Advanced Review

Categorical perception

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Categorical perception (CP) is the phenomenon by which the categories possessed by an observer influences the observers' perception. Experimentally, CP is revealed when an observer's ability to make perceptual discriminations between things is better when those things belong to different categories rather than the same category, controlling for the physical difference between the things. We consider several core questions related to CP: Is it caused by innate and/or learned categories, how early in the information processing stream do categories influence perception, and what is the relation between ongoing linguistic processing and CP? CP for both speech and visual entities are surveyed, as are computational and mathematical models of CP. CP is an important phenomenon in cognitive science because it represents an essential adaptation of perception to support categorizations that an organism needs to make. Sensory signals that could be linearly related to physical qualities are warped in a nonlinear manner, transforming analog inputs into quasi-digital, quasi-symbolic encodings. *WIREs Cogn Sci*

When we look at a rainbow, we tend to see about seven distinct bands of color, even though we know from physics that the dominant wavelength of light that meets one's eye changes smoothly from the top to bottom of the rainbow. Although the rainbow presents itself to us with a continuous and full range of visible wavelengths of light, we tend to see it in terms of distinct colors such as red, yellow, blue, and violet. This effect is a striking example of categorical perception (CP). According to this phenomenon, we tend to perceive our world in terms of the categories that we have formed. Our perceptions are warped such that differences between objects that belong in different categories are accentuated, and differences between objects that fall into the same category are deemphasized. This is allegorically illustrated in Figure 1.

CP is an important phenomenon in cognitive science because it involves the interplay between humans' higher-level conceptual systems and their lower-level perceptual systems. Traditional information flow diagrams in cognitive science typically draw a clean division between perceptual and conceptual systems with information moving only from perception to the conceptual system; the frequency of CP effects indicates permeability and bidirectional influence between these systems. We humans do not simply base our categories on the outputs of perceptual systems independent of feedback. Instead, our perceptual systems become customized to the task-useful categories that we acquire, slowly at the evolutionary timescale or quickly at the timescale of individual learning.

Another reason why CP is theoretically important is that offers a potential account for how the apparently symbolic activity of high-level cognition can be grounded in perception and action.[1] A basic feature of human symbolic thought is that people form equivalence classes. In the classical notion of an equivalence class, distinguishable stimuli come to be treated as the same thing once they have been placed in the same category.[2] This kind of equivalence is too strong when it comes to human concepts because even when we place two objects into the same category, we do not treat them as the same thing for all purposes and objects can be placed in different categories when in different contexts. Some researchers have stressed the intrinsic variability of human concepts—variability that makes it unlikely that a concept has the same sense or meaning each time it is used.[3,4] Still, it is impressive the extent to which perceptually dissimilar things can be treated equivalently given the appropriate conceptualization. To the biologist armed with a strong *mammal* concept, even whales and dogs may be treated as equivalent in contexts related to biochemistry, child rearing, and thermoregulation. Even

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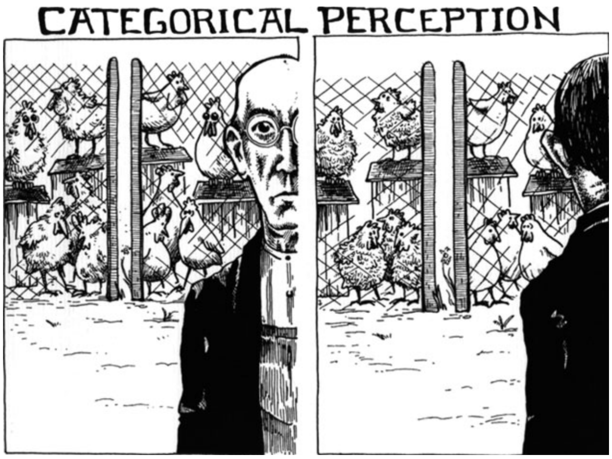

FIGURE 1 | An illustration of categorical perception. When an observer looks at objects (chickens) that fall into two or more categories (coops), differences among objects that fall into different categories are exaggerated, and differences among objects that fall into the same category are minimized. Conceived by Robert Goldstone, Made perceptual by Joe Lee.

sea lions may possess equivalence classes, as Schusterman et al.[5] have argued that these animals show free substitution between two entities once they have been associated together.

CP provides a mechanism for the origin of these (near-) equivalence classes. By CP, our perceptual systems transform relatively linear sensory signals into relatively nonlinear internal representations. The extreme case of this kind of nonlinear transformation is a step function by which increases to a sensory signal have no effect on perception until the signal reaches a certain threshold. At that threshold, perception changes qualitatively and suddenly. During the flat portion of the staircase function, different input signals have equivalent effects. Hence, CP can provide us with equivalence classes, the beginning of proto-symbolic thought.

Why would we, or mother nature, want to build cognitive systems with equivalence classes? One reason is that they are relatively impervious to superficial similarities. Once one has formed a concept that treats all skunks as equivalent for some purposes, irrelevant variations among skunks can be greatly deemphasized. People may never be able to transcend superficial appearances when categorizing objects,[6] nor is it clear that they would want to.[7] Still, one of the most powerful aspects of concepts is their ability to make superficially different things alike.[8] If one has the concept 'Things to remove from a burning house', even children and jewelry become similar.[9] Across modalities, the spoken phonemes /d/ /o/ /g/, the French word 'chien', the written word 'dog', and a picture of a dog can all trigger one's concept of *dog*,[10] and although they may trigger slightly different representations, much of the core information will be the same. Equivalence classes are particularly useful when we need to make connections between things that have different apparent forms.

