Categorical Perception as a Combination of Nature and Nurture

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Abstract

This paper reviews the existing literature on categorical perception of sounds and colors in different animals including humans. We highlight that categorical perception is a combination of nature and nurture; to be specific, categorical perception is innate with a phylogenetic root, but it can also be modified by postnatal experience. We also suggest that language is not wholly the basis for categorical perception, as what Sapir-Whorf hypothesis posits; instead, language is one type of experience that can affect the nurture part of categorical perception across domains and modalities in humans.

Keywords: categorical perception, nature, nurture, language, sounds, colors, simulation

Introduction

Categorical perception (CP) is to perceive continuous physical stimuli into discrete categories (Goldstone & Hendrickson, 2010). Language, as a human unique trait, has been proposed to play a critical role in CP. However, the nature of CP and its relation to language are still under debate (Holmes & Wolff, 2012; Simanova et al., 2016). As for the nature of CP, firstly, whether it is innate or acquired remains controversial. Secondly, there exists evidence that CP could simply be a phenomenon at the perceptual level (e.g. Pilling et al., 2003), whereas other evidence implies that CP is a reflection of high-level cognition (e.g. Roberson & Davidoff, 2000). As for the CP-language relation, a number of existing experiments have showed that how one categorizes perceptual stimuli actually depends on the language(s) he/she speaks, thus showing a diversity, which appears to be in favor of the early version of Sapir-Whorf hypothesis that language determines thought. On the other hand, universality has also been identified in the way perceptual stimuli from certain domains such as colors are categorized across different languages (e.g. Kay & Reiger, 2003).

This paper attempts to discuss the nature of CP and its relation with language from a perspective of evolution and development. To address the inquiry about the nature of CP, we would like to review CP of sounds and colors in nonhuman animals and humans, which suggests that the domain- and modality-general CP is a combination of innateness and experience across species, i.e., CP results from both nature and nurture. With respect to the role of language in CP, we would like to stress that although being a form of high-level cognition, language affects perception in a complex way at multiple levels: language is undeniably one kind of experience that affects CP at the low-level perception in humans, and so is the high-level cognition abilities. In other words, we suggest there is no need to put language in a distinct position from other forms of experience.

The nature-nurture essence of CP

World objects are perceived categorically by living organisms. CP is to qualitatively differentiate continuous stimuli into discrete categories. The mechanism of CP is one of the basic questions of cognitive science (Harnad, 1987), since it presents interaction between high-level conceptualization and low-level perception (Goldstone & Hendrickson, 2010). The psychophysical approach has been widely used in experimental paradigms on CP, in which subjects were asked to discriminate and label a set of stimuli presented to them. However, CP is a broader phenomenon across domains and modalities, suggesting that CP has its phylogenetic origin. Indeed, existing literature has shown that nonhuman animals also exhibit CP cross-domain and cross-modality, and skills acquired by them for survival and reproduction could have shaped their CP progressively. We will review CP of sounds and colors in nonhuman animals in the following parts. Ontogenetically speaking, studies on infants and adults also indicate that CP has its innate part and is "refined" by postnatal experience. Therefore, from the perspectives of development, CP is partly innate and partly influenced by experience across species. In this sense, both universality and diversity should be observed in humans because of the heterogeneous postnatal experiences from different cultures.

CP in nonhuman animals

This section reviews studies on CP in invertebrates and vertebrates to show that CP is a conserved phenomenon, and postnatal experience affects CP. We focus on CP of sounds and colors.

CP of sounds

CP has been investigated in some invertebrates across modalities. For example, male crickets sing calling song to attract mate and courtship song to promote copulation, both of which are at low-frequency (Alexander, 1961). Crickets are also sensitive to high-frequency ultrasounds emitted by their predators, bats (Nolen & Hoy, 1984). Using the

psychophysical labeling and habituation-dishabituation paradigm, Wyttenbach et al. (1996) have found that Polynesian field crickets (*Teleogryllus oceanicus*) were able to discriminate both attractive and repulsive sounds with the sharp boundary lying between 13 and 16 kilohertz. The discrimination happening within this large gap between communicative songs produced by crickets around 4 to 5 kHz and ultrasounds produced by bats around 25 to 80 kHz is closely related to survival. Interestingly, ter Hofstede et al (2009)'s experiments showed that such crickets lack reaction to echolocation of sympatric gleaning bats on the ground, suggesting that the acoustic response of wild crickets could be adapted by the environment, where bats mainly prey in the air. In this sense, it seems that the frequency range between 13 and 16 kHz also bridges the innateness, i.e. their communication calls, and experience, i.e. ultrasounds of their predators, suggesting that the observed CP of sounds in crickets is a combination of nature and nurture.

