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The Myth of Categorical Perception

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Abstract

Categorical perception is likely the single finding from speech perception with the biggest impact on cognitive science. However, within speech perception, it is widely known to be an artifact of task demands. Categorical perception is empirically defined as a relationship between phoneme identification and discrimination. As discrimination tasks do not appear to require categorization, this was thought to support the claim that listeners perceive speech solely in terms of linguistic categories. However, 50 years of work using discrimination tasks, priming, the Visual World Paradigm, and Event Related Potentials has roundly rejected this account. This paper reviews the origins and impact of this scientific meme and the work challenging it. It discusses work showing that the encoding of auditory input is continuous, not categorical, and describes the modern theoretical synthesis in which listeners preserve fine-grained detail to enable more flexible processing. This synthesis is fundamentally inconsistent with categorical perception. This leads to a new understanding of how to use and interpret the most basic paradigms in speech perception – phoneme identification along a continuum and has implications for understanding language and hearing disorders, development, and multilingualism. This challenges the field to develop new ways to describe and measure speech categorization.

Keywords:

Speech Perception; Categorical Perception; Categorization; Gradiency; Theories of Speech Perception

I. Introduction

In the rich history of work on speech perception, Categorical Perception (CP) (Liberman et al., 1957; Repp, 1984) is a breakout. It is one of a few findings to have made a lasting impact outside of speech perception (Goldstone & Hendrickson, 2010; Harnad, 2003) and its influence has only grown (). CP is both an empirical phenomenon and a theoretical claim about the nature of the representations that support speech perception. Empirically, it is observed whenever discrimination (the ability to distinguish two stimuli) is affected by the presence of categories, usually, when discrimination is poorer for two tokens in the same category than for tokens that cross the boundary (despite similar physical distance). Theoretically, it has led to claims that perception is “warped” by the

presence of categories, and to the broader claim that “analog or continuous inputs are transformed into quasi-digital, quasi-symbolic encodings” (paraphrased from Goldstone & Hendrickson, 2010).

The problem is that both

claims are wrong. Speech

perception researchers who are

actively working on CP have known

this for many years (e.g., Massaro & Cohen, 1983; Pisoni & Lazarus, 1974). And yet long after

the seminal work ruling out CP (both empirically and theoretically), CP continues to live on a

sticky scientific meme¹. It exerts a strong influence on the way speech perception is conceived

Figure 1: Number of new citations in consecutive 5-year periods starting in 1955. Search was conducted on Google/Scholar with the term “categorical perception”

¹ Here, I don't mean a clever animated gif that bounces around the internet. Rather I use meme in Dawkin's original sense as a sort of sticky idea that persists because it fills a sociocultural niche, that is, an idea that has socio-cultural fitness.

in broader work on language development (Maurer & Werker, 2014), and communication disorders (Serniclaes et al., 2004) and neuroscience (Chang et al., 2010); and it continues to appear in other areas of perception (Beale & Keil, 1995; Franklin et al., 2008; Freedman et al., 2001), and in other species (Freedman et al., 2001; Green et al., 2020). Even within speech, the assumptions made by categorical perception often implicitly shape ideas about what an ideal listener should be aiming for, or our understanding of why an impaired listener may differ. And CP has left us with problematic and poorly understood tasks that are still used today for many purposes besides categorization research.

Despite the substantial work countering the claims of CP there are few (if any) accessible reviews that explain why it is wrong, or that wrestle with the consequences of the failure of CP for both our understanding of speech perception, and for the methods we use to study it. This may be why CP still appears unchallenged in many textbooks, and why so many subfields of cognitive science do not appear to be aware of its demise. Thus, the purpose of this review is to directly lay out the evidence against CP and for alternative conceptualizations of speech categorization. By doing so I hope to challenge speech researchers to think deeper about the basic problems of perceptual categorization, and to spur our friends and colleagues in these other fields to do the same.

Given the vast quantity of work on CP, this review is not exhaustive. I focus my review on work that has directly examined categorization in its “distilled” form (e.g., laboratory studies of monolingual typical adults)—my own area of expertise—and I lack the space and expertise to offer more than a superficial discussion of other fields. This is not to claim that the work I chose to focus on is uniquely reflective of speech perception in general, nor that it offers greater insight than the much larger variety of work in areas like sociolinguistics, speech pathology, development, L2 learning, and other fields that contribute to speech perception as a whole. I encourage the reader to consult those other literatures directly with these ideas in mind. Rather I focus on this subfield because this is where the key ideas challenging CP originated, and

where arose the largest body of literature that has directly sought to understand CP (rather than using it to make other insights). In many cases, it is this field where a critical breakdown in scientific story telling began.

This review is also a bit more blunt than is typical. The widespread view in the narrow community of researchers working on speech categorization is that CP is done, and there is no need to continue studying it: the apt titles of both Crowder's (1989) and Schouten, Gerrit and Van Hessen's (2003) papers say it all. However, the persistence of CP both in, and outside of, speech perception suggests the need for a more direct treatment. To be clear, I am not arguing that people do not **categorize** speech. In fact, the evidence for categorization is strong. Rather, as I lay out here, CP is a deeper claim about perceptual representations below the level of the category, and it is those claims that I attempt to refute here.

I start with a short overview of CP and its theoretical impact before discussing the evidence against it, and the modern theoretical accounts that require us to abandon CP. I then discuss areas of research where CP has led us astray and end with thoughts for the future.

II. Categorical Perception

Categorical perception (CP) simultaneously is defined as both an empirical phenomenon and a theoretical view of speech perception.

A. Empirical Definition of CP

CP is typically assessed in experiments in which listeners hear tokens from a continuum of speech sounds (e.g., spanning /b/ to /p/ in small steps). CP requires tasks that assess labeling (is each token a /b/ or a /p/?) and discrimination (are two tokens the same or different?). It is generally thought to be observed when three conditions are met: 1) listeners must show a sharp labeling function (Figure 2, dashed line): as the speech continuum advances, there is a sudden shift in the categorization; 2) listeners should be poor at discriminating tokens from the same

category; 3) they should be good at discriminating tokens that cross the boundary (solid line).

The first criterion is difficult to assess. Given a two alternative forced choice task, the psychophysical function cannot mathematically be linear: a listener cannot choose any category more than 100% of the time.

Thus, the function must reach asymptotes at either end, and even if it appears linear this is probably an artifact of where the endpoints are set. Thus, the classic sigmoidal curve associated with CP in fact, means very

Figure 2: Canonical results of a categorical perception experiment. On the X axis, step refers to step from a speech continuum, where step 1 might be a prototypical /b/ and step 10, a prototypical /p/. Identification (dashed line, left axis) is coded as the proportion of responses that match one of the endpoints. Here, 0 is /b/ and 1.0 is /p/, so that 0% responding indicates the participant consistently heard /b/. Discrimination is assessed between neighboring points (e.g., between step 1 and 2, 2, and 3, and so forth). The peak indicates that discrimination is better between steps 5 and 6 (spanning the boundary shown by the identification results) than between steps 1 and 2 (both /b/).

little other than that subjects had to make a forced choice task from a continuum. It is not and can never be evidence for CP. Moreover, the steepness of the function is similarly problematic.

While the strongest form of CP claims a perfect step function (a transition of 100% between the smallest possible distance), this has never truly been tested (e.g., with adaptive approaches that use increasingly smaller steps). Instead, researchers generally informally evaluate the slope and declare it steep. But the slope is in part related to the step size and the range of the continuum (Brady & Darwin, 1978; Rosen, 1979). By selectively testing a narrow range (or a small step size), a researcher could in principle create a sharper or shallower transition.

Moreover, across different speech cues, step is often meaningless and incommensurate (how does one compare a 5 msec Voice Onset Time [VOT] difference for a voicing continuum to a 40 Hz F1 difference in a vowel continuum), and there have been few attempts to standardize them

(see Box 1 for thoughts). Thus, for all intents and purposes, the first criterion cannot be rigorously evaluated.

The second and third criteria are often treated similarly loosely. Some have caricatured CP as requiring *no above chance within-category discrimination*. It has been pointed out that even the original demonstration of CP (Liberman et al., 1957) did not observe this (and in fact it found robust discrimination within the /g/ category). However, this characterization is not baseless. Indeed, Liberman et al. (1961) writes in the abstract to the second CP paper: “The perception of these stimuli is essentially categorical in that *S can hear no differences among the stimuli beyond those that are revealed by the phoneme labels* he applies to them.” Nonetheless, this high bar is not conventionally required to establish CP and many studies have collapsed the second and third criteria to the *relative* difference (discrimination is *better* for tokens that span a category boundary than those that lie within).

A more rigorous approach than comparing within- and between-category discrimination, is to directly predict discrimination from the labeling responses using formal models (Gerrits & Schouten, 2004; Liberman et al., 1957; Schouten et al., 2003). Such models start from the strong assumption that listeners perceive speech solely in terms of labels. Under this assumption, discrimination should be at chance if two tokens are labeled the same 100% of the time, and should increase if labeling of those tokens differs. The predicted discrimination function is generated from an individual subject’s labeling and can then be compared to the obtained discrimination. To the extent that they match, CP can be claimed. To the extent that discrimination exceeds predictions, some within-category sensitivity must be present. Again, perfect predictability need not be found to claim CP (e.g., identification and discrimination do not need to be 100% isomorphic), any influence of identification on discrimination is sufficient.