Equivalence classes are particularly useful when we need to make connections between things that have different apparent forms. CP is the first stage of this process of responding to the essential, rather than superficial, aspect of an entity. It is the same reason why most current electronics are digital: To provide tolerance to superficial variation in voltage signals that are irrelevant to the critical information. It may well be that current computers are too brittle because they throw away too much analog variation in their pursuit of discrete symbols. Still, it is worth remembering that the informational system benefiting from the most years of 'research and development', provided by evolution is the genetic code of life itself, which closely approximates a digital code consisting of nucleotides and codons. Complex cellular machinery is dedicated to assuring that the code is relatively inert, and is protected from many contextual influences.[11] It is reasonable to think that our cognitive system benefits from the same strategy of developing (quasi-)reusable codes.

CP IN SPEECH

As operationalized in psychology, CP is said to be present when people more reliably distinguish physically different stimuli when the stimuli come from different categories than when they come from the same category.[12] The effect was originally established with speech phoneme categories. For example, Liberman et al.[13] generated a continuum of equally spaced consonant-vowel syllables with endpoints reliably identified as /be/ and /ge/, as shown in Figure 2 (top left graph) by varying the second formant transition.[14] There is a point (around stimulus value 4) where there is a relatively rapid decrease in the probability of observers hearing the sound as a /be/ to hearing it as /de/. At a later point, around values 9 and 10, observers rapidly shift from /de/ to /ge/ identifications. In addition to giving participants an identification task, participants were also given an ABX discrimination task. In this task, observers listened to three sounds—A followed by B followed by X—and indicated whether X was identical to A or B. Observers performed the task more accurately when syllables A and B belonged to different phonemic categories, as indicated by their identification probabilities, than when they