Concerning vertebrates, for example, Baugh, Akre, & Ryan (2008) have demonstrated that female tungara frogs respond to mating calls from males in a categorical fashion, which is critical for reproduction. This is possibly the only study on CP of sounds in frogs.

CP in auditory modality has been intensively studied in avian species. Dating back to 1980s, the psychophysical methods were used to investigate CP of auditory systems in birds. Combining the operant conditioning and multidimensional scaling, Dooling, Brown, et al., (1987) found that budgerigars have exceptionally low threshold of discrimination frequency at 2-4 kHz, which fall into the spectrum of their contact calls produced when separated (Dooling, Park, et al., 1987). This suggests that budgerigars' auditory system could be modified by experience of separation. The subsequent study also demonstrated that perceptual learning can alter the salience of perceptual categories (Brown et al., 1988), suggesting that experience affects CP of sounds in birds. However, the similar perception of major call classes of budgerigars in humans and budgerigars also indicate a shared mechanism of auditory discrimination system in birds and humans (Brown et al., 1988). Such findings prompt researchers to wonder whether birds could categorically perceive continuous human speech sounds absent in their environment, and if so, whether their CP is similar to that of humans or not.

A number of studies around the late 1990s investigated if birds are able to discriminate continuous natural and synthesized human speech sounds. Dooling, Okanoya, & Brown (1989) have found that budgerigars share with humans and other animals in the range of VOTs (voice onset time) from 0 to +70ms in the perceptual change of bilabial, alveolar, and velar continua. However, it is possible that the budgerigars could refer to temporal feature as perceptual cues, since VOTs involve variants of temporal instead of spectral information. Dooling & Brown (1990) took naturally produced vowels as the stimuli to examine the perceptual categorization of purely spectral features that

had been reported to be engaged in vowel perception in humans. The results demonstrate that budgerigars utilize the same cues as those of humans—the relation between F1 and F2 formant frequencies—to discriminate vowel categories. Using synthesized vowels, wild blackbirds and pigeons are also able to discriminate between four vowels (Hienz et al., 1981). Besides, after training, Japanese quails were reported to be capable of categorizing explosives [p, d, g] combined with different vowels (Kluender et al., 1987). These data seem to reflect that categorization of speech sounds is not limited to humans, but general auditory processing across species. However, detailed discussions are needed for such a conclusion, which is not the focus of the current paper (cf. Kriengwatana, Escudero, & Cate, 2014).

The same question of whether CP of speech sounds is species-general or human specific has also been explored in nonhuman mammals, since their auditory systems are more similar to that of humans. Chinchillas, a rodent species, had been shown to successfully discriminate voiced and voiceless alveolar plosive consonants naturally produced by different talkers and label the phonetic boundaries of the /d/-/t/ continuum similarly to that of English-speaking adults (Kuhl & Miller, 1975). The follow-up study confirmed the same result in discrimination and labelling of bilabial and velar plosives by chinchillas (Kuhl & Miller, 1978). Apart from consonants, chinchillas were also evidenced to be able to discriminate vowels /a/ and /i/ recorded by American English talkers with three pitch levels (high, natural, and low) (Burdick & Miller, 1976). With human-like absolute auditory sensitivity, Mongolian gerbils were selected as an animal model to investigate CP of speech sounds. Presented with synthesized vowels, liquids and stops (plosives) continuums, the Mongolian gerbils also exhibit phonetic boundaries of all these three kinds of stimuli comparable to humans (Sinnott & Mosteller, 2001). Furthermore, a number of studies have focused on CP of speech sounds in rats. Reed, Howell, Sackin, Pizzimenti, & Rosen (2003) have shown that rats can be trained to discriminate fricatives and affricates and label the phonetic boundaries of the continuums with the rise time as the salient cues. What is interesting about rats is that they resemble human infants in that the unimodal or bimodal distributional exposure to phonetic continuums has an effect on the subsequent performance of the discrimination of these phonemes (Pons, 2006; Eriksson & Villa, 2006). This indicates that experience also shapes CP of non-conspecific sounds in rats. Although there exist no studies on CP of conspecific sounds (e.g. CP of ultrasonic vocalizations) in rodents, the data collected so far implicate a general mechanism of CP of vocalizations across mammals including humans.

