10-month-old infants have difficulties discriminating two out of three non-native vowel contrasts. This finding is consistent with a vast amount of studies showing decline in non-native, and enhancement in native phoneme perception during the first year of life. Yet, our adult results revealed a high accuracy in discrimination of the same non-native vowel contrasts, which is consistent with results from Polka and Werker (1994). Thus, perceptual narrowing of certain non-native contrasts as observed in infants does not imply that adults are not able to discriminate these same contrasts later on. What, then, do the infant results tell us? Polka and Werker (1994) pointed out that infant discrimination tasks reflect their ignoring of certain cues at a certain stage rather than the actual ability to detect a difference. Indeed, the decline in infants' ability to discriminate non-native contrasts is not caused by a loss of sensitivity to acoustic cues per se. Instead, infants' perception of speech sounds goes through a "reorganization" (Werker & Tees, 1992). It appears that young infants process speech sounds via a general auditory processor. Sometime around the middle of their first year, infants' perception of ambient human speech is reorganized such that the sounds of

their native language are processed as linguistically relevant (Best & McRoberts, 2003; Kuhl et al., 2008; Werker & Tees, 1992, 1999, 2005). Supporting evidence for such reorganization comes both from behavioral and brain imaging studies. Infants who show reduced discrimination of non-native contrasts show latent sensitivity to relevant acoustic cues (Mazuka, Cao, Dupoux, & Christophe, 2011; Tees & Werker, 1984). Additionally, it has been shown that perceptual reorganization is associated with changes in underlying neural processes for native speech contrasts (Kuhl et al., 2008; Sato, Sogabe, & Mazuka, 2010b; Werker & Tees, 2005). It is well established that linguistically relevant segmental information is associated with left-lateralized activation (c.f., Zatorre, Belin, & Penhune, 2002). In particular, data from recent imaging studies suggest that the processing of native sound contrasts before and after reorganization may be associated with a shift in the functional lateralization for the processing of the contrast (Minagawa-Kawai, Mori, Naoi, & Koijima, 2007; Sato et al., 2010b).

Thus, even if changes in infants' discrimination performance might not inform us about adults' actual ability to purely perceive the difference between two sounds, they are no doubt highly useful in informing us about infants' language-dependent perceptual reorganization. That being said, the results for the /be:k/-/bi:k/ contrast, thus enhancement without exposure, point to factors beyond mere native language exposure that could alter infants' discrimination performance, as outlaid in the previous section.

## Implications for Further Study

The results of the present study seem to differ substantially from previous studies that have generally reported positive discrimination for vowel contrasts for very young infants, directional asymmetries, as well as decline of non-native as opposed to maintenance or enhancement of native phoneme discrimination. We will derive two relevant factors for further study from our results. First, not enough vowel contrasts have been tested in previous studies. Even though young infants' ability to discriminate subtle vowel contrasts such as /i/-/I/ (Swoboda, Morse, & Leavitt, 1976) and /a/-/ɔ/ (Kuhl, 1983) in their native language has been tested, their number is limited. In fact, we are not aware of a study that tested whether German-learning infants are able to discriminate the /bi:k/-/be:k/ or /bu:k/-/bo:k/ contrasts reliably at 4.5 months of age. Considering that languages differ widely in how finely vowel spaces are divided, it is quite possible that many of the finer contrasts would be difficult for young infants to discriminate, whether native or non-native. Additional

studies are needed to capture the different responses young infants may have to phonemic contrasts of various subtleties, where multiple contrasts are compared systematically, either based on adult discrimination difficulties, or on specific theoretical predictions based on acoustic or articulatory distances as in Best and McRoberts (2003).

Second, not enough infants from different language backgrounds have been tested. As discussed above, previous studies that tested infants' discrimination on non-native vowel contrasts were restricted primarily to English and several other European languages. Japanese differs from previously studied languages in its rhythm (mora-timed, as opposed to stress-timed or syllable-timed rhythm), lexical-level prosody (lexical-pitch accent as opposed to lexical stress or tone, Vance, 1987), intonation (edge-based intonation as opposed to prominence-based intonation, Jun, 2005), and phonotactic constraints that determine syllable structure (Vance, 1987). It is generally assumed that infants' perception of speech sounds is still not tuned for their native language at 4.5-months of age. Yet, it is well established that even neonates are sensitive to prosodic properties of their language (Nazzi, Bertoncini, & Mehler, 1998), and fetuses can learn the prosody of the stories mothers read (DeCasper & Spence, 1986). More recently, Yeung, Chen, and Werker (2013) have argued that the influence of native languages may emerge as young as 4 months of age, on the basis of their study of tone perception with infants learning English, Mandarin, and Cantonese. Since vowels carry lexical level prosody such as tones and lexical pitch-accent, it is conceivable that Japanese infants' perception of vowels is already impacted by Japanese phonology at these prosodically relevant levels even as early as 4 months of age, in such a way that it prevents them from discriminating some of the German vowel contrasts. In order to evaluate whether infants' native language properties, such as the use of pitch for lexical level prosody, impact their discrimination of vowel contrasts early on, it is necessary to test infants learning tonal languages such as Chinese, Thai or Vietnamese on their discrimination of non-native vowel contrasts. Testing infants younger than 4 months of age could also be important.

## CONCLUSION

The current study tested Japanese infants' ability to discriminate three German vowel contrasts and revealed that they developed in three different ways. Not all contrasts were discriminated by young infants, and their ability to discriminate a contrast improved even

when they did not receive exposure to a language in which the relevant contrast is contrastive. It demonstrated that perceptual narrowing is not sufficient to capture the complex nature of how infants' ability to discriminate phonemic contrasts develops. It suggests that perceptual narrowing is part of a larger development that infants experience during this period.

## NOTES

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