A Domain-General Theory of the Development of Perceptual Discrimination

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ABSTRACT—*In this article, we posit a domain-general principle that may account for the improvement that is observed in several aspects of perceptual development over the first years of life. Development during this time frame is characterized by a process of perceptual narrowing, whereby the discrimination of perceptual information is broadly tuned at first and then declines to more selective levels with experience. This process appears to cut across both the visual and auditory modalities and may reflect the development of a common neural architecture.*

KEYWORDS—*perceptual narrowing; face perception; speech perception*

A question that permeates the study of developmental psychology is whether there are domain-general developmental principles that generalize across perceptual domains. For example, previous theories of the development of speech and face perception posit similar developmental mechanisms that account for changes in the discriminatory abilities of infants. Indeed, there is a growing body of evidence from research on the development of phonemic perception (e.g., Kuhl et al., 2006), face perception (e.g., Pascalis, de Haan, & Nelson, 2002; Pascalis et al., 2005), intersensory perception (i.e., perceiving an integrated visual and auditory stimulus, such as a talking face; Lewkowicz & Ghazanfar, 2006), visual language discrimination (i.e., viewing but not hearing talking faces; Weikum et al., 2007), and the discrimination of culturally specific musical rhythms (Hannon & Trehub, 2005a, 2005b) that collectively suggest the emergence of a domain-general principle of perceptual development. Across these areas of development, perceptual discrimination is tuned to environmentally relevant distinctions by 9 to 12 months of age, whereas the discrimination of environmentally irrelevant, or less frequently encountered, distinctions declines. It is important to note that this does not suggest a developmental regression but a progression toward greater efficiency at perceiving and processing salient rather than less-salient environmental input.

An integration of the behavioral evidence with evidence from recent studies examining the neural correlates of perceptual narrowing suggests that, in the absence of behavioral discrimination, there may be neural discrimination (Rivera-Gaxiola, Silva-Pereyra, & Kuhl, 2005; Scott, Shannon, & Nelson, 2006). In other words, the brain may maintain the ability to perceptually discriminate, but this discrimination is not manifest in behavior unless recruited though experience. We begin by reviewing the evidence for this account. We then review the research examining the neural correlates of perceptual narrowing. Finally, we posit both behavioral and neural mechanisms that may mediate perceptual narrowing.

EVIDENCE OF PERCEPTUAL NARROWING ACROSS DOMAINS

Development of Phonemic Perception

The development of phonemic perception is characterized by a decline in the discrimination of speech sounds not present in one's native language. Thus, native-language experience functions to tune, maintain, and facilitate the perception of phonemes. Currently, there is substantial evidence suggesting that this specialization occurs between 6 and 12 months of age and is dependent on perceptual exposure to native (as opposed to nonnative) phonemic contrasts (Werker & Tees, 2005). For example, there is a decline in the ability of English-speaking infants to distinguish the Hindi phonemic contrasts /Ta/ and /ta/ from 6 to 12 months of age (Werker & Tees, 1984). In addition to

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experience-driven maintenance of native contrasts, there is also evidence of facilitation of these native contrasts (Kuhl et al., 2006). Thus, phonemic-contrast detection in the native language is not simply maintained over development but that there is environmental facilitation of the contrasts infants have experienced.

Development of Face Perception

It has been hypothesized that the ability to discriminate between faces that are not consistently present in infants' early environment declines between 6 and 9 months of age (Nelson, 2001). This hypothesis is supported by recent reports examining the development of discriminatory abilities when infants view both monkey faces and faces of unfamiliar races (Kelly et al., in press; Pascalis et al., 2002; Pascalis et al., 2005). In these experiments, a visual paired-comparison (VPC) task, which capitalizes on infants' preference for novelty, was used to infer perceptual discrimination. In the VPC task, participants are first familiarized to a single stimulus. Then the familiarized stimulus is paired with an unfamiliar or novel stimulus. Using this task, researchers observed that 6-month-old infants exhibited novelty preferences for monkey faces; however, neither 9-month-old infants nor adults showed evidence of such discrimination (Pascalis et al., 2002). These data suggest that younger infants exhibit a more broadly tuned face-processing system that can discriminate among exemplars within multiple categories of faces (e.g., two human or two monkey faces) and that this system becomes more specific (e.g., discrimination between human faces only) and less flexible with age. A very similar pattern of results was observed for infants viewing faces of unfamiliar races, suggesting that 3- and 6-month-old infants exhibit differentiation of faces from other ethnic groups, whereas 9-month-olds only show differentiation of faces within their own ethnic group (Kelly et al., in press)