Using variants of this definition based on identification and discrimination, CP has been shown across a variety of speech contrasts including place of articulation (Liberman et al., 1957) and voicing (Liberman et al., 1961) in stop consonants, vowels (Van Hessen & Schouten,

1999) (though see Fry et al., 1962), liquid contrasts like l/r (Miyawaki et al., 1975), as well as the fricative/affricate contrast (Cutting & Rosner, 1974).

This definition of CP has not been consistently applied. First, many studies and presentations use the term Categorical Perception to refer to a steep labeling function alone (even as steepness itself is fraught); others use CP to refer to any experiment that asks subjects to label tokens from a continuum even with no discrimination measure. *This is wrong. We must end this rhetoric.* CP invokes a specific theoretical view of speech, which as I argue shortly, no longer holds. Thus, by invoking CP as a sort of shorthand for this approach, researchers are unintentionally making stronger claims about perception than they intend. Even as a purely methodological term, these studies are simply measuring categorization—not CP.

Second, in other cases, CP is sometimes claimed on the basis of discrimination data alone in the absence of a labeling task. This is commonly the case in the infant literature where most infant measures only permit a measure of discrimination (see McMurray, in press, for a review); however, it also applies to neuroimaging techniques that use approaches such as the mismatch negativity in EEG or representational similarity analyses to construct a neural version of discrimination, but without any corresponding neural version of identification. Such practices risk affirming the consequent: we know a particular profile of discrimination is consistent with CP; CP requires categorization; therefore, when that profile is observed, we can assume categorization. However, as I describe shortly, the evidence against CP as an empirical description of adult speech perception is now substantial and in retrospect the evidence for it appears weaker than one might think. If we remove CP from the derivation chain, it is not clear what can be concluded from discrimination alone.

B. Theoretical Implications of CP

CP is more than an interesting empirical phenomenon—it makes deep theoretical claims about speech. In fleshing out these claims, CP starts from a model of speech recognition with (at

Figure 3: A rough conceptual model of the speech chain assumed by CP. Speech input is first mapped to a continuous auditory encoding that represents something like continuous cue-values. This space is then carved into categories.

specific cues, and most likely this level is a multidimensional representation across multiple cues. Critically, this level of representation is continuous: at some level it preserves the gradient nature of the input in a way that reflects acoustic similarity. Second, cues are then carved into categories like phonemes, features, or words. In the framing of CP, *perception*, refers to the continuous auditory encoding, and categorization is a later cognitive process operating on perception. This is an important contrast from the more modern (looser) use of these terms where perception might include a wide range of processes, including categorization.

What are the consequences of this framing for the empirical paradigm of CP?

Discrimination tasks do not require labeling. For example, in the ABX task used by Liberman et al. (1957), listeners hear two sounds that are different (the A and B sounds) followed by a third that matches one or the other. They indicate which of the first two matches the third. For example, if they heard “ba pa pa”, the correct answer is #2. In principle, a listener could perform this task this without categorical labels; if they heard ba ba ba (where the underline indicates a

lower pitch), they could correctly identify the second as the match. Thus, discrimination tasks were presumed to tap the auditory level of encoding.

If we assume that discrimination only reflects the auditory level, CP makes a bold claim: that the fundamental encoding of the continuous cues is altered or warped by perception: tokens from different categories are heard as further from each other, and tokens from the same category are closer in perceptual space. This violated Weber's law (that perceptual distance is a monotonic function of stimulus distance), as perception is "warped" toward a more discrete representation of speech. In some ways this can be seen as a form of perceptual constancy – despite differences in the phonetic cues, stimuli are perceived as the same (as long as they are within the same category). The perceptual warping reflected by CP was a view that was well suited for its moment in the history of cognitive science for two reasons.

First, at this time, work at Haskins Laboratories, the Massachusetts Institute of Technology, and Brown University was starting to flesh out *the problem of lack of invariance* (Blumstein & Stevens, 1979; Delattre et al., 1955): the idea that variability due to talker differences, speaking rate, and coarticulation makes it such that there is no one-to-one mapping between an acoustic form and an underlying category. This is illustrated in Figure 4 which shows a set of measurements of /s/ and /ʃ/ across multiple vowels and talkers by Jongman et al. (2000). Figure 4A shows the raw values along with the boundary computed from a discriminant analysis. Note the considerable overlap between the categories; this is created by the fact that this corpus contains 20 different talkers and 6 different coarticulatory contexts (the neighboring vowel). Figure 4B shows these same measurements transformed by a simple version of CP which warps these measurements to enhance between-category distance and minimize differences within the category. Here, tokens to the left of the discriminant boundary are shifted leftward and upward (the reverse for those on the right), and the variance within each category was halved. This illustrates how CP could alter the auditory representation to highlight categories (I discuss 4C and D later). The critical idea is that CP seems to make the problem of

Figure 4: A) Spectral mean and F2 onset frequencies for /s/ and /ʃ/ from Jongman et al. (2000). The line represents a linear discriminant analysis that can separate the categories at about 92%. B) A simulation of CP generated by assuming the linear boundary in A, and then doubling the distance between tokens on each side of the boundary and halving the variation within each side of the boundary; C) A simulation of CP generated by only increasing the distance, without adjusting within-category variation. D) Same data after compensating for talker and vowel differences using the regression approach of C-CuRE (McMurray & Jongman, 2011); the discriminant analysis achieves 96.6% accuracy.

invariance less challenging. CP does not solve this problem—in fact the few tokens on the other side of the boundary are now misclassified in even more extreme ways. However, it may make the initial percept more robust against later noise. More broadly, at the time it was discovered, the empirical evidence for CP implied that listeners may be equipped with mechanisms that are specialized for speech to solve the problem of lack of invariance (by some means).

Second, in the late

1950s, the cognitive revolution was underway. In fact, Chomsky's (1959) review of Skinner's (1957) *Verbal Behavior*, which in part sparked this revolution, was published shortly after the seminal CP paper (Liberman et al., 1957). The cognitive revolution argued for a view of cognition that was built on symbolic operations. CP supported this symbolic view by arguing for the existence of mechanisms that rapidly transduce the continuous signals into discrete categories. Moreover, as research on CP developed, it became linked to other key ideas in the cognitive revolution: for example, it may be innate and specific to speech (Liberman et al., 1967). Supporting this special mode of speech perception, there were early demonstrations that CP could be observed with speech, but not non-speech sounds that capture similar acoustic

relationships (Liberman et al., 1961) (and see Cutting & Rosner, 1974, for a nice review of these early attempts to find CP in non-speech analogues).

As I describe, the place of CP in arguing for “speech is special” claims did not hold up: it appears with a variety of non-speech auditory stimuli, in many other domains, and in other species. Nevertheless, the broader theoretical claim has persisted: that the perception of continuous acoustic representations is warped by higher-level language knowledge and in a way that support categorization. A variety of mechanisms have been posited to account for CP.

One early prominent account is that CP derives from natural **discontinuities in the auditory system** itself (e.g., discontinuities in perceiving any time difference near 20 msec, the typical VOT boundary); this was supported by work showing CP in non-human animals (Kuhl & Miller, 1975), and by work with new non-speech analogues that capture similar acoustic dimensions (e.g., tone-onset-time as an analogue of VOT) and that showed similar discrimination peaks to CP, and boundaries at similar locations to those of speech continua (Cutting & Rosner, 1974; Pisoni, 1977). Auditory discontinuities were also supported by later electrophysiological work using direct recordings from auditory cortex (Steinschneider et al., 1999). Under this view, languages evolved to take advantage of these inherent discontinuities.

The discontinuity approach, however, was unlikely to fully explain the phenomenon. First, this work focused on a handful of phonetic contrasts (largely voicing and place of articulation in stop consonants) and it is not clear if auditory discontinuities could be found for many other phonemic contrasts needed to fill out a language. Moreover, languages vary in where they place their boundaries, and it is not clear if discontinuities would line up cross-linguistically. If CP derives from such discontinuities and if CP is invoked as a general theory of speech perception, these facts must be explained. Second, some empirical results with non-speech analogues have not held up to scrutiny and may derive from methodological confounds (c.f., Rosen & Howell, 1981). Third, animal models are problematic as animals must be extensively trained to do these tasks. CP in animals could be an artifact of learning, not an

305 inherent property of the auditory system.