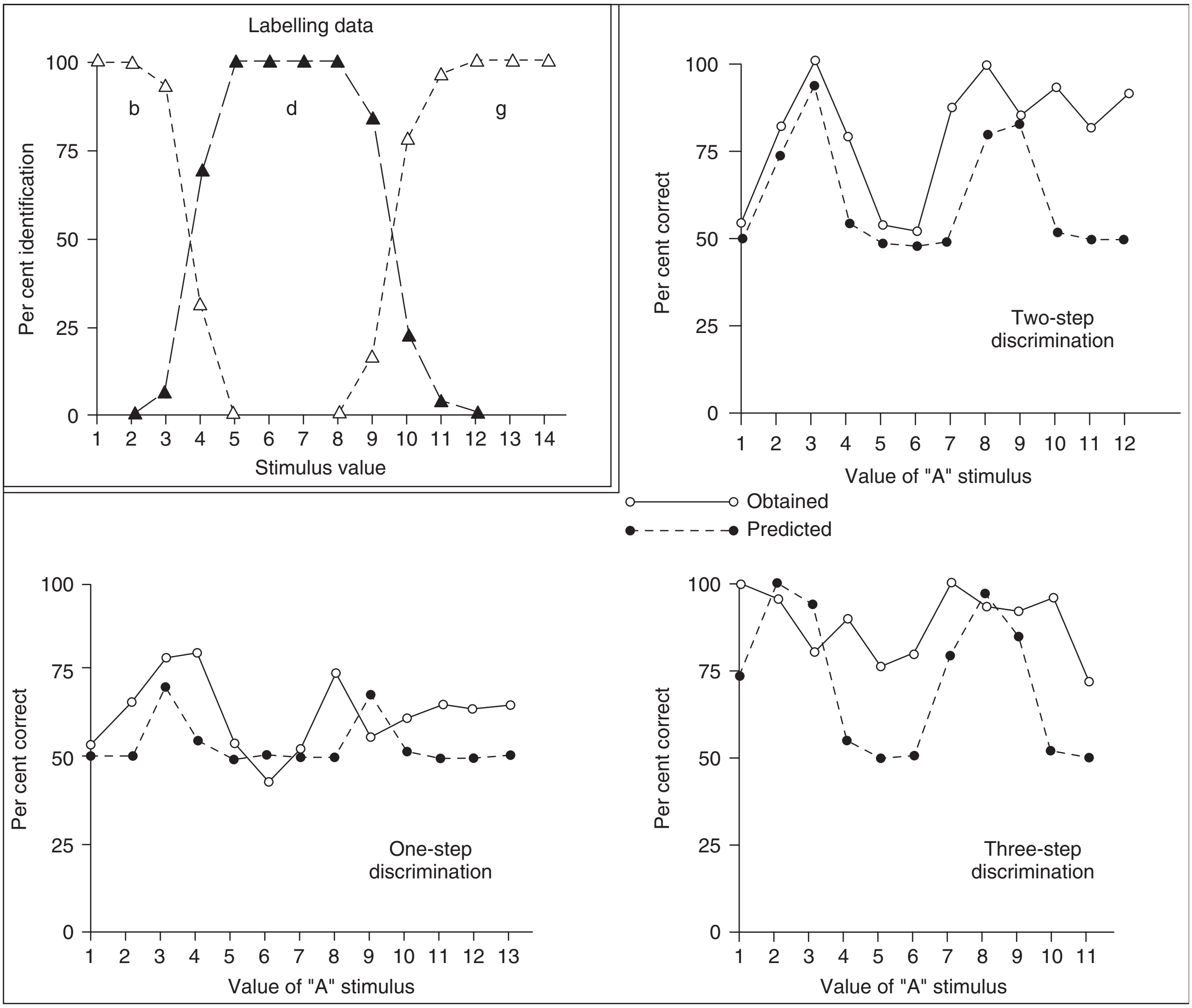

FIGURE 2 | As a physical variable (the direction and extent of the second formant transition) describing speech sounds is varied linearly along the horizontal axis, a person's perception relatively rapidly shifts from hearing the sound as a /be/ to hearing it as a /de/, and then rapidly shifts again to hearing it as a /ge/ (upper left panel). The perceiver's ability to discriminate sounds improves as the sounds become less similar—going from discriminations of sounds that differ by one step to two steps to three steps along the horizontal continuum. However, in all cases, discrimination ability peaks near the boundary separating phonemic categories. Reprinted with permission from Liberman et al.[13]

were variants of the same category, even when physical differences were equated. As shown in Figure 2, observers' discrimination accuracy tended to peak at the boundaries between the phonemic categories. Liberman et al.[13] concluded that the phonemic categories possessed by an adult speaker of English influence the perceptual discriminations that they can make.

The strongest version of CP claims that the probabilities from the category identification task can completely predict discrimination performance. That is, people use only their categorizations in order to determine whether two stimuli are identical. For a situation in which each stimulus must belong to either Category A or Category B, this strong statement can be mathematically expressed as

$$P(c) = \frac{1 + (p_1 - p_2)}{2}$$

where $P(c)$ is the probability of a correct ABX discrimination between Stimulus 1 and Stimulus 2, p_1 is the probability of placing Stimulus 1 in category A, and p_2 is the probability of placing Stimulus 2 in that same category.[15] This strong relation is rarely found in empirical results.[16] Listeners are better able to discriminate between two sounds than is predicted only by their categorization performance, indicating that participants are supplementing their categorical codes with a richer, perceptual, less digitized encoding as well. With passing time, the categorical codes apparently become increasingly important compared to the more analog perceptual representation, as shown by the increasingly good prediction of discrimination by categorization performance as sounds must be remembered for a longer period of time.[17] Accordingly, strictly category-based theories of perceptual discrimination have been called in doubt. Researchers have argued that discrimination for physical differences within a category is not at chance for either adults[18,19] or infants,[20] as would be expected if discrimination is based entirely on category membership. In fact, allophonic variation within speech sounds that are categorized as the same phoneme are not only perceptually discriminable, but they also have measurable impact on people's spoken word recognition.[21]

The degree to which CP phenomena are learned rather than innate is not clear.[18,22] Consistent with an innatist perspective, it appears that discriminability in some regions of acoustical continua is higher than in other regions, irrespective of category structure. Infants of only 4 months show increased sensitivity to acoustical differences in the same region of physical continua as do adults.[23,24] Human languages may have adapted to use phoneme category boundaries located in regions with intrinsically higher discriminability.[25,26] Thus, there is evidence that suggests that people's increased sensitivity to acoustical differences that straddle category boundaries may be a combination of innate properties of the auditory system and the acoustical signal, rather than learned. Similar claims have been made for vision, with researchers finding that color categories for 110 widely varying cultures are highly similar, perhaps even universal,[27] that these categories may be determined by general optimality considerations,[28] and in turn determine patterns of perceptual sensitivity.

However, there is also evidence that CP for auditory stimuli is subject to learning.[29] Using laboratory-created, speech-like stimuli that were assigned to different categories based on their labels, Lane[30] found CP effects despite a lack of correspondence between the trained categories and naturally occurring language categories. Cross-cultural evidence suggests that the learning of a particular language influences the pattern of discriminability between speech sounds. In general, a sound difference that crosses the boundary between phonemes in a language will be more discriminable to speakers of that language than to speakers of a language in which the sound difference does not cross phonemic boundaries.[31,32] In fact, giving English speakers practice with a discrimination that is present in other languages but not English causes them to show a CP effect for these discriminations.[33] Recent evidence suggests that infants' ability to retain discriminability for speech sounds that belong in the same category in their native language is promoted by exposure to a language where the sounds are categorized differently, but only if they are spoken by a present speaker, not merely a pre-recorded video.[34]

Another issue in CP research concerns whether it is a general perceptual effect, or it is only found for language-related stimuli. Liberman et al.[35] originally argued that CP is found for speech-like stimuli, but not for control stimuli that do not sound like speech (also see Ref [36]). However, Burns and Ward[37] found that expert but not novice musicians showed a CP effect for pitch differences, suggesting that extended training could create differential sensitization for nonlanguage semitone boundaries. In addition, other researchers[38] (see also Ref [39]) have found CP effects for nonspeech auditory materials.