As our closest relatives, nonhuman primates have also become the subjects for investigating CP of non-speech sounds, conspecific calls, and speech sounds. A series of early studies took old world monkeys and macaques as references to explore the same question on species-general or species-specific CP of sounds in human speech. The results showed that although monkeys performed a little

worse than humans in frequency of pure tone perception (Sinnott, Brown, & Brown, 1992), their performance on discrimination of speech sound continuum including English liquid contrast /ra-la/ (Sinnott & Brown, 1997), VOT /ba-pa/ (Sinnott & Adams, 1987), place of articulation /ba-da/ (Sinnott, Beecher, Moody, & Stebbins, 1976), stop-glide /ba-wa/ (Sinnott, Brown, & Borneman, 1998), and front and back vowels (Sinnott, 1989; Sinnott & Kreiter, 1991) indicate that monkeys perceive speech sounds also in a categorical manner. Concerning conspecific monkey calls, inconsistent results have been obtained. Japanese macaques were reported to be able to perceive contact calls categorically (May et al., 1989). However, neither humans nor macaques exhibited CP of the synthesized coo calls continuum (Hopp et al., 1992), suggesting that the CP of conspecific calls have to be natural instead of synthesized. These data also indicate that nonhuman primates may already possess auditory ability for speech perception, albeit quantitatively less capable.

CP of colors

Before going into details of CP of colors in nonhuman animals, we need to clarify that the fact that one species is capable of categorically perceive colors does not amount to what type of color vision they have. Rather, what we argue is no matter the color vision they possess is dichromatic or trichromatic, the species are able to perceive color in a categorical fashion, and tune the categories according to the postnatal environment.

In visual modality, bees have been investigated to explore color discrimination. By adjusting the light intensity of the stimuli, von Helversen (1972) (from Hempel de Ibarra et al., 2014) tested whether bees are sensitive enough to the spectrum of colors and capable of discriminating the wavelength. Three spectral sensitivity peaks at the UV, blue and green ranges of the spectrum correspondingly matched the three types of photoreceptors in honeybees. In addition, two minima were found to show the wavelength discrimination function between the peaks of S- and M-, and M- and L-receptors respectively. These findings strongly suggest that color vision of honeybee exhibits the trichromatic nature. Further studies training bees to learn color discrimination in a short period of time indicated that the CP of color wavelength could be shaped by learning (Menzel, 1967) (from Hempel de Ibarra et al., 2014). Besides, the color visual system of bees was shown to be tuned to the variability of environmental flowers (Garcia et al., 2018). The neuroanatomy of color processing in bees also suggests that multiple systems in the brain mediate color discrimination dependent on individual experience (Dyer et al., 2011). All these reflect the fact that that environmental experience plays an important role in shaping CP of colors in bees.

CP of colors was also examined in goldfish. Using a generalization approach, in which the fish was trained to obtain a reward in the presence of colors with different wavelengths, and afterwards tested whether generalization occurred when presented with novel colors, Goldman et al. (1991) reported that, controlling both wavelengths and brightness, goldfish exhibited color boundaries accordingly to the training stimuli. However, Kitschmann & Neumeyer, (2005)'s simultaneous testing on wavelength discrimination and generalization demonstrated that "generalization measurements are not suitable to uncover possible color categories". In order to exclude the possibility of remembering the training colors after weeks of training, Poralla & Neumeyer (2006) used six wavelengths for training goldfish, and found that goldfish exhibited human-like "focal" colors. Similar to bees, experience could also reshape the color vision of goldfish (Neumeyer & Arnold, 1989), and its color vision system exhibits considerable developmental plasticity (Wagner & Kroger, 2005). This confirms the role of experience in CP of colors in goldfish.