To further investigate the role of experience in the tuning of face processing, Pascalis et al. (2005) gave 6-month-old infants 3 months of perceptual experience with monkey faces by sending them each home with a picture book containing monkey faces (see Fig. 1). After this experience, 9-month-olds maintained the ability to discriminate monkey faces (see Fig. 2). It is important to note that discrimination was not only found for faces from the picture book but was also generalized to previously unseen monkey faces.

Overall, much like the development of phonemic perception, face-processing abilities develop on the basis of specific types of faces present in the visual environment. To date, there have not been any studies examining whether the discrimination of commonly experienced types of faces is better characterized as being maintained or facilitated. For example, does the decline of discrimination in one category (i.e., monkey faces) occur in the service of better discrimination in another category (i.e., human faces), or is the ability to discriminate commonly experienced

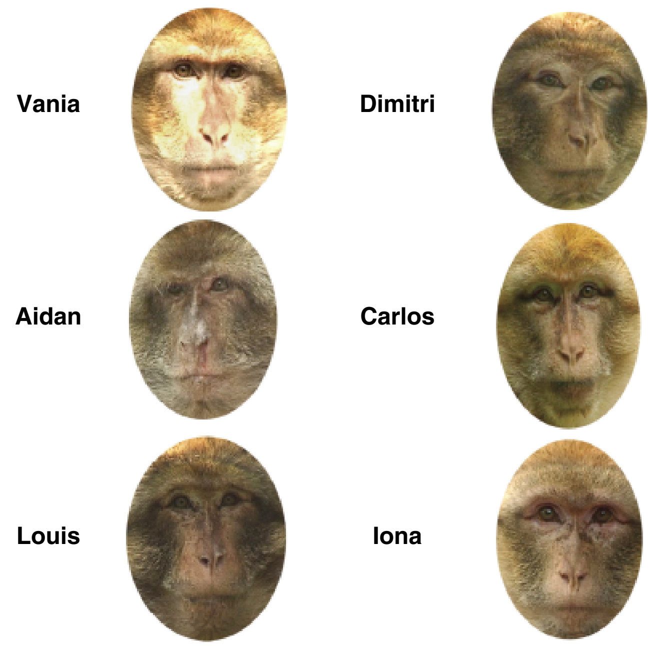

Fig. 1. Examples of trained monkey faces and their corresponding names.

faces simply maintained over development? If perceptual narrowing cuts across perceptual domains, one would expect to obtain facilitation effects for face processing that are similar to those found for speech processing.

Development of Intersensory Perception

To test whether perceptual narrowing operates in the development of intersensory perception, Lewkowicz and Ghazanfar (2006) investigated infants' ability to match face and voice pairings across development. Infants aged 4, 6, 8, and 10 months viewed two side-by-side images of vocalizing monkey faces while listening to one of the two vocalizations. Results reveal that only the younger infants were able to correctly match the vocalization they heard with the monkey face making that

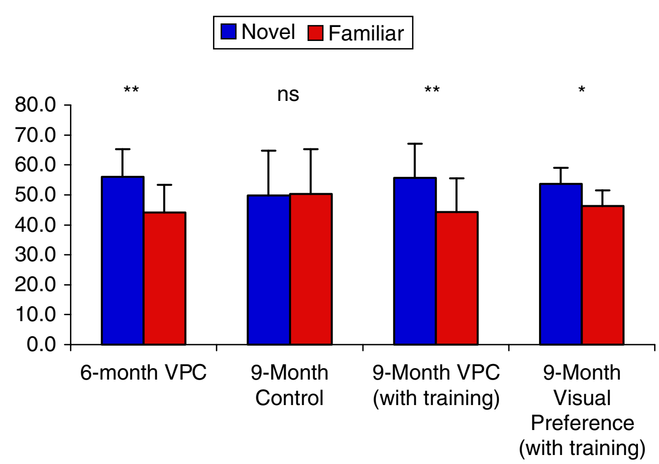

Fig. 2. Preferential looking times for infants viewing novel and familiar trained and untrained monkey faces. VPC = visual paired comparison.