CP IN VISION

Consistent with the preceding results indicating that speech is not unique in producing CP, considerable work has also shown CP for visual categories. The notion that experience and expectations can influence perception can be traced back to the 'New Look' movement of the 40s and 50s.[40] Evidence suggests that experts who have specialized concepts for their fields perceive structures in x-rays[41] and infant chickens[42] that are missed by novices. As the experts in these fields learn to distinguish between the concepts in their domain (types of fractures or gender of chickens), they seem to acquire new ways of perceptually structuring the objects to be categorized. Consistent with CP effects, the perceptual differences among objects that belong to different categories are sensitized, and differences among objects belonging to the same category are desensitized.

Lawrence[43] developed a theory of acquired distinctiveness, according to which cues that are relevant for determining category membership become generally distinctive. In one experiment, Lawrence trained rats on either a black/white or a rough/smooth discrimination. Rats received a reward for choosing one stimuli rather than another. Subsequently, rats were transferred to a discrimination in which, for example, when black shapes were presented, the rat was rewarded for a left response, and when white shapes were presented, the rat was rewarded for a

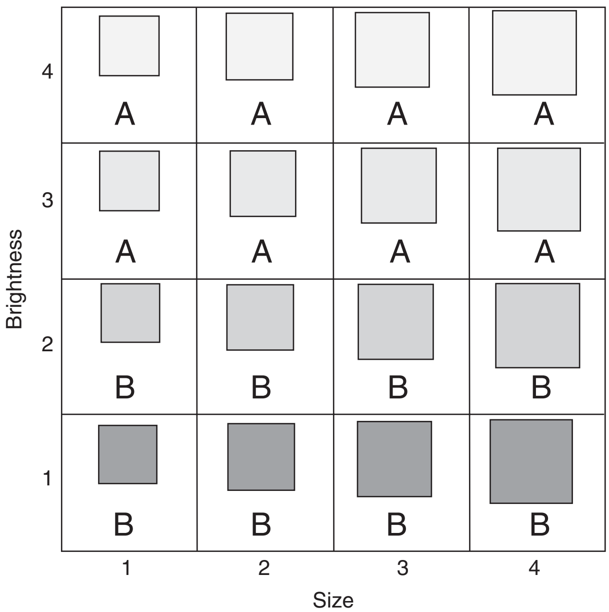

FIGURE 3 | Stimuli used by Goldstone.[47] Sixteen squares were constructed by combining four values of brightness with four values of size. The letters show the categorizations of the squares when brightness was relevant, and for other participants size was relevant. Categorization training on the shown categories leads to heightened discriminability of pairs of squares that differ on brightness, and is at a peak at the boundary between the As and Bs. Reprinted with permission from the authors.

right response. Rats learned this second discrimination better when they had been trained earlier to make a black/white discrimination. Stimuli also acquire 'nondistinctiveness' (or 'equivalence'). When cues are irrelevant for an earlier discrimination, there is a deleterious effect on subsequent discrimination learning with them.[44] Both of these effects are commonplace in human subjects,[45,46] and provide mechanisms for an influence of categorization on visual discriminations.

Researchers have explored the question of whether arbitrary new visual categorizations can be learned, and if so, whether they alter perceptual sensitivities. Using the stimuli shown in Figure 3, Goldstone[47] first gave participants categorization training involving either brightness or size. Subsequent to categorization training, participants were given a same/different judgment task in which horizontally or vertically adjacent squares from Figure 3 were presented, or the same square was repeated twice and participants were required to respond as to whether the two squares were exactly identical on both their size and brightness, or differed even slightly on either dimension. When a dimension had been relevant for categorization, participants' same/different judgments along this entire dimension were more accurate, compared to those from participants for whom the dimension was irrelevant or control participants who did not undergo categorization training. In addition, consistent with an acquired CP effect, the greatest increase in accuracy was found for those particular dimension values that were at the boundary between learned categories (i.e., comparing values 2 and 3 on brightness).

Other researchers have shown similar CP effects with richer, more realistic stimuli. Whereas Goldstone[47] found mostly increased discriminability for objects belonging to different categories (akin to Lawrence's acquired distinctiveness), Livingston et al.[48] found mostly decreased discriminability for objects belonging to the same category (akin to acquired equivalence), using complex line drawings reminiscent of biological cells. Levin and Beale[49] found CP effects along continua that were created by morphing from one realistic face to another, again indicating relatively rapid acquisition of perceptual equivalence classes. Using the same morphing technique to create new dimensions between arbitrarily paired endpoints, Newell and Bulthoff[50] found that classifying familiar, three-dimensional objects produced increased perceptual discriminability for these objects at the classification boundary. Results suggest that CP effects with faces are more robust when the faces that serve as endpoints of a morph continuum are familiar rather than unfamiliar faces, or when they have been labeled to make them unique.[51] The difference in CP effects because of face familiarity have been localized to a few brain regions in the right hemisphere, including the middle occipital gyrus, the posterior fusiform gyrus, and the inferotemporal cortex.[52] Goldstein and Davidoff[53] found CP of animal patterns for members of a culture where differences between patterns are important and captured by their system of animal terms. All of these results suggest that CP is a general and robust phenomenon in visual processing, providing a rationale for developing a general account of it in terms of the development of perceptual expertise.[54]