When it comes to avian species, early studies found that pigeons also show spectrum transition, but at different points from those of humans (Wright & Cumming, 1971). For example, Jones, Osorio, & Baddeley (2001) investigated how poultry chicks responded to wavelength continuum. The chicks preferred intermediates if they were initially trained to two colors. Moreover, although songbirds communicate mainly by vocalizations, visual perception is also important in their daily lives. Recently, a couple of studies have shown that birds exhibit CP of color signals. Mating choice of female zebra finches is crucial for reproduction since they are socially monogamous. Thus, proper evaluatingsuch body condition of males visually should be gained through evolution by females. Because the carotenoid-based color of male beak reflects their immunity, namely the darker the beak the better the immune system functions (Blount et al., 2003), females prefer redness than orangeness in their mating choices (Collins & Cate, 1996). Caves et al. (2018) provided evidence that female zebra finches could perceive carotenoid-based spectrum ranging from light orange to dark red categorically associated with an assessment signal, namely color of the male beak, which reflects immunity condition of males. This in turn implies that CP of colors in birds is closely related to reproduction. Subsequently, the same research group found that zebra finches also show CP of blue-green range, suggesting a general mechanism for CP of colors (Zipple et al., 2019). CP occurs in both orange-red and blue-green ranges suggestive of general mechanisms, which are innate, and the better discrimination of orange-red range over blue-green range could be influenced by mating choice and natural surroundings important for reproduction and survival, which are experience.

Coming to nonhuman primates, experiments of CP of colors had been conducted using psychophysical and naming paradigms. Macaques were evidenced to categorize the spectrum into the same basic hues as humans, namely green-blue-yellow-red (Sandell et al., 1979). To address the linguistic relativity inquiry, Matsuzawa (1985) tested not only color categorization but also color naming in a chimpanzee. The result showed that the chimpanzee was

capable of both tasks, and the named colors were consistent to the focal colors observed in human language. Furthermore, using the matching-to-sample tasks, a later study showed that the experience of training also affects the color naming of two chimpanzees, one of whom had a longer training period than the other (Matsuno et al., 2004). However, also using the matching-to-sample paradigm, baboons were reported to be good at color discrimination, but incapable of matching individual boundaries as humans do. Instead, their performance exhibited two boundaries corresponding to the training stimuli (Fagot et al., 2006). The data reviewed above on nonhuman primates also lead to the conclusion that CP of colors seems to be endowed, while how primates categorize colors depends on their color vision systems (trichromatic or dichromatic) and also appears to be affected by later experience or training.

CP in humans

The linguistic relativity hypothesis has encouraged cross-linguistic investigations on how particular languages affect thinking, most of which focused on CP of colors, and the discussion about whether CP of color is universal or diverse is still under dispute. However, as argued in the previous section, CP seems to have a phylogenetic root that is innate and still influenced gradually by environmental experience ontogenetically. In this sense, to some extent, the observed universality and diversity of CP of colors could amount to both nature and nurture of CP cross-modality and cross-domain as reviewed above.

Revisiting the Sapir-Whorf hypothesis

This hypothesis posits that the language one speaks affects his/her thinking. Perception is an important part of thinking. In light of this hypothesis, colors of a spectral wavelength have been proposed to be perceived categorically with reference to the particular linguistic system that describes colors. Similar influence of specific languages on perception that is categorical can also be found in the modality of speech sounds.