vocalization, as indicated by a looking preference (i.e., looking for longer duration) for the sound–face match. However, by 8 to 10 months of age, no sound–face match was made.

Evidence in support of the multimodal nature of perceptual narrowing also comes from research investigating the development of language discrimination using talking face stimuli presented without sound (Weikum et al., 2007). Weikum and colleagues report that English and French monolingual 4- and 6-month-old infants are able to discriminate both French and English silent articulations. However, after 8 months of age, only French–English bilingual infants could discriminate the same silent articulations. Combined, these investigations provide direct evidence that perceptual narrowing operates in the development of intersensory perception, as well as in the development of unimodal visual and auditory perception.

Development of the Perception of Musical Rhythm

The development of the perception and discrimination of musical rhythms has also been studied in infants and adults (Hannon & Trehub, 2005a, 2005b). North American music often differs in metrical structure from that of other cultures (e.g., metrical structure in North American music contains simple duration ratios, whereas metrical structure in Bulgarian music contains complex duration ratios). Whereas North American adults can identify violations in music containing simple, but not complex, metrical structure, Bulgarian adults can identify violations in music containing complex structure (Hannon & Trehub, 2005a). Furthermore, 6-month-old North American infants can also discriminate violations in both complex and simple rhythms (Hannon & Trehub, 2005a, 2005b). It is not until 12 months of age that the detection of violations in musical rhythm becomes adultlike (Hannon & Trehub, 2005b). However, if 12-month-olds are briefly exposed to music containing complex metrical structure, they are able to later perceive these violations. This same exposure in adults does not influence the ability to detect complex metrical violations (Hannon & Trehub, 2005b).

NEURAL CORRELATES OF PERCEPTUAL NARROWING

The studies discussed above have recently been complemented by investigations into the neural correlates of perceptual narrowing. However, this research is limited to the development of speech and face perception and to the recording of event-related potentials (ERPs). ERPs reflect electrical activity of simultaneously active populations of neurons in response to the presentation of images or sounds, and are recorded from the scalp's surface.

Recently, researchers examined ERPs to native and nonnative speech contrasts by following 7-month-old infants until they were 11 months of age (Rivera-Gaxiola, Silva-Pereyra, & Kuhl, 2005). Overall, this investigation suggests that the electrophysiological response discriminates both the native and nonnative speech contrasts at 7 months, but at 11 months the infants could be clearly divided into two groups. Both of these 11-month groups exhibited ERP discrimination of nonnative contrasts, but one group discriminated early in processing (150–250 milliseconds after onset of the stimulus), and the other group discriminated late in processing (250–550 milliseconds). These data suggest that, despite previous behavioral evidence for a decline in the ability to discriminate nonnative contrasts, neural differentiation of this ability is maintained at 11 months.

To date, no longitudinal investigations of the neural correlates of visual perceptual narrowing have been conducted. However, cross-sectional investigations have provided evidence of a gradual experience-dependent cortical specialization of face processing (e.g., Halit, de Haan, & Johnson, 2003). Comparisons of infant ERPs in response to human and monkey faces at different ages reveal that adultlike patterns of neural activity are not present until 12 months of age (Halit et al., 2003).