One visual domain worthy of singling out is color. Early work on the cross-cultural perception of color suggested that cultures with very different color categories, as indicated by their color words, nonetheless, showed similar perceptual memory differences for different colors.[55] However, more recent work has shown that cultures that organize colors into different categories show differences in their perceptual memory and sensitivity that are consistent with these categories.[56] For example, people show better ability to remember which of two colors has just been shown to them when the colors belong to different color categories.[57] In a related study testing English and Russian speakers, who differ in their color categories in the range of colors English speakers call 'blue' and 'green', Winawer et al.[58] find that both groups are faster to discriminate between two colors that fall into different, rather than the same, linguistic category. Moreover, this category advantage was eliminated by a simultaneous verbal, but not spatial, interference task (for similar results, see Ref [59]). These results suggest that linguistic categories facilitate recognition and influence perceptual judgments, and that these influences may be mediated by the active labeling of colors as they are presented. Laboratory analogs of these cross-linguistic influences have been performed in which people are given laboratory experience with different color terms, and these too show perceptual discriminability coinciding with experience-dependent categories.[60]

Color has been a valuable attribute for identifying both developmental and neural underpinnings of CP. CP for color is stronger for the left, compared to right, hemisphere of adults, but for prelinguistic infants, the opposite pattern is found.[61] This suggests that language may not build on top of early perceptual category structures in the right hemisphere so much as it imposes its categories on a less constrained left hemisphere. Consistent with this interpretation are additional results indicating that CP effects are found for toddlers' right hemisphere processing for colors with unknown terms, but left hemisphere for colors with known terms.[62] Accordingly, the lateralization of color CP is affected by the acquisition of color terms, and this influence of language has a lasting impact on functional brain organization.

An important question about these visual CP effects is 'Where does the influence of categorization experience on representation occur in the information processing stream?' Does categorization and labeling influence the early perceptual encodings of objects, or do they only influence later processes that determine how the objects are remembered, interpreted, or judged? The result in the preceding paragraph about the influence of verbal interference tasks in eliminating CP suggests that some of the influences of labeling are not chronic changes to how an object is perceptually encoded, but rather are due to on-line and optional verbal encodings. Other results suggest earlier and longer lasting influences on perceptual encodings. Goldstone et al.[63] found that objects that are placed in the same category not only become more similar to each other, but they also become more similar in their similarity to other neutral objects that were never categorized. They concluded that the categorized objects are changing their representations, and people are not simply increasing similarity judgments to objects that receive the same label. Consistent with an early locus of perceptual plasticity, Notman et al.[64] found that participants who learned to place oriented line gratings into different categories developed patterns of sensitization that were tightly tuned around the diagnostic orientations. The researchers interpret the lack of transfer from one orientation to others as evidence for relatively early perceptual changes. This inference is based on the finding from visual neuroscience that as visual information is more deeply processed in the cortex, neurons respond to larger spatial regions, and a greater range of orientations. Accordingly, the inference is often made that if categorization-induced learning is tightly restricted to trained spatial regions or orientations, then it is because of changes to early stages in the stream of visual processing. In one study that directly investigated changes in the responding of single cells due to category learning in monkeys, cells in the temporal cortex were observed to change their responsivity, a locus that would be considered mid-to-late-stream in visual processing.[65] In sum, there is evidence for a variety of loci of plasticity due to category learning, and it is likely that categorization has an influence on the relatively low-level perception of elementary visual features, mid-level shape recognition, and late processes involved with language, object-to-label associations, and decision making.

MODELS OF CP

Several models of CP, both mathematical and computational, have been proposed. It has been a ripe area for modeling because the behavioral phenomena are robust and amenable to quantitative measurement. Interestingly, two almost opposite approaches for representing categories have successfully accounted for the basic CP effect. One approach is to represent a category by its prototype—its most typical example or central tendency.[66,67] The other approach is to represent a category by its boundaries.[68] The category boundary approach represents categories by their periphery, not their center.

CP effects have been have been shown to emerge from either prototype or boundary representations. An item to be categorized might be compared to the prototypes of two candidate categories. Increased sensitivity at the category boundary would be because people represent items in terms of the prototype to which they are closest. Items that fall on different sides of the boundary would have very different representations because they would be closest to different prototypes.[13] Alternatively, the boundary itself might be represented as a reference point, and as pairs of items move closer to the boundary, it becomes easier to discriminate between them because of their proximity to this reference point.[18]

Computational models have been developed that operate on both principles. Following the prototype approach, Harnad et al.[69] describe a neural network in which the representation of an item is 'pulled' toward the prototype of the category to which it belongs. Following the boundary representation approach, Goldstone et al.[70] describe a neural network that learns to strongly represent critical boundaries between categories by shifting perceptual detectors to these regions; empirically, the results are mixed. Consistent with prototype representations, some researchers have found particularly good discriminability close to a familiar prototype.[71,72] Consistent with boundary representations, other researchers have found that the sensitivity peaks associated with CP heavily depend on the saliency of perceptual cues at the boundary.[25] Rather than being arbitrarily fixed, category boundaries are most likely to occur at a location where a distinctive perceptual cue, such as the difference between an aspirated and unaspirated speech sound, is present. A possible reconciliation is that information about either the center or the periphery of a category can be represented, and that boundary information is more likely to be represented when two highly similar categories must be frequently discriminated and there is a salient reference point for the boundary.