The term of the Sapir-Whorf hypothesis is coined from the debate by Edward Sapir and Benjamin Lee Whorf on the proposal that a particular language one speaks could affect the speaker's thoughts. The hypothesis is also known as the linguistic relativity hypothesis. Specifically, Whorf proposed that languages with their specific lexical and grammatical categories that were groupings of experience were expressed by speakers analogically across-language in the form of speech, and the way the linguistic categories assemble is a coherent system of reference, which guides the habitual interpretation of experience in speakers (Lucy, 2001). This guidance is unwitting, in the sense that speakers are not aware of the association between their native language and the way they perceive the world. Whorf's classical work to contrast the concept of time in Hopi and English elegantly illustrated the effects different languages have on thoughts. Three types of approaches used in empirical studies were summarized by Lucy (2001):

Structure-centered, domain-centered, and behavior-centered. In this section, we focus on the domain-centered approach, especially on the CP of colors and speech sounds. The influence of different languages on color perception, whether universal or specific, has been intensely studied using behavioral methods and later neuroimaging techniques with relation to the Sapir-Whorf hypothesis across languages. However, although also strongly influenced by native language, the perception of speech sounds was rarely linked to the Sapir-Whorf hypothesis. Furthermore, the reason why the linguistic camp concentrates on the role of language in human thoughts is likely to be that language is regarded as a special trait of humans. However, as postnatal experience(language) in a species (humans), it is not surprising that language affects the thinking (nonhuman animals thinking?) of such species. In this sense, the Sapir-Whorf hypothesis falls into a general belief in cognitive psychology that experience plays a crucial role in the development of cognition (Taylor, 2005), and in evolutionary biology that cognition could have been modified by the acquisition of language in evolution (Lupyan, 2015).

It is worth noting that we do not mean that the Sapir-Whorf hypothesis or linguistic relativity is wrong or deny the crucial impact language has on shaping CP. Indeed, we admit that as a complex system, language must have influenced CP in a complex way. However, the focus of the current paper is not how language could have reshaped the CP of humans, but the fact of language as a kind of experience belonging to nurture.

CP of speech sounds in humans

This section reviews studies on CP of speech sounds from the perceptive of ontogeny, namely from preverbal infants to monolingual and multilingual adults to illustrate that CP of speech sounds is also a combination of innateness and experience in humans, and the role language plays is beyond the Sapir-Whorf hypothesis, which is one of many environmental factors that influence CP.

Using the /b-d-g/ identification task, Liberman, Harris, Hoffman, & Griffith (1957) found that the listeners tend to divide this plosive continuum into three sharp categories. After that, a large number of studies have been conducted to investigate how speakers with different native languages categorize speech sounds. As the empirical work accumulated, more questions on CP of speech sounds arose. One is whether CP of speech sounds is specific to human language or belongs to general auditory perception. This could extend to the inquiry of the current paper that whether CP of sounds is shaped by experience—language, or innate—general auditory perception. The question has been approached by investigating how nonlinguistic creatures, including nonhuman animals and prelinguistic infants, categorize speech sounds. Concerning prelinguistic infants, technically speaking, they are not fully nonlinguistic since before birth, the fetus could hear the mother talk from 25-week gestation onward (Graven & Browne, 2008).

Therefore, we prefer to say infants are preverbal instead of prelinguistic. Another question concerns how multilinguals categorize the same continuum if the phonemic boundaries locate at different points within the continuum. For example, the phonemic boundary of plosives in English and Spanish lies at different points of VOT. How will an early bilingual of English and Spanish categorize the plosives? If learning affects CP of sounds, will late learning of a new foreign language affect the CP of the speaker? Studies on multilinguals could provide interesting insights on the innateness and learning effects of CP of speech sounds in humans.

To explore whether CP of speech sounds is language-specific, or whether speech perception in development is auditory-general, preverbal infants serve as the best candidates. Using the high-amplitude sucking paradigm, infants as early as one month were shown to be able to perceive speech sounds (plosives) categorically (Eimas et al., 1971). Employing a cardiac orienting response paradigm, Miller & Morse (1976) demonstrated that infants of 3 to 4 months old can categorically discriminate the cues of place of articulations. A series of worksbody have revealed that infants before 6 months old were able to discriminate speech phonemes in all languages, even nonhuman primate calls (Perszyk & Waxman, 2016), but from 6 months on, such ability wanes and infants become tuned to merely discriminate contrastive sounds in their ambient language(s) (Werker & Tees, 1984; Kuhl et al., 2006), indicating the key impact of language as experience in speech perception. Studies on categorization of speech sounds in infants of 6-12-month-old surrounded by multilingual environments further implicate the role of language in reshaping the CP. For example, English-French bilingual infants at 10- to 12-month were reported to be able to discriminate native boundaries of both languages (Burns et al., 2007).