ERPs were also recorded from typically developing 9-month-olds while they were presented with pictures of newly familiar and unfamiliar monkey or human faces in both a frontal and profile orientation (Scott, Shannon, & Nelson, 2006). Although differential ERP responses were found between human and monkey faces, there was also evidence of neural differentiation of familiar and unfamiliar monkey faces. More specifically, as illustrated in Figure 3, the amplitude of an ERP component known to index face processing in infants differentiated among familiar and unfamiliar frontal and profile human faces, whereas the response to monkey faces only differentiated between familiar and unfamiliar faces (not between frontal and profile faces). Thus, the response to human faces was more specific than the response to monkey faces was, but, unlike behavioral responses, the ERPs indicated that the infants did discriminate familiar and unfamiliar monkey faces. This suggests that although human faces are discriminated at a more specific level than are monkey faces, there is still residual neural evidence of the ability to discriminate monkey faces.

PROPOSED MECHANISMS OF PERCEPTUAL NARROWING

Why do discriminatory abilities in the visual and auditory systems appear to follow a common developmental trajectory? A recent study suggests that, in an immediate paired-comparison task, a newborn can discriminate static images of its mother's face from that of a stranger if it has been exposed to its mother's voice and face in combination. If the infant is tested prior to seeing its mother's voice–face combination, discrimination of the mother's face is not demonstrated (Sai, 2005). This, in addition to research finding perceptual narrowing when infants view silent articulations (Weikum et al., 2007), suggests that face and speech perception are linked from an early age. Neural evidence of this link comes from a positron emission tomography

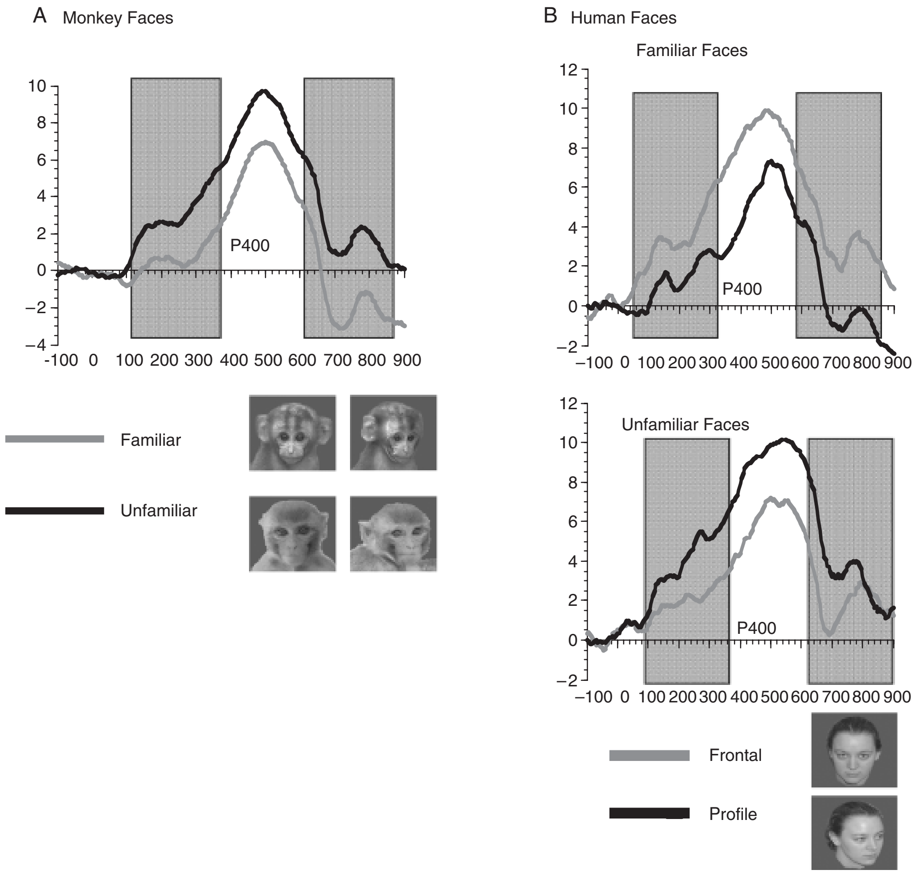

Fig. 3. Event-related potential (ERP) results for the 9-month-old P400 component. The P400 component is a neural response occurring approximately 400 milliseconds after the presentation of the stimulus and is thought to be an index of face processing in infants. An average of electrodes A1, A2, T5, T6, O1, and O2 is pictured. Panel A shows ERP results in response to monkey faces. The familiar monkey face (collapsed across the different orientations shown in the lower right of the panel) elicited greater-amplitude P400 than did the unfamiliar monkey face. Frontal and profile monkey faces were not electrophysiologically distinguished. Panel B shows ERPs in response to human faces, indicating more specific perceptual processing than in response to monkey faces. For familiar faces, the frontal face elicits a greater P400; however, for the unfamiliar face, the profile face elicits a greater P400.