Massaro[73] and Massarro & Cohen[74] have developed a fuzzy logical model of perception (FLMP) that produces results that others have taken to be indicative of CP, even though the model assumes completely continuous perceptual information. In particular, FLMP predicts increased sensitivity to discriminations along boundaries between categories. In FLMP, continuous perceptual information from different dimensions is integrated together, and classification of an item depends on the relative similarity of the perceptual information to each of the candidate categories. Thus, the simple presence of sharp boundaries between categories is not sufficient to conclude that perceptual dimensions are perceived categorically or even nonlinearly.

In FLMP and similar models, categories are explicitly represented as alternatives and similarity of inputs to categories is a major determinant of perceptual judgments. This approach of explicitly representing categories is strongly contrasted to Beer's[75] dynamical systems approach of using genetic algorithms to evolve agents' nervous systems as they learn a task requiring them to catch circular objects and to avoid diamond-shaped ones. Learning produces equivalence classes based on shape and CP emerges through the coupling of the agent and environment even though no categorization is explicitly represented. The success of such a wide variety of learning and judgment models to explain CP effects have led researchers to argue that this effect may emerge out of any sufficiently powerful learning system.[76] This may not bode well for CP serving as strong diagnostic tool for choosing between competing models of cognition, but it does speak to the ubiquitous importance of the phenomenon.

CONCLUSION

The fundamental importance of CP to cognition, and how it is found across sensory modalities, levels of processing, and methods for characterizing differential sensitivity, overshadows the poor diagnosticity of CP for discriminating between formal models of cognition. It may be the case that multiple cognitive mechanisms, all capable of producing CP effects at different levels of processing, underlie the striking prevalence of CP effects ranging from differential sensitivity found in one-dimensional, low-level visual discriminations to equivalence classes for spoken words in highly varied dialects. In addition, the qualitative differences in the patterns of sensitivity changes, each of which is consistent with CP of visual objects, highlight the possibility of learning mechanisms producing CP effects at varying levels stimuli complexity.

The pervasiveness of CP across many cognitive domains, through innate or learned mechanisms, emphasizes the importance of the transformation of continuously varying sensory dimensions into quasi-symbolic equivalence classes for producing reliable behavior. This transformation of continuous to discrete is especially critical for language. Language, at both phoneme and word levels, tends to regularize object descriptions. Giving multiple objects the same label increases their subjective similarity, particularly if the objects are well fit by the label.[77] More generally, the existence of CP makes the theoretically important point that people organize their world into categories that, in turn, alter the appearance of this perceived world.

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REFERENCES

1. Harnad S. The symbol grounding problem. *Physica D* 1990, 42:335–346.
2. Sidman M. *Equivalence Relations and Behavior: A Research Story*. Boston, MA: Authors Cooperative; 1994.
3. Barsalou LW. The instability of graded structure: Implications for the nature of concepts. In: Neisser U, ed. *Concepts and Conceptual Development*. New York: Cambridge University Press; 1987, 101–140.
4. Thelen E, Smith LB. *A Dynamic Systems Approach to the Development of Cognition and Action*. Cambridge, MA: MIT Press; 1994.
5. Schusterman RJ, Reichmuth CJ, Kastak D. How animals classify friends and foes. *Curr Directions Psychol Sci* 2000, 9:1–6.
6. Goldstone RL. The role of similarity in categorization: providing a groundwork. *Cognition* 1994, 52:125–157.
7. Jones SS, Smith LB. The place of perception in children's concepts. *Cogn Dev* 1993, 8:113–139.
8. Sloman SA. The empirical case for two systems of reasoning. *Psychol Bull* 1996, 119:3–22.
9. Barsalou LW. Ad hoc categories. *Memory Cogn* 1983, 11:211–227.
10. Snodgrass JG. Concepts and their surface representations. *J Verbal Learn Verbal Behav* 1984, 23:3–22.
11. Rocha LM, Hordijk W. Material representations: from the genetic code to the evolution of cellular automata. *Artif Life* 2005, 11:189–214.
12. Harnad S. *Categorical Perception*. Cambridge: Cambridge University Press; 1987.
13. Liberman AM, Harris KS, Hoffman HS, Griffith BC. The discrimination of speech sounds within and across phoneme boundaries. *J Exp Psychol* 1957, 54:358–368.
14. Pisoni D, Casserly E. Speech perception and production, *Cogn Sci* 2010 (submitted).
15. Pollack I, Pisoni DB. On the comparison between identification and discrimination tests in speech perception. *Psychon Sci* 1971, 24:299–300.
16. Pisoni DB, Tash J. Reaction times to comparisons within and across phonetc categories (1974). *Percept Psychophys* 1974, 15:285–290.
17. Pisoni DB. Auditory and phonetic memory codes in the discrimination of consonants and vowels. *Percept Psychophys* 1973, 13:253–260.
18. Pastore RE. Categorical perception: some psychophysical models. In: Harnad S, ed. *Categorical Perception*. Cambridge: Cambridge University Press; 1987, 29–52.
19. Pisoni DB. Identification and discrimination of the relative onset time of two-component tones: Implications for voicing perception in stops. *J Acoust Soc Am* 1977, 61:1352–1361.
20. McMurray B, Aslin RN. Infants are sensitive to within-category variation in speech perception. *Cognition* 2005, 95:B15–B26.
21. McMurray B, Tanenhaus M, Aslin R. Gradient effects of within-category phonetic variation on lexical access. *Cognition* 2002, 86:B33–B42.
22. Rosen S, Howell P. Auditory, articulatory, and learning explanations of categorical perception in speech. In: Harnad S, ed. *Categorical Perception*. Cambridge: Cambridge University Press; 1987, 455–490.
23. Eimas PD. Auditory and phonetic coding of the cues for speech: Discrimination of the [r-l] distinction by young infants. *Percept Psychophys* 1974, 18:341–347.
24. Eimas PD, Miller JL, Jusczyk PW. On infant speech perception and the acquisition of language. In: Harnad S, ed. *Categorical Perception*. Cambridge: Cambridge University Press; 1987, 161–195.
25. Kuhl PK, Miller JD. Speech perception by the chinchilla: voice-voiceless distinction in alveolar plosive consonants. *Science* 1975, 190:69–72.
26. Stevens KN. Constraints imposed by the auditory system on properties used to classify speech sounds: Data from phonology, acoustics and psycho-acoustics. In: Meyers TF, Laver J, Anderson J, eds. *The Cognitive Representation of Speech*. Amsterdam: North Holland; 1981, 61–74.
27. Kay P, Regier T. Resolving the question of color naming universals. *Proc Natl Acad Sci U S A* 2003, 100:9085–9089.
28. Regier T, Kay P, Khetarpal N. Color naming reflects optimal partitions of color space. *Proc Natl Acad Sci U S A* 2007, 104:1436–1441.
29. Logan JS, Lively SE, Pisoni DB. Training Japanese listeners to identify /r/ and /l: a first report. *J Acoust Soc Am* 1991, 89:874–886.
30. Lane H. Motor theory of speech perception: a critical review. *Psychol Rev* 1964, 72:275–309.
31. Repp BH. Categorical perception: Issues, methods, findings. *Speech Lang Adv Basic Res Pract* 1984, 10:243–335.
32. Strange W, Jenkins JJ. Role of linguistic experience in the perception of speech. In: Walk RD, Pick HL Jr, eds. *Perception and Experience*. New York: Plenum Press; 1978, 125–169.
33. Pisoni David B, Aslin Richard N, Perey Alan J, Hennessy Beth L. Some effects of laboratory training on