CP of colors in humans

It has been argued that the CP of colors may derive from color naming of a particular language. The language-specific color naming system seems to determine how speakers of such language categorize colors, for instance, the categorical boundaries of green-blue continuum observed in native speakers of Welsh, English and Turkish (Lazar-Meyn, 2004; Özgen & Davies, 1998). Such findings appeared to be evidence for the Sapir-Whorf hypothesis, or linguistic relativity, in the sense that color naming is determined by particular language(s) one speaks. However, as reviewed in the previous section, nonhuman animals who lack language also display CP of colors. This not only shows that language is not a necessity for CP of colors, but also demonstrates that CP of colors has an evolutionary origin, which in turn predicts that preverbal infants will also perceive colors categorically. As shown in CP of speech sounds, infants from diverse cultures could perform similarly in the task of color categorization, and as they are exposed to ambient language(s), their CP of colors would be tailored to the color naming system in that language. In this

sense, instead of abody prerequisite, language only serves as environmental experience that modifies color categorization.

In preverbal infants, behaviorally, using the habituation-dishabituation paradigm, Bornstein, Kessen, & Weiskopf (1976) have found that 4-month-old infants perceive hues categorically, similarly to normal adults. Utilizing the eye-tracking technique, Ozturk et al. (2013) have reported that 8-month-old infants can also perceive colors categorically, and detect the between-category stimuli faster than the within-category stimuli. Besides, 7- to 8-month-old infants were reported to be able to distinguish stimuli between yellow and gold (Yang et al., 2013). This is exceptional, because both the chromaticity and surface specular reflectance decide the perception of colors, which is two-dimensional. Taking the full hue circle into consideration, Skelton et al. (2017)'s findings suggested that the recognition memory of 4- to 6-month-old infants parses hue continuum into red, yellow, green, blue, and purple, and a correspondence was detected between the categorical distinctions the infants performed and those seen in color naming lexicon. These data demonstrate that CP of colors is partially innate before acquiring language, which could already be biologically rooted in early invertebrates.

When does acquiring a particular language affect CP of colors? Before discussing this, we would like to clarify that the universality of CP of colors can be understood from two aspects. On the one hand, it refers to the universal boundaries between colors. It has been proposed that color boundaries are universal across cultures, which are hard-wired in human visual systems (Berlin & Kay, 1969). On the other hand, it also denotes the mechanisms underlying CP of colors, which are biologically endowed, meaning the perception of color spectrum into categorization. In this way, the universality of CP of colors reflects both interpretations, yet the diversity corresponding to different languages seems to refute the former but the later. In other words, what we argue here is that CP is a biological trait and modified by postnatal experience like language. The connection between CP of colors and language is mediated by naming or labelling, reflected by color lexicon. This must have happened consequentially to CP of speech sounds, since words are acquired later than sounds. To put it another way, the influences from language exposure in CP of speech sounds and colors might be different. CP of speech sounds was proposed to be inferred from statistical learning, based on the distribution of different sounds (Saffran et al., 1996). In contrast, CP of colors is affected by lexicon learning, which involved meaning. Franklin et al. (2005) have shown that there is little cross-language/culture knowledge that affects CP of colors in Himba and English in 2- to 4-year-old toddlers. Lexicon acquisition occurs in such ages. Thus, the perceptual reorganization of CP of colors under the influence of particular language(s) happens in concordance with lexicon acquisition. In this regard, we do not deny the influence of language on CP, but include language as one type of postnatal experience.

Conclusion

From the perspective of evolution and development, this paper reviews CP of sounds and colors in animals including humans and demonstrates that CP not only has its phylogenetic root (nature) but also can be modified by postnatal experience (nurture). The findings in nonhuman animals provide explicit evidence for the nature aspect of CP, whereas the nurture aspect of CP is too complex to capture using the traditional behavior and newly developed neuroimaging methods. Other approaches, such as computational simulation, become necessary to better understand how CP is affected by experiences such as language (or vice versa) (e.g., Puglisi et al., 2008 or Filatova & Miller, 2015).

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