306 One compelling alternative account of CP was that the auditory space is **warped by**
307 **learning**. Overtraining on particular classes of sounds (over development) has led the system to
308 devote more representational or neural space to certain subregions of the acoustic space
309 (Guenther & Gjaja, 1996; Liberman et al., 1961). This still posits the same fundamental
310 discontinuity in the auditory system that is the basis of CP, but its origin is learning. In some
311 ways, this is more parsimonious as it can in principle apply to any speech sound or to any set of
312 boundaries used by a given language. It is supported by work, for example, showing that CP
313 peaks align closely with the language of the listeners: Japanese listeners, for example, show no
314 discrimination peaks in an /l/-/r/ continuum while English speakers do (Miyawaki et al., 1975);
315 similarly with non-speech sounds, the degree of CP for a major/minor continuum is related to
316 the amount of musical experience (Howard et al., 1992). This has been instantiated in neural
317 models (Gauthier et al., 2007; Guenther & Gjaja, 1996) and empirically examined with MRI
318 (Guenther et al., 2004), suggesting plasticity in neural “maps” (of the continuous acoustic space)
319 such that more representational space is given to categories.

320 In a similar vein, CP may derive from an **interactive feedback loop** (Anderson et al.,
321 1977; McClelland & Elman, 1986) (and see Lupyan, 2012 for extensive discussion of this idea in
322 visual CP); that is, as the system settles on one choice, activation at the category level feeds
323 back to earlier levels of analysis, aligning the perceptual representation with the category
324 decision. This can be seen as an indirect effect of learning (since the initial decision is grounded
325 in learning), but one that doesn’t alter the inherent structure of the auditory representation;
326 rather it is functionally altered in real time as perception and cognition align.

327 Whatever the theory, the strong assumption of CP is that the perceptual space (defined
328 by CP as the pre-categorical, auditory encoding) is at least partially discontinuous. The depth of
329 this assumption is perhaps illustrated by the TRACE model of speech perception and word
330 recognition (McClelland & Elman, 1986). This model was built on fundamentally different

assumptions about cognition from the information processing view: it rejects both the need for discrete symbols, and the specialness of speech. Yet McClelland and Elman still felt the need to extensively explain CP (pp. 43-50) as a product of competition. This has left a consensus – reflected in virtually all psycholinguistics and phonetics textbooks -- that whatever the mechanism, the auditory encoding does not faithfully reflect the input and is warped in a way to rapidly transduce auditory input to something that is quasi-discrete.

C. Beyond Speech

This formulation has now extended beyond speech. CP has been shown in complex auditory domains such as musical categories (Howard et al., 1992; Locke & Kellar, 1973). It has appeared in several domains of visual perception including lower-level visual cues like color (Bornstein & Korda, 1984) and line orientation (Quinn, 2004), and to higher-level visual stimuli like faces (Beale & Keil, 1995), facial emotion (Hess et al., 2009), and object categories (Newell & Bülthoff, 2002). It has been shown in the tactile and haptic (touch) perceptual systems (Gaißert et al., 2012; Knight et al., 2014). And it has even been observed in students' judgements of p-values (Rao et al., 2021), a domain in which *perception* is hardly relevant! It has been shown in a variety of species, often for species-relevant signals (e.g., birdsong) (Lachlan & Nowicki, 2015; May et al., 1989; Wyttenbach et al., 1996), suggesting a general adaptation that is a consequence of learning meaningful signals.

This work outside of speech has enriched the debate. It would be surprising (though not impossible) if fundamental perceptual discontinuities appeared in all of these domains, supporting theories based on learning and/or feedback. Moreover, this research has revealed unequivocally that CP is at least a partially learned phenomenon (also consistent with the feedback hypothesis). For example, it appears for familiar but not unfamiliar faces (Beale & Keil, 1995) and it can be invoked by learning new faces (Goldstone et al., 2001). It appears in musical chords only for musically trained people (Howard et al., 1992). And CP in color vision is

linked to the specific color terms of the participant's language (Roberson et al., 2000), and developmentally linked to learning the color words (Franklin et al., 2008).

In these domains, CP has often been used to support similar viewpoints as in speech: that a given domain is handled by a system that transduces a continuous sensory space to categories (Knight et al., 2014), often by specialized mechanisms. For example, inverted faces are often used in studies of whether there are face-specific processing modules and CP is reduced (or eliminated) in inverted faces (McKone et al., 2001) (though see Levin & Beale, 2000). Similarly, hemispheric asymmetries are often invoked to argue for a role of language, and color CP is stronger when stimuli are presented to the right visual hemifield (Franklin et al., 2008), which projects most strongly to the left hemisphere. In fact, the power of the CP metaphor for rapidly transducing a noisy signal to an abstract quasi-symbolic code has led to the broader claims that it is foundational to cognition (Harnad, 2003)!

D. But...

CP appears to offer a compelling package. The work reviewed so far suggests CP is a domain-general (and maybe species-general) mechanism in which learning warps the perceptual space in a way that may help deal with the substantial variability in the input.

Unfortunately, it is wrong.

The empirical evidence for CP is not strong, and the theoretical views it inspired is fundamentally inconsistent with modern theories of speech. This is not to rule out categorization as an essential aspect of speech perception. Rather, what's wrong is the deeper claim about auditory/perceptual encoding. In making this argument I address two claims. First, is the direct claim of CP for sensory warping (Section III). Second, is the broader claim about the functional goal of transducing speech to quasi-discrete categories (Section IV). While this latter point is direct evidence against CP, it is evidence against the broader view of speech rooted in CP.

III. CP is an inaccurate empirical description of perception

Compelling evidence against CP as an empirical phenomenon is found in several lines of work.

A. CP is not universal across speech sounds

From the beginning, it was known that CP was not observed for all speech contrasts. Early studies with vowels did not show CP (Fry et al., 1962) (though Van Hesson & Schouten, 1999, later showed that you can with the right stimulus manipulations), with no difference between within- and between-category discrimination and fricatives show reduced CP (Healy & Repp, 1982), less of a difference than would be expected. More recent work has shown non-categorical perception for Mandarin tones (Francis et al., 2003). Idiosyncratic findings of CP are also seen in vision: Newell and Bühlhoff (2002) report CP across only a subset of visual objects.

It might be easy to chalk these cases up as exceptions to a general principle of CP. This is problematic for three reasons. First, the number of speech sounds for which CP has been shown is not large. Much of the work has examined only stop consonant place and voicing. There are large swaths of the phonetic space that have not been systematically examined: many vowel contrasts, nasals, some approximants, and some manner of articulation distinctions. Consequently, it is not clear if the contrasts showing non-categorical perception are the exceptions, or if the cases showing CP are! Second, if CP derives from a learned warping or feedback mechanism (which appear to be the dominant accounts at the moment), why do these mechanisms not operate for all sounds? It's not clear how the general principles invoked by CP interact with the specifics of the phonetic cues to give rise to such idiosyncratic effects. Finally, these findings are inconsistent with the theoretical view that CP reflects adaptations designed to help cope with the problem of lack of invariance. Vowels, fricatives and tones all show some of the strongest contextual dependencies due to talker and coarticulatory differences. These are the contrasts for which lack of invariance is arguably a more serious problem. If CP is supposed to be part of the solution to lack of invariance, why is it not seen for these phonemes?

409

410 **B. Discrimination is not categorical...**

411 A more direct challenge to CP comes from work explicitly assessing discrimination tasks. The
412 classic work on CP relies on the previously described ABX task. Ostensibly, this task does not
413 require labeling. However, it has a high memory load – listeners must encode both the A and B
414 stimulus and retain them, to compare them to the X stimulus. Here, a phonological code may be
415 a more efficient and durable form of encoding than an auditory one. That is, if the auditory
416 (perceptual) code fades, all that may be left is the categorical one. Under this view, the
417 discrimination peaks seen in standard CP experiments do not reflect categorical *perception*, but
418 rather, categorical *memory* or categorical *judgements* (Pisoni, 1973).

419 In response, this led to detailed analyses of the discrimination tasks that were used to
420 assess CP (Macmillan et al., 1977; Pollack & Pisoni, 1971); these generally led to the
421 conclusion that the ABX and AX (same/different) tasks were perhaps the least suited for
422 assessing pre-categorical auditory encoding, as they are both memory-intensive, and have
423 unclear response criteria (e.g., a subject could choose to respond at a phonemic or auditory
424 level). This led to the development of discrimination tasks that are less memory-intensive or
425 biased. For example, in an “oddball” task participants hear three stimuli and identify which one
426 differs. This reduces memory demands since listeners only need to remember one token at any
427 given moment. Carney et al. (1977) used this task to show substantial within-category
428 discrimination, and no discrimination peak at the boundary. Perhaps the least biased task is the
429 4AIX task (which is highly similar to Gerrit & Schouten's 2004, 2IFC task). In this task,
430 participants hear two pairs of stimuli, one of which differs and the other is a perfect match, and
431 their job is to indicate which pair matches. Pisoni and Lazarus (1974) first demonstrated non-
432 categorical perception with this task (no difference between within- and between-category
433 discrimination). More impressively, Schouten, Gerrits and Van Hessen (Gerrits & Schouten,
434 2004; Schouten et al., 2003) first conducted a series of experiments to establish nearly perfect

CP (perfect predictability of discrimination from identification) with a standard ABX task. When they then switched to the 4AIX/2IFC task, there was no evidence for CP – discrimination was not predicted by identification. Thus, even playing by the rules of CP, there is no evidence for a warping of discrimination when we properly understand the demands of the discrimination tasks.