identification and discrimination of voicing contrasts in stop consonants. *J Exp Psychol Hum Percept Perform* 1982, 8:297–314.

34. Kuhl PK, Tsao F-M, Liu H-M. Foreign-language experience in infancy: effects of short-term exposure and social interaction on phonetic learning. *Proc Natl Acad Sci U S A* 2003, 100:9096–9101.

35. Liberman AM, Harris KS, Kinney JA, Lane H. The discrimination of relative onset time of the components of certain speech and nonspeech patterns. *J Exp Psychol* 1961, 61:379–388.

36. Miyawaki K, Strange W, Verbrugge R, Liberman AM, Jenkins JJ, et al. An effect of linguistic experience: the discrimination of [r] and [l] by native speakers of Japanese and English. *Percept Psychophys* 1975, 18:331–340.

37. Burns EM, Ward WD. Categorical perception—phenomenon or epiphenomenon: evidence from experiments in the perception of melodic musical intervals. *J Acoust Soc Am* 1978, 63:456–468.

38. Cutting JE. Plucks and bows are categorically perceived, sometimes. *Percept Psychophys* 1982, 31:462–476.

39. Bornstein MH. Perceptual categories in vision and audition. In: Harnad S, ed. *Categorical Perception: The Groundwork of Cognition*. Cambridge: Cambridge University Press; 1987, 287–300.

40. Bruner JA, Postman L. Perception, conception, and behavior. *J Pers* 1949, 18:14–31.

41. Sowden PT, Davies IRL, Roling P. Perceptual learning of the detection of features in X-ray images: a functional role for improvements in adults' visual sensitivity. *J Exp Psychol Hum Percept Perform* 2000, 26:379–390.

42. Biederman I, Shiffrar MM. Sexing day-old chicks: a case study and expert systems analysis of a difficult perceptual-learning task. *J Exp Psychol Learn Mem Cogn* 1987, 13:640–645.

43. Lawrence DH. Acquired distinctiveness of cues: I. Transfer between discriminations on the basis of familiarity with the stimulus. *J Exp Psychol* 1949, 39:770–784.

44. Waller TG. Effect of irrelevant cues on discrimination acquisition and transfer in rats. *J Comp Physiol Psychol* 1970, 73:477–480.

45. Gibson EJ. *An Odyssey in Learning and Perception*. Cambridge: MIT Press; 1991.

46. Goldstone RL. Perceptual Learning. *Annu Rev Psychol* 1998, 49:585–612.

47. Goldstone RL. Influences of categorization on perceptual discrimination. *J Exp Psychol Gen* 1994b, 123:178–200.

48. Livingston K, Andrews J, Harnad S. Categorical perception effects induced by category learning. *J Exp Psychol Learn Mem Cogn* 1998, 24:732–753.

49. Levin DT, Beale JM. Categorical perception occurs in newly learned faces, other-race faces, and inverted faces. *Percept Psychophys* 2000, 62:386–401.

50. Newell FN, Bulthoff HH. Categorical perception of familiar objects. *Cognition* 2002, 85:113–143.

51. Kikutani M, Roberson D, Hanley JR. What's in the name? Categorical perception for unfamiliar faces can occur through labeling. *Psychon Bull Rev* 2008, 15:787–794.