(PET) study with infants (Tzourio-Mazoyer et al., 2002). The PET technique uses radioactively labelled substances, which are introduced into the bloodstream, to visualize neural activity. Tzouriro-Mazoyer and colleagues report adultlike brain activation when 2-month-old infants are presented with faces. However, faces also activated areas that are typically devoted to language in adults, supporting the existence of an early link between the visual and auditory systems.

Another mechanism, which may mediate perceptual narrowing, is discriminatory learning occurring at the subordinate or individual level. As described above, behavioral work shows that 9-month-olds can discriminate monkey faces when given previous experience with individually named monkey faces (Pascalis et al., 2005). Infants learned the faces using both the picture of the face and its corresponding name. This experience not only increased their ability to later discriminate these faces, but it also led to better discrimination of new monkey faces. One question that arises is whether experience naming faces individually leads to a maintenance of perceptual discrimination that does not occur if, for example, each monkey is labeled at the category level (i.e., all faces named "Monkey") or if infants are trained without labels.

This review presents an accumulation of evidence of developmental specialization in perceptual discriminatory abilities during the 1st year of life. This specialization corresponds to improved perceptual discrimination for stimuli predominant in the environment relative to declining perceptual discrimination for stimuli not present in the environment. What is currently not well understood is what mechanisms are responsible for perceptual narrowing and the maintenance or facilitation with experience. We also do not know how a decline in discriminatory abilities manifests itself in the brain. However, coincident with this decline, the brain experiences an exuberance of synaptic connections, followed by the pruning of these connections to adult levels. We hypothesize that pruning is the neural mechanism mediating perceptual narrowing across domains, leading to entrenched discriminatory abilities. Also, Hebbian Learning, or the modification of neural circuits and synaptic connections with repeated use and disuse, may be operating to increase synaptic efficacy of environmentally relevant information. This neuronal property may contribute to the observed behavioral phenomenon of perceptual narrowing. For example, as perceptual experience with human faces increases, the strength of the neural circuit responding to human faces is strengthened. On the other hand, the lack of experience to monkey faces leads to neural disuse and inefficient processing. This may be why we observe neural (i.e., ERP) but not behavioral discrimination of monkey faces at 9 months of age. Thus, perceptual narrowing may not reflect the complete erasure of neural connections, making these systems flexible and ready to be reactivated at a later period in time. One likely hypothesis is that perceptual systems are flexible enough to learn to discriminate new visual and auditory distinctions after the formation of neural circuitry. However, the effects of continued disuse across the lifespan and its influence on both the behavioral and neural correlates of perceptual abilities have yet to be fully investigated.

The findings described above have implications spanning multiple fields within the area of developmental psychology; however, more research is needed to answer some very fundamental questions about the nature of perceptual narrowing. First, it is unclear whether the ability to discriminate commonly experienced stimuli at 9 to 12 months of age represents maintenance or facilitation of an ability present at 6 months. Furthermore, if facilitation is occurring across multiple domains, is there competition for neural resources within each domain? In other words, can the developmental progression be characterized as the dividing up of limited resources for efficient processing? Moreover, what is it that is narrowing? Is learning to individuate exemplars (whether it be faces, phonemes, musical rhythms, or cross-modal matches) an important factor, or does mere exposure influence the specificity of this system? Finally, can research on perceptual narrowing lead to specific hypotheses about how neural development is responsive to environmental input? Answering these questions and others will lead to a clearer understanding of the development of perceptual abilities over time.

Recommended Reading

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