As our understanding of discrimination tasks grew, Pisoni developed an insightful analysis that

undercuts the premise of using any discrimination task to infer CP (Pisoni, 1973; Pisoni & Tash, 1974). Again, he starts from a conceptualization of speech perception as a series of transformations from the continuous perceptual signal to categories like phonemes or features (Figure 5, left pathway). The typical assumption of CP is that discrimination tasks primarily tap the continuous perceptual space. However, what if discrimination judgements involve both perceptual and category information (Figure 5, right pathway)? Under this assumption, a within-category contrast has essentially one source of evidence favoring discrimination (any auditory difference), while a between-category contrast has two (the auditory difference + the difference in labeling) (Figure 5, embedded table). That is, even if the internal perceptual difference is equivalent for within- and between-category contrasts (no sensory warping), one should still observe CP.

This model has a radical consequence: CP (as an empirical finding) should be evident,

Figure 5: The Pisoni and Tash (1974) model of discrimination. Speech is transduced to a continuous perceptual space, then to categories and words (left branch). Discrimination, however, can use either the perceptual or category representation (right branch). Under these assumptions, between-category contrasts should almost always be more discriminable than within (embedded table), even if the perceptual encoding is continuous.

461 *even if auditory perception is continuous!* Any differences among discrimination tasks in their
462 ability to show CP or non-CP may derive from differences in the degree to which a given task
463 (or stimulus) differentially emphasizes category-level or perceptual-level information when
464 making the judgment. But CP can be seen even in the absence of a warped auditory encoding.
465 This is a powerful argument—largely ignored by much of the literature—suggesting a
466 fundamental limit in the degree to which the combination of identification and discrimination can
467 tell us anything about CP as a theory of speech (see also Massaro & Hary, 1984).

468 Critically, this argument makes it clear that a) there will be differences in the degree to
469 which discrimination tasks show CP-like performance; but b) some discrimination tasks (ABX
470 and AX) do not accurately isolate pre-categorical perceptual encoding; d) in many cases, a CP-
471 like profile of discrimination can be predicted even in the absence of true categorical perception;
472 and consequently. As a result of this there, turns out to be little clear unambiguous positive
473 evidence for CP from the very tasks that define it. This does not rule out CP, but it leaves us
474 with little evidence for it. This prompts the need for methods to better isolate auditory encoding.

476 **C. ...and perception is continuous (mostly)**

477 Pisoni and Tash (1974) argue that discrimination tasks may not reveal the continuous or
478 categorical nature of the auditory-perceptual space. To do this we must assess the perceptual
479 space more directly. Massaro and Cohen (1983) proposed an innovative way to do this.
480 Subjects used a continuous rating scale to rate how /b/-like or /p/-like the stimulus was (they
481 also tested place of articulation and vowels). Unlike a traditional forced choice labeling task, this
482 task can potentially reveal the degree to which listeners track the continuous input. When
483 averaged across trials, such measures were predicted to show the standard sigmoidal function;
484 however, Massaro and Cohen argued that a sigmoidal function could derive from one of two
485 underlying models (Figure 6) that can be revealed by examining the distribution of responses.

486 If listeners encode speech categorically, they should not hear continuous differences

Figure 6: Distribution of rating scale responses for individual subjects as a function of continuum step (each row) from Massaro and Cohen (1983) (estimated from their Figure 7). A) Under a categorical model, listeners should use only the ends of the scale, and should only vary in how frequently they choose the /b/ or /p/ ends. B) Under a continuous model, the mean rating should shift with step. C) Estimated data from a typical listener.

likelihood of hearing one or the other may vary. In contrast, if listeners encode the continuous difference between tokens, one might expect the mean rating to advance linearly as the step increases (Figure 6B). Massaro and Cohen (1983) compared the fit of these two models to individual subjects and found the continuous model offered a better fit for most subjects. This provides strong evidence of a continuous underlying auditory percept— if it was warped, listeners would not have access to the continuous information for their ratings (for replications, see Kapnoula et al., 2021; Kapnoula & McMurray, 2022; Kapnoula et al., 2017; Kong & Edwards, 2011) (and see Apfelbaum et al., submitted, for further discussion of this task and the limits of the 2AFC task).

More recent work has used electrophysiology to more directly assess early auditory encoding. Building on prior work by Frye et al. (2007), Toscano et al. (2010) measured event related potentials (ERPs) from the scalp while listeners categorized tokens from a VOT

Figure 7: Results from (Toscano et al., 2010). A) Voltage at front-central channels as a function of time and VOT. The large negative deflection at 100 msec is the N1 and its depth is related to VOT. B) Mean N1 amplitude as a function of VOT.

continuum. They examined the N1, an early negative deflection of the waveform at around 100-200 msec that has been linked to some of the first cortical processing of sound. They found a linear relationship between the VOT of the stimulus and the amplitude of the N1 (Figure 7): shorter VOTs showed a more negative N1, which increased linearly with VOT. Critically, there was no effect of the subject's response, and no evidence for warping near the category boundary (see Sarrett et al., 2020; Toscano et al., 2018, for a replication) (Getz & Toscano, 2021, for a review). This offers clear evidence that at the earliest stages of perception (100 msec in), the encoding of speech is not warped by the presence of categories.

Given these results, what is to be made about prior neuroscience results suggesting warping? For example, direct recordings from the human auditory cortex (Steinschneider et al., 1999) show a discontinuity such that lower VOTs have a single negative deflection, while longer VOTs have two. Such a discontinuity appears to accord with some kind of warping. However, for long VOTs, these two deflections linearly tracked the VOT – suggesting gradiency—and it is not clear whether the measurement techniques have the fidelity to distinguish two deflections at the lower VOTs where there the two peaks may be close enough to smear together.

Similarly, Chang et al. (2010) measured from superior temporal gyrus while listeners

heard a place of articulation continuum, and used a representational similarity analysis to demonstrate that tokens within a category were closer than those spanning a boundary (the classic definition of CP). However, that cortical region is also a locus of phonological processing (Mesgarani et al., 2014), raising the possibility that this measure does not isolate auditory encoding, but rather it may also reflect category representations. Such a model would be consistent with the Pisoni and Tash (1974) model in which there is a continuous perceptual encoding alongside a category representation and both contribute to discrimination (Figure 5)².

Finally, an intriguing challenge to linear cue encoding comes from work by Kapnoula and McMurray (2022). They also applied the N1 paradigm of Toscano et al. (2010), but examined individual differences by relating the N1 response function to the degree of gradiency shown in a VAS task (e.g., Figure 4). They found that more categorical listeners showed a small bump at the category boundary; while gradient listeners were linear. However, even the categorical listeners still encoded continuous detail *within each category*. That is, there was a strong linear trend, with an additional change near the boundary. Thus, the presumed acoustic space of this subset of listeners would look more like the visualization in Figure 4C in which the distance between categories is expanded but without altering the ability to represent within-category detail. Such models – which may only apply in some listeners – are not commonly considered in the CP pantheon, though they are potentially consistent with it. In principle, if the N1 is picking up phonological representations from STG, this may be consistent with the Pisoni and Tash (1974) model (linear cue encoding + categories). However, no existing models are equipped to account for such differences at an individual level, raising the need for further investigation.

D. ... And meanwhile in other subdomains.

Outside of the small community of researchers actively working on CP, CP appears (at least to

² Notably, Pasley et al (2012) used similar recordings from STG to reconstruct the spectro/temporal form of heard speech. This would not have been possible with the information loss implied by CP.

me) to offer a less than compelling model, and one that is often bypassed to do useful work. For example, sociolinguistic variation (gender, dialect and identity marking) often relies on within-category variation to signal identity. If auditory representations were warped to minimize such variation, how could this important function of speech be communicated, and how could children learn to produce these markers? Similarly, speech pathologists, second language teachers and dialect coaches, must often hear fine-grained differences within a category to help clients achieve more canonical productions. Again, CP would seem to work against this important function of speech perception. I return to some of these points in the next section.

E. Summary

The foregoing discussion challenges CP as an empirical phenomenon at every level. CP does not appear uniformly across speech contrasts, challenging its generality as a model of perception and raising questions about which is the more common pattern. The discrimination tasks commonly used to establish CP have deep issues of memory and bias, and when these are eliminated, perception is not categorical. Moreover, the Pisoni and Tash (1974) model (Figure 5) convincingly argues that if we eliminate the assumption that discrimination *only* assesses the perceptual space, then CP can be observed even if that space is non-categorical (linear). The underlying representation of the continuous space – revealed by both continuous ratings and by neurophysiological measures – appears linear. And auditory perception must do more than simply yield categories, and long-recognized listening skills like talker or dialect recognition attest to the fact that some within category is preserved, and may be more difficult if we assume CP. There's no reason to hold on to CP anymore and by abandoning it, we can achieve a much more coherent and compelling theoretical account of speech recognition.

IV. Speech Categories are not quasi-discrete (and that's good)

Categorization is a small part of a system that must ultimately recognize meaningful units—

phonemes, words, intention, emotion and social identity—from a continuous and variable system. CP makes claims that both the level auditory representations and the level of categories are quasi-discrete. At the time, this aligned with broader thinking in how the problem of speech perception is solved. However, at both levels, new (and old) thinking suggests that the solution implied by CP is not how listeners approach speech perception. This evidence is built on the idea that speech categorization is a gradient process. As I describe, this claim, in and of itself, does not constitute strong evidence against weaker forms of CP. However, it does challenge the broader view of speech implied by CP.