52. Rossion B, Schlitz C, Robaye L, Pirenne D, Crommelinck M. How does the brain discriminate familiar and unfamiliar faces?: a PET Study of face categorical perception. *J Cogn Neurosci* 2001, 13:1019–1034.

53. Goldstein J, Davidoff J. Categorical perception of animal patterns. *Br J Health Psychol* 2008, 99:229–243.

54. Bukach CM, Gauthier I, Tarr MJ. Beyond faces and modularity: the power of an expertise framework. *Trends Cogn Sci* 2006, 10:159–166.

55. Rosch E, Heider E, Olivier DC. The structure of the color space in naming and memory for two languages. *Cognit Psychol* 1972, 3:337–354.

56. Roberson D, Davidoff J, Davies IRL. Color categories: evidence for the cultural relativity hypothesis. *Cognit Psychol* 2005, 50:378–411.

57. Roberson D, Davies I, Davidoff J. Color categories are not universal: replications and new evidence from a stone-age culture. *J Exp Psychol Gen* 2000, 129:369–398.

58. Winawer J, Witthoft N, Frank MC, Wu L, Wade AR, et al. Russian blues reveal effects of language on color discrimination. *Proc Natl Acad Sci U S A* 2007, 104:7780–7785.

59. Roberson D, Davidoff J. The categorical perception of colors and facial expressions: the effect of verbal interference. *Mem Cognit* 2000, 28:977–986.

60. Ozgen E, Davies IRL. Acquisition of categorical color perception: a perceptual learning approach to the linguistic relativity hypothesis. *J Exp Psychol Gen* 2002, 131:477–493.

61. Franklin A, Drivonikou GV, Bevis L, Davies IRL, Kay P, et al. Categorical perception of color is lateralized to the right hemisphere in infants, but to the left hemisphere in adults. *Proc Natl Acad Sci U S A* 2008, 9:3221–3225.

62. Franklin A, Drivonikou GV, Clifford A, Kay P, Regier T, et al. Lateralization of categorical perception of color changes with color term acquisition. *Proc Natl Acad Sci U S A* 2008, 105:18221–18225.

63. Goldstone RL, Lippa Y, Shiffrin RM. Altering object representations through category learning. *Cognition* 2001, 78:27–43.

64. Notman LA, Sowden PT, Ozgen E. The nature of learned categorical perception effects: a psychophysical approach. *Cognition* 2005, 95:B1–B14.

65. Sigala N, Logothetis NK. Visual categorization shapes feature selectivity in the primate temporal cortex. *Nature* 2002, 415:318–320.

66. Posner MI, Keele SW. On the genesis of abstract ideas. *J Exp Psychol* 1968, 77:353–363.

67. Rosch E. Cognitive representations of semantic categories. *J Exp Psychol Gen* 1975, 104:192–232.

68. Ashby FG, Gott R. Decision rules in perception and categorization of multidimensional stimuli. *J Exp Psychol Learn Mem Cogn* 1988, 14:33–53.

69. Harnad S, Hanson SJ, Lubin J. Learned categorical perception in neural nets: implications for symbol grounding. In: Honavar V, Uhr L, eds. *Symbolic Processors and Connectionist Network Models in Artificial Intelligence and Cognitive Modelling: Steps Toward Principled Integration*. Boston, MA: Academic Press; 1995, 191–206.

70. Goldstone RL, Steyvers M, Spencer-Smith J, Kersten A. Interactions between perceptual and conceptual learning. In: Diettrich E, Markman AB, eds. *Cognitive Dynamics: Conceptual Change in Humans and Machines*. Mahwah, NJ: Lawrence Erlbaum Associates; 2000, 191–228.

71. Acker BE, Pastore RE, Hall MD. Within-category discrimination of musical chords: perceptual magnet or anchor? *Percept Psychophys* 1995, 57:863–874.

72. McFadden D, Callaway NL. Better discrimination of small changes in commonly encountered than in less commonly encountered auditory stimuli. *J Exp Psychol Hum Percept Perform* 1999, 25:543–560.

73. Massaro DW. Categorical partition: a fuzzy-logical model of categorization behavior. In: Harnad S, ed. *Categorical Perception*. Cambridge: Cambridge University Press; 1987, 254–283.

74. Massaro DW, Cohen MM. Evaluation and integration of visual and auditory information in speech perception. *J Exp Psychol Hum Percept Perform* 1983, 9: 753–771.

75. Beer RD. The dynamics of active categorical perception in an evolved model agent. *Adap Behav* 2003, 11:209–243.

76. Damper RI, Harnad SR. Neural network models of categorical perception. *Percept Psychophys* 2000, 62:843–867.

77. Lupyan G. From chair to "Chair": a representational shift account of object labeling effects on memory. *J Exp Psychol Gen* 2008, 137:348–369.

FURTHER READING

Anderson JA, Silverstein JW, Ritz SA, Jones RS. Distinctive features, categorical perception, and probability learning: some applications of a neural model. *Psychol Rev* (1977) 84:413–451.

Etcoff NL, Magee JJ. Categorical perception of facial expression. *Cognition* (1992), 44:227–240.

Stevens SS. *Psychophysics*. New York: John Wiley & Sons; 1976.