A. Speech Categories are Gradient

CP implies that the goal of the perceptual system is to transduce a continuous signal to something resembling a discrete category. However, substantial empirical work suggests that the end result is not discrete, but gradient, and that this may be important.

The earliest work on this comes from Joanne Miller and colleagues (Miller & Volaitis, 1989) (Miller, 1997, for a review). They used a task in which listeners heard tokens from a speech continuum with a large range and rated how good of a /p/ each exemplar was. With the large range, some tokens would be a /b/ and rated low, others were near typical values for a /p/, and yet others were quite extreme, but not consistent with another speech sound (e.g., a VOT of 150 msec). This allowed a visualization of the “structure” of the entire category. Critically, this revealed that speech categories have a highly gradient, prototype-like structure and this entire structure – not just the boundary—was sensitive to contextual factors like speaking rate (Miller & Volaitis, 1989) (see Figure 8A). Moreover, the structure and shape of these goodness ratings roughly align with the distributions of VOTs that listeners experience (Figure 8B)—listeners categorize speech in a way that is sensitive to the statistical distributions of those cues.

It is possible that early representations of phonological categories are gradient but are transformed into something more discrete before accessing higher-level units like words. This

was disconfirmed by later work by Blumstein and colleagues (Andruski et al., 1994; Utman et al., 2000). They used a cross-modal priming task to ask if small within-category differences in a target word (e.g., *king* with VOTs that were either prototypical or near the boundary) altered priming for a related word (e.g., *queen*). They found that even a small change in the VOT—which do not alter the perceived category—reduced priming, suggesting that gradiency in speech categories is preserved through the level of words.

Figure 8: Typical results of phoneme goodness rating experiments of Miller and colleagues (data estimated from Miller & Volaitis, 1989). A) /p/ goodness as a function of VOT and speaking rate (the length of the following vowel). B) Phonetic measurements showing the distribution of VOT as a function of speaking rate.

One concern with both the priming and goodness rating techniques is that they could represent an average of different types of trials. For example, in the Andruski et al. (1994) paradigm, on some trials, *king* may be fully active and shows full priming of *queen*, but on other trials it may be inactive (the listener thought they heard *ging*) and shows no priming. Critically, more of the trials when the VOT was close to the category boundary should fall into this latter group (in which *king* is inactive). This could attenuate the priming effect on the average, even if the priming effect on any individual trial was the same across VOTs (an averaging artifact). This would be consistent with CP, but with noise from trial to trial. To rule out this concern, one needs a technique that queries which category the listener heard on that trial, while simultaneously assessing the degree of underlying activation for that category.

A number of studies have accomplished this using the Visual World Paradigm (VWP) (McMurray, Aslin, et al., 2008; McMurray et al., 2002). In these studies, listeners hear a token from a speech continuum spanning two words (e.g., *beach* and *peach*), and click on the

corresponding picture. Critically, on each trial, the words and their locations change, necessitating one or more eye-movements to plan the motor response. These fixations can reveal the underlying activation of a word. For example, if the listener heard *beach*, fixations to the *peach* prior to the response can indicate how active this competing word is.

These studies have taken several steps to rule out the averaging artifact. First, each subject's own category boundary was computed from their identification data, and all data were recoded relative to that boundary. Here, -5 msec of VOT then refers to 5 msec from the boundary (toward /b/), and +10 is 10 msec toward /p/. This avoids the possibility that increased looking is driven by variation in the boundary across subjects. Second, the analysis of fixations is conditioned on the response by discarding trials in which the "incorrect" response was chosen. That is, given that the listener heard a sound on the /b/ side of their boundary, and that they ultimately reported a /b/, do competitor fixations nonetheless vary as a function of VOT?

With this analytic approach, these studies typically find a linear effect of VOT on competitor fixations. Figure 9A shows looks to the competitor (/p/ when hearing a token on the /b/ side of the continuum) as a function of time and relative VOT (from McMurray et al., 2002). As the VOT moves toward the boundary (at relative VOT=0), there are systematically more fixations to the competitor. Figure 9B shows the area under the curve and shows the same gradiency as a function of VOT (for replications, see Kapnoula & McMurray, 2022; McMurray, Aslin, et al., 2008; McMurray et al., 2014). This analytic approach has also been applied to an ERP index of categorization, the P3 (Kapnoula & McMurray, 2022; Toscano et al., 2010). Here, a stronger P3 indicates more robust categorization. As with the VWP studies, these analyses accounted for both the subject's boundary and their response on each trial and find a stronger P3 for more prototypical VOTs. Critically, these findings are highly robust across individuals. Kapnoula and McMurray (2022) tracked individual differences in the gradiency of a listener's speech categorization using the continuous VAS task and related it to both VWP and ERP/P3 measures. They found correlations between these measures: more gradient VAS responding

Figure 9: Results of VWP experiments documenting gradient within-category sensitivity to fine-grained detail. A) Fixations to the competitor as a function of time, and distance from the category for tokens on the voiced side of the continuum from McMurray et al. (2002). B) Average fixation from 200 to 2200 msec as a function of relative VOT in that study. C) 2AFC labeling function for children in McMurray et al. (2018); here, identification becomes steeper (more categorical) with development. D) In contrast, competitor fixations as a function of relative VOT show increasing sensitivity with development.

led to more gradient competitor fixations and P3s. However, critically, all listeners were gradient (see also Kapnoula et al., 2021), they just varied in degree.

The results from goodness ratings, the VWP and ERPs all suggest that speech categories are highly gradient—even when we control for the labeling on each trial and for variance in participants' boundaries. This provides indirect evidence against an entirely discrete representation at the auditory/perceptual level: if these representations were discrete, within-category detail would not be available to higher-level phoneme or lexical processes. This is not strong evidence against weaker forms of CP. It is possible that within-category discrimination is

reduced, but not lost, and yet is sufficient to support a gradient representation. The point is not that these kinds of results directly refute CP. Rather, gradiency conflicts with the more discrete results, commonly seen in 2AFC identification tasks, and it challenges the functional “goal” of speech categorization implied by CP. That is, the goal of speech perception is not to ignore irrelevant variation within a category but to systematically track it. Two extensions of this work highlight this fact in distinct ways.

First, this mismatch between the underlying [gradient] activation and the overt [categorical] labeling is highlighted by a recent developmental study. McMurray et al. (2018) tested children from 7 to 18 in a variant of the McMurray et al. (2002) paradigm. When we examined the identification curves (Figure 9C), we found increasingly steep categorization with development. This would appear to be consistent with a view in which children become increasingly categorical over development. By the standard view of CP, this implies they increasingly lose access to fine-grained detail. However, the fixations showed the opposite pattern (Figure 9D): the 7-8 year-olds (red curve) showed essentially no sensitivity to fine-grained detail, and this emerged in later years. Thus, rather than development leading to the loss of sensitivity, it appears that children achieve greater sensitivity to fine-grained detail with age, and this in turn enables apparently sharper categorization³. This undercuts a core assumption of CP but also suggests limits to 2AFC categorization (Apfelbaum et al., submitted).

Second, Myers et al. (2009) used fMRI to localize the neural basis of speech categorization. They found a highly gradient pattern in Superior Temporal Gyrus (STG)—an auditory/phonological area, but a more categorical response function in the inferior frontal gyrus, a down-stream language area (see also Toscano et al., 2018). This supports a model closer to that of Figure 5 in which the system maintains both a continuous perceptual representation of the signal (in earlier areas like STG), and something more abstract and cognitive (in IFG).

³ This mirrors work by Van Hoesen and Milner (1967) which found that increasing the quality of the continuum—enhancing access to fine grained detail—led to sharper categorization and more robust CP.

B. ...and Gradiency is Helpful

Modern theories of speech perception all agree that auditory input is represented continuously, and that activation for categories is gradient. This is true for a wide variety of theories from radically different theoretical groundings, including theories from an information integration perspective (McMurray & Jongman, 2011; Nearey, 1997; Oden, 1978), connectionism (McClelland & Elman, 1986), Bayesian/ideal observer frameworks (Kleinschmidt & Jaeger, 2015), auditory accounts (Kluender et al., 2003), and exemplar theories (Goldinger, 1998). This is for a good reason – many of these theories posit representations or operations that are simply incompatible with a discontinuous auditory input or a discrete category. CP is fundamentally about *losing or reducing access to (within-category) information in the signal*, while all of these theories attempt to maximize how this information is maintained and used.

It is beyond the scope of this paper to attempt a detailed review of all of these theories. However, it is important to discuss the general principles, the facts about speech, and the empirical results that argue that gradient representations at every level are beneficial for solving the challenging computational problem of speech perception. In this section, six perceptual problems illustrate the inconsistency between CP as a theoretical account, and the way most people now think about speech, and they augment arguments for the gradient alternative.

1. Cue Integration.

It has long been known that multiple cues contribute to phonemic percepts (Lisker, 1986; Oden & Massaro, 1978; Repp, 1982). For example, voicing is primarily cued by VOT (in English), but factors like F0, F1 frequency, the length of the subsequent vowel and the preceding speaking rate all contribute. These sort of trading relationships often appear as a shift in the boundary along a primary dimension (e.g., VOT) as a function of a secondary cue (Figure 10A). Critically, to perform these kinds of sensitive boundary shifts, listeners must be able to encode cues with a fairly high degree of precision. If all they heard was /b/ or /p/, it is not clear how this could occur.

Figure 10: A) Schematic results of a typical trading relations experiment examining voicing categorization (/b/ vs. /p/) as a function of VOT (x-axis) and F0 (separate curves). B) Schematic results of an experiment examining voicing categorization in younger and older children, or in disordered and typical children.

This argument has been used frequently – including by me (Kapnoula et al., 2017). However, the fundamental work on trading relations was not seen as inconsistent with CP (Repp, 1982). Part of the issue is the question of *what* is warped by CP: an individual cue (like VOT), or a multi-dimensional space. If cues are coded independently (and warped independently) this argument holds – if VOT is collapsed into /b/ or /p/, it cannot be integrated with F1 or F0 in any meaningful way because the fine-grained differences are lost. However, what if phonological dimensions are a composite across cues (e.g., a combination of VOT and F0), as a sort of two-dimensional space with a diagonal boundary (e.g., Figure 4A). Under this assumption, trading relations may come for free without the need for actively shifting the boundary. For example, in Figure 4A we could imagine a continuum of spectral mean (along the horizontal dimension) with an F2 onset of 1500 Hz. Here, the boundary should be around 5000 Hz; in contrast, with an F2 onset of 2500 Hz, the boundary needs to be at 6000 Hz. However, if we assume that the auditory representation is multi-dimensional, the spectral mean boundaries does not shift due to a secondary cue (F2); rather the multi-dimensional space is simply sampled along a different orientation (the diagonal). Critically, CP could operate over the entire space (Figure 4B), not on individual cues, and thus could be consistent with trading relations. While this appears to reconcile CP and trading relations, it may be insufficient for two reasons.

First, for most speech sounds, not all cues arrive at the same time. In word-initial voicing, vowel length arrives after VOT; for sibilant fricatives, formant frequencies arrive after the frication spectrum. A wealth of work suggests that listeners do not wait to integrate cues, but rather use each cue as it arrives (McMurray, Clayards, et al., 2008; Reinisch & Sjerps, 2013; Toscano & McMurray, 2015) (though see Galle et al., 2019). This means that even if the auditory space is multi-dimensional, at least for a brief period, some cues need to be coded in isolation. If CP operated then on these individual cues, it would be hard to integrate later cues when they arrived. Consequently, a gradient representation may be needed to avoid making an erroneous commitment on the basis of an initial cue while waiting for later cues.

Second, a number of studies have used an individual differences paradigm to assess this (Kapnoula et al., 2021; Kapnoula et al., 2017; Kong & Edwards, 2011; Ou et al., 2021). These experiments use a continuous rating scale similar to Massaro and Cohen (1983), now referred to as a Visual Analogue Scale (VAS) task (see Apfelbaum et al., submitted). Subjects' gradiency is quantified as a continuous estimate of their slope and this can be related to other measures. On balance, these studies show evidence for the hypothesis that gradient speech categories are functionally beneficial. Gradiency in VOT has been linked to the degree to which listeners also use F0 (Kapnoula et al., 2021; Kapnoula et al., 2017; Kong & Edwards, 2011; Ou et al., 2021); and gradiency in tracking formant frequencies has been correlated with the use of duration in vowel judgements (Ou et al., 2021); however, correlations have not been observed for other cue combinations such as fricative spectra and formant transitions, or VOT and vowel length (Kapnoula et al., 2021). This may derive from issues such as when the cues arrive (relative to each other), or whether cues are coded independently or in some kind of multi-dimensional space (see also Toscano & McMurray, 2010). However, for at least some cues, the claim that a gradient representation is linked to better cue integration is observed empirically.

2. Accounting for Context.

A related phenomenon is context. Phonetic boundaries also shift as a function of factors that

themselves do not directly cue a phoneme. For example, listeners can shift fricative boundaries depending on the talker (Strand, 1999) or neighboring sounds (Mann & Repp, 1981). This is distinct from trading relations. Whether or not a speech sound was spoken by a male or female does not directly inform the listener whether a sound is /s/ or /ʃ/. However, both physiological and sociolinguistic differences lead male and female talkers to produce these sounds differently. Consequently, listeners can do better if they can adjust their boundaries based on the context. As with cue integration, such operations require a fine-grained analysis of the signal, and they may require retaining early phonetic cues until later context arises – for example, in a fricative-vowel sequence, the talker identity may not be available until the onset of the vowel.

Work on the C-CuRE (Computing Cues Relative to Expectations) model of speech perception exemplifies the need for a fine-grained representation of the continuous cues to deal with context (Cole et al., 2010; McMurray & Jongman, 2011). In this model, phonetic cues are encoded continuously, but they are adjusted relative to contextual expectations. For example, an F0 of 160 Hz is recoded as 40 Hz below the expected pitch for a woman (200 Hz). Critically, when this simple strategy is applied to real phonetic measurements, it has been shown to account for virtually all the variance in F1/F2 measurements in a corpus of vowels featuring 10 talkers and multiple coarticulatory contexts. Moreover, McMurray and Jongman (2011) applied this to a large corpus of fricatives featuring all 8 fricatives, 20 talkers, and multiple vowel contexts (Jongman et al., 2000). They showed that a simple classifier model based on these adjusted cue-values could yield a pattern of performance that closely mirrored that of listeners (both in accuracy and the pattern of errors), while the same model trained on raw cues was both substantially less accurate and did not match listeners' patterns of errors. Figure 4D offers a visualization of the same fricative cues from 4A but after compensating for talker and vowel differences. Note here, that like the CP models, variance is reduced. But unlike those models, this variance is not just discarded; it was used to make inferences about the talker and the vowel. Moreover, discriminability is now increased. The discriminant analysis went from 92% to

96.6% correct, while preserving the continuous variability. Thus, it is possible to obtain the supposed benefits of CP without throwing away within-category detail (in fact, by harnessing it).

This work speaks to the value of a continuous representation of acoustic cues (contra CP). Given that any cue may be adjusted on the basis of multiple factors (talker, coarticulation), and by small amounts, the system must retain as close to a continuous representation as possible to get the most out of this form of processing. Critically, like CP this model does not posit a veridical representation of the cue: cue values are coded relative to internally generated expectations (e.g., this spectral mean is low for a woman). However, the fundamental operations are different: CP dichotomizes a dimension in a way that rather arbitrarily eliminates variability, whereas C-CuRE shifts the estimated cue value to more sensitively account for context. Again, these kinds of processes are not inconsistent consistent with a partial form of CP in which within category differences are reduced but not lost. But at the same time the nonlinearity imposed by the categories on the signal may add substantial noise, making this compensation accurate. Moreover, the nature of the compensation is at odds (harnessing variance) with the CP-inspired theoretical view (of ignoring it). Given this, what is the value of hanging on to CP in some kind of reduced form?

3. *Listeners do more than one thing with any speech cue.*

Perhaps the deepest challenge to CP is rooted in an observation made by Mermelstein (1978): every speech cue is used for more than one thing (see also, Smits, 2001; Whalen, 1992). For example, in English, vowel length may serve as a cue to speaking rate, it may distinguish tense and lax vowels, and it contributes to both syllable-initial and syllable -final voicing! This was a fundamental part of the indeterminacy that comprises the problem of lack of invariance: each cue value can be affected by multiple factors, and each factor affects multiple cue values.

The problem is that if a listener categorically warps the auditory input for one set of categories, he or she may lose information that could be used for another. For example, the spectral mean of a fricative is a robust cue for whether it is /s/ or /ʃ/. However, that same cue

also contains useful information for the upcoming vowel: /s/ before a rounded vowel like /u/ will have a lower spectral mean than before an unrounded vowel like /i/ (Daniloff & Moll, 1968). Critically, both /si/ and the /su/ have spectral means that are still within the boundary for /s/. Consequently, if CP operated to minimize within-category differences, these subtle differences would be lost and listeners would not be able to use the frication to anticipate an upcoming vowel—as they clearly can do (McMurray & Jongman, 2015; Yeni-Komshian & Soli, 1981).

Virtually every speech cue is affected by multiple factors (a key underpinning of the problem of lack of invariance). CP ignores this, to focus on the coding and perception of a limited number of cues for a single phonetic contrast. But when we consider CP in light of this basic fact about speech perception, it is hard to see how perception can be discontinuous, and yet listeners could still use all of this gradient information.

4. *Speech Cues do not just encode Phonological Categories.*

Building on this, speech cues do more than just carry categories. VOT is related to the gender of the talker (Allen et al., 2003), fricative spectra carry information about gender (Zimman, 2017) and the degree to which the talker identifies as part of the gay community (Munson, 2007); and of course vowels carry substantial information about dialect and language community. Beyond social marking, cues like F0 which are used to signal vocal emotion also contribute to vowel and consonant identity (Ohde, 1984). And people must use fine-grained within-category differences to tune both their own productions (e.g., to cope with something in their mouth or a missing tooth), or others (e.g., a parent or speech pathologist working with a child). To the extent that within-category information is entirely lost (the strong form of CP), these judgements become even impossible. But even under weaker forms of CP they become more difficult. In this view, CP appears to privilege the goal of identifying phonological categories over these other crucial roles of speech. In contrast, a continuous representation of the auditory space coupled to gradient categories would not sacrifice these abilities. While these fields have not widely wrestled with the deep implications of these functions for CP (I could find few published papers),

these phenomena are widely acknowledged, and my view as an outsider is that fields like socio-linguistics or speech pathology have often just ignored CP and moved on (though see Plichta & Preston, 2005, for an elegant demonstration of non-categorical perception of geographic dialect). However, abandoning CP as a core property of speech, may permit more unification of our models of phoneme recognition and these other functions.

5. Flexibility.

A gradient representation – at the level of categories – has also been linked to perceptual flexibility. That is, even with multiple cues and compensation mechanisms, the speech input may be ambiguous due to speech errors, an unfamiliar accent or context, or just plain variability. In these cases, it may be helpful to avoid making a strong categorical commitment and keep options available in case later information suggests the need to revise this initial commitment.

McMurray et al. (2009) offered one of the first tests of this using a “lexical garden path” paradigm inspired by work in sentence processing. Participants responded to words from a p/b continuum that created a form of temporary ambiguity. For instance, in a word like *parricade*, if the onset sound was ambiguous between /b/ and /p/, the word could be briefly consistent with both *barricade* and *parakeet*, and resolution would not occur until late in the word (at *-cade* or *-keet*). This study tested listeners’ ability to recover from these ambiguities in a VWP experiment. When listeners heard *parricade* with a VOT of 40 msec, they were initially biased to interpret the input as the beginning of *parakeet*, and then would need to revise their decision when *-cade* arrives. However, when the VOT was 30 msec (still a /p/), listeners were still biased to *parakeet*, but recovery was faster, because *barricade* was more active. In contrast, if listeners had been categorical, there would not be an ongoing activation of *barricade* for either VOT, as the activation of /p/ necessitates full suppression of /b/. Under CP, then, they could not have shown this gradient recovery. Several additional VWP experiments show supporting evidence suggesting that a partial commitment is helpful for maintaining this flexibility (Brown-Schmidt & Toscano, 2017; Gwilliams et al., 2018; Szostak & Pitt, 2013). Critically, Kapnoula et al. (2021)

tested subjects both in this lexical garden-path paradigm and in a VAS / speech categorization task (as in Figure 6). As in her prior work, Kapnoula and colleagues used the VAS to establish the relative amount of gradiency and found that participants with a more gradient profile of speech categorization were better able to recover from the garden-path. This validates a core prediction of this argument—more gradiency leads to more flexibility—while also raising questions about individual differences that are not accounted for by current models.

In principle, one could argue that these sorts of effects could be handled by a system that was initially gradient, but which rapidly resolved to more discrete (either/or) commitment to a category (in the lexical garden-path paradigm, ambiguity was typically resolved by around 250 msec). However, later studies using sentential context show that these benefits can last a second or more (Brown-Schmidt & Toscano, 2017; Falandays et al., 2020). Moreover, ERP work by Sarrett et al. (2020) applied the N1 / VOT paradigm of Toscano et al. (2010) (Figure 5) to complex sentences and found a linear effect of VOT on the EEG as late as 900 msec after the VOT. Critically, the target word was at the end of these sentences—no further information was coming. Thus, participants maintain a gradient representation for quite a while, even if they aren't going to need it. Again, we also point out that this kind of gradiency is not strong evidence against any but the most extreme form of CPs. But again, this kind of gradient sensitivity is clearly at odds with the notion of a quasi-discrete category space.

6. Learning / Plasticity.

Finally, gradiency may be necessary for learning and adaptation. Both infants and adults take advantage of statistical learning mechanisms to acquire the categories of their language (Maye & Gerken, 2000; Maye et al., 2008; Werker & Curtin, 2005), acquire new categories of a second language (Escudero et al., 2011; Escudero & Williams, 2014), and tune existing categories to adapt to novel talkers or contexts (Munson, 2011). These mechanisms work by tracking the frequency of occurrence of individual cue-values (e.g., how frequent is a VOT of 20 or 25 msec); they use the kinds of distributions depicted in Figure 6B to identify the number of categories

888 along a dimension as well as their prototypical values and the allowable extent.

889 While there is debate about the sufficiency of these mechanisms to fully account for first-
890 language speech category acquisition (McMurray, in press; Schatz et al., 2021), it is clear that
891 listeners can learn from such statistically structured input (Escudero et al., 2011; Maye et al.,
892 2003). In fact, to some extent, the gradiency observed at the level of categories (e.g., Figure 8)
893 may reflect the fact that these categories are a product of statistical learning. That makes sense
894 if the goal is to adapt the system to the degree of uncertainty: when there is clear evidence that
895 a given token is a /p/, there is no need to hedge one's bets, but when the current input is from a
896 less frequent region of the space it may be useful to withhold a strong commitment (McMurray &
897 Farris-Trimble, 2012). This kind of statistical learning is impossible in a system that doesn't
898 preserve speech cues in a veridical form (e.g., if we assume CP). That is, to track the frequency
899 of specific cue values (e.g., how often a VOT of 20 msec occurs), listeners must maintain a
900 continuous representation of the cues (McMurray & Farris-Trimble, 2012).

901 Of course, standard views of infant development assume a more or less categorical
902 result of development (Werker & Curtin, 2005); these models might argue that babies are
903 continuous or gradient long enough for such mechanisms to acquire the phonemes of the
904 language, at which point a more categorical system develops. However, two arguments speak
905 against this. First, even after infants have achieved native-language like discrimination of
906 voicing (at 4 months), they discriminate speech in a gradient, not categorical manner (McMurray
907 & Aslin, 2005; Miller & Eimas, 1996). Second, statistical learning of this sort is clearly operative
908 in adults and may play an important role in second language acquisition or in fine-tuning
909 categories to new dialects or talkers. A categorical representation in adults would preclude
910 these mechanisms from being used for adaptation in adulthood.

911 The most compelling link between these kinds of gradient representations, plasticity and
912 flexibility comes from a series of studies manipulating the amount of variability faced by subjects
913 (Clayards et al., 2008; Theodore & Monto, 2019). In these studies, listeners performed a series

of standard identification or word recognition trials with stimuli spanning a speech continuum. However, unlike most studies, the distribution of stimuli across the continuum was not uniform. For some subjects, the distribution was tightly clustered around two prototype values (e.g., VOTs of 0 and 40 msec) with little variation; for others, the distribution had a much higher variance, creating more uncertainty. Critically, the subjects that received wider distributions showed shallower identification slopes, or more gradient eye-movement responses. Thus, fine-grained continuous detail is used not only to track the distributions of cues that comprise phonetic categories, but the learning itself is geared toward managing uncertainty in the system.

C. Summary

As this review attests, there is not strong evidence that fundamental auditory representations are warped by categories (Gerrits & Schouten, 2004; Schouten et al., 2003) and mounting evidence that it is not (Toscano et al., 2018; Toscano et al., 2010). Further, speech categories are gradient, and this gradiency is preserved both at later levels of the system (e.g., lexical) (Andruski et al., 1994; McMurray et al., 2002) and for considerable periods of time (Falandays et al., 2020). As I have described, this kind of gradiency is not inconsistent with weaker (and more realistic) forms of CP – as long as some amount of within-category sensitivity is available, listeners can exhibit a gradient category. However, that is not the point of this argument.

Many if not most theories of speech perception are motivated in part by design principles (Kapnoula & McMurray, 2022): processes and representations are built in part to help listeners functionally overcome the difficult problem of categorizing speech (chiefly, the problem of lack of invariance). A continuous representation of speech cues and a gradient representation of categories offer a number of useful design principles that are embraced by widely diverging theories. Gradiency may help with integrating multiple cues and contextual factors; it is necessary to deal with the fact that speech cues serve multiple goals—phonetic, articulatory and sociolinguistic; it helps maintain flexibility in the face of uncertainty; and it is an essential

ingredient—and product of—perceptual plasticity and learning. The essence of CP is an arbitrary reduction of within-category phonetic detail information; however, all of these functional benefits require the opposite: preservation or utilization of such detail (something which children are trying to achieve over development, Figure 7D). While gradiency will not solve the problems of lack of invariance alone (Kapnoula & McMurray, 2022), the benefits of this type of processing are too wide-ranging to ignore.

V. Can some form of CP be saved? And should we?

At this point many readers may be looking for alternatives. Can some form of CP be salvaged? Given the state of the evidence, CP cannot be fully ruled out. But why keep it?

First, let's consider what we can conclude. Clearly, there is some within-category sensitivity, and there is some level of the system that encodes speech cues linearly. But could there be other auditory representations that are warped in some way? Perhaps.

It is difficult at this point for discrimination tasks to provide strong positive evidence for CP – there are too many alternative approaches (e.g., Figure 5) that have not been ruled out. But what about the gradiency at the level of categories? In fact, a gradient category representation can live on top of (or in parallel to) a partially warped can have a gradient categorization on top or in parallel to a partially warped cue encoding. So, none of the work on gradient categories completely rules out weaker forms of CP. Perhaps more hopefully (if you want to retain some version of CP), the neuroscience is still poorly understood and can be interpreted in terms of some kind of hybrid. The prior work showing a partially warped N1 in some listeners (Kapnoula & McMurray, 2022) could be an example of some form of CP (in at least some listeners), or it could be explainable in a Pisoni and Tash (1974) model as the simultaneous contribution of a linear cue encoding and a category on the N1. Similarly, the MMN (Phillips, 2001) is well-replicated as a tool for eliciting CP. It is unclear if this too reflects simultaneous comparison at cue- and category-levels; or if it is strong evidence for CP. The fact

that it is pre-attentive (it can be elicited while subjects sleep), rules out explicit strategies, but not necessarily implicit category activation. Thus, we need more work on these basic neuroscience measures to understand what they are assessing.

Even as we can't rule out CP, is there really that much evidence for CP? Once you understand the discrimination tasks, it is less clear that any of these constitute strong evidence for it. And the alternative theoretical model is compelling. CP is a strong claim that something that supposedly occurs prior to categorization (auditory encoding) is warped by categorization. It requires strong evidence. The converse: Categorization acts to carve up continuous cues is not controversial. So given the dearth of hard evidence, and to the extent that many studies can be explained by simple categorization, maybe we just want to posit that categorization occurs.

Given that we know there is some level of continuous encoding, the real question isn't just is there or isn't some additional a warping somewhere else in the system. The real question is whether listeners (and downstream speech processes) have access to a veridical representation of the speech signal (and they clearly do), and which kind of representation is more important for language. Even the original conception of CP would be perfectly happy with a veridical representation that was transformed into a warped one, but that this warped one was the basis of downstream processes. Rather showing that this veridical one is available to support downstream processes or behavior is the crucial insight (and the evidence presented here clearly suggests it is). And even if you want to admit a role for some kind of warped representation of the auditory encoding, given the role of fine-grained detail in most modern theories of speech do we really want to make CP so central to our field? Should it really be the one of the few things that are taught about speech perception in introductory cognition tasks? Or is it a side issue or a caveat to the prevailing model?

Finally, can be argued that I'm splitting hairs. Perception isn't just auditory encoding—it should include anything that reaches the level of awareness. I agree. The arbitrary line between cognition and perception is old fashioned and out of date. But if we embrace this more holistic

view, CP becomes trivial. That is, it just means that people categorize things. Part of the theoretical richness of CP is that it offers clear definitions about levels of the system that allow it to posit counterintuitive mechanisms. But by expanding our notion of perception to include categorization, when we argue that people “perceive” items within a category as more similar, that also entails the trivial point that they categorize them more similarly, or that they judge the more similarly. Under this assumption, what is the added insight of invoking CP?

VI. CP is dangerous for other fields

The foregoing discussion has focused on whether speech is perceived categorically or gradually – a set of issues that are internal to CP. However, CP has also been impactful in a whole range of fields other than the narrow community that has worked on this core problem in typical adults. It has informed theoretical debates external to CP on the nature of speech categories over ***development, in communicative disorders and bilingualism/L2 speech perception***. In these domains, the question is not whether or not speech is perceived categorically; rather, studies have assumed CP to make insights into the nature of perception in different populations. That is, CP serves as a sort of linking hypothesis to allow us to make inferences about speech perception from an empirical paradigm. But with the fall of CP, where does that leave these endeavors? In fact, CP has arguably led to incorrect conclusions in many cases. Moreover, CP has informed work outside of speech in ***other domains of perception***. Here, the presumption of CP has supported claims about modularity or linguistic relativity, but often without an attempt to wrestle with the trickiness of discrimination tasks, or with ideas like the Pisoni and Tash (1974) model. I briefly discuss these various domains before concluding.

A. Infancy.

There has been near consensus in the developmental literature on how speech categorization develops (Kuhl, 2004; Werker & Yeung, 2005) (but see McMurray, in press, for a more critical

review). Seminal work by Eimas et al. (1971), Werker and Tees (1984) and Kuhl (1979) argues that infants start with the ability to discriminate many (if not most) speech contrasts in the world's languages, and their perceptual abilities narrow over the first 12-18 months such that only the sounds of their language are discriminable. Given that infants at these ages know few words, cannot produce speech, and get little direct social feedback, the assumption is that this development is guided by some form of statistical learning (Maye et al., 2003). This body of work appears to challenge the account laid out here as the changes in infant discrimination appear to reflect increasing warping of speech categories over development. However, as I describe, the modern understanding detailed here offers a simpler explanation. Moreover, in a somewhat circular fashion, the canonical view of speech development (c.f., McMurray, in press) was built on two strong assumptions from CP. Consequently, the demise of CP poses fundamental challenges to it which I describe next.

1. Does infant work support CP?

The dominant view of infant speech development is one of progressive loss of within category sensitivity. This would seem to fit neatly with CP. However, the framing of (Pisoni & Tash, 1974; Figure 5) offers a compelling alternative. These results are also consistent with a model in which infants have categories (or even sets of micro-categories: Schatz et al., 2021) alongside a veridical auditory/perceptual representation and both contribute to the response (much like in adult discrimination tasks). In this light, consider a standard habituation/dishabituation design in which discrimination is tested by repeating a single baseline stimulus and then changing it to either a within-category variant or a between-category variant (with the same physical distance) (e.g., Eimas et al., 1971). It is reasonable to expect a larger dishabituation response when the stimulus seems more novel. Thus, when the baseline stimulus changes from a /b/ to a /p/ it is more novel to the infant as it differs at both the cue and the category level, than if it changes from one /b/'s to another /b/ with a different VOTs. That is, even without a warping of the auditory encoding, the presence of some kind of category on top of that may be sufficient to

drive what appears to be increasing sensitivity to the native language. In this model, what is changing with development is not any kind of warping of the space, but rather, the strength and confidence of the category representations which gradually come to dominate the sense of novelty (discrimination). Supporting this, meta-analyses (Galle & McMurray, 2014; Tsuji & Cristia, 2014) and individual studies (Kuhl et al., 2006) suggest that the growth of between-category sensitivity may be a dominant pattern of change, rather than the loss of within-. While it is no longer entirely clear that phoneme categories are even acquired during infancy (Feldman et al., 2021; McMurray, in press; Schatz et al., 2021), this argument demonstrates how infant results—like adult discrimination—provide little strong evidence for perceptual warping (CP).

2. Methods.

In a somewhat circular development, even as infant work has argued for CP, CP has also served as a critical underpinning of the methods used to establish this framing. Virtually, all infant methods rely on discrimination. In habituation/preference measures like the head-turn preference procedure (Jusczyk & Aslin, 1995) or high amplitude sucking (Eimas et al., 1971), infants engage in some action (fixating a light, sucking on a pacifier) to cue a baseline stimulus (e.g., a repeating /b/). Once they habituate or are familiarized with it, this behavior is reduced. Then, the stimulus is changed. If the change is detectable, the behavior should be reengaged. Similarly, in the conditioned head-turn procedure (Kuhl, 1979), the infant hears a repeating baseline stimulus and is conditioned to look to the side whenever a change is detected. Both are measures of discrimination.

In fact, there are few good ways to instantiate a labeling or identification task with babies (though see Albareda-Castellot et al., 2011), consequently discrimination is all we have. Under the assumption of CP, this is not problematic. If discrimination is predicted by identification, we can use differences in discrimination to make inferences about categorization. A failure to discriminate two tokens that are presumably from the same category indicates categorization; successful discrimination implies two categories. However, if we cannot assume CP, what are

1070 we to make of such data?

1071 Moreover, it is not clear that CP holds in infancy: two studies show evidence of within-
1072 category discrimination in infancy (McMurray & Aslin, 2005; Miller & Eimas, 1996) and Galle and
1073 McMurray (2014) conducted a systematic review across multiple studies showing evidence for
1074 gradient sensitivity when data was pooled across studies that individually reported CP. Clearly,
1075 the differences in discrimination that have been reported are not irrelevant to categorization, but
1076 we may not be able to make strong claims that infants have speech categories. In short, we
1077 need a clearer understanding of the link between these infant discrimination measures and
1078 categorization (the derivation chain) in order to know what we know (see McMurray, in press, for
1079 further discussion of the limits of infant methods).

1080 **3. *Perceptual Narrowing.***

1081 The dominant story of early development is a form of perceptual narrowing (Maurer & Werker,
1082 2014)—infants lose discriminative sensitivity to things they don't need. This is consistent with
1083 the broader meta-theoretical view of CP that the goal of perception is to filter out unnecessary
1084 variation. But given the research presented here, that view is no longer tenable. Instead, it
1085 appears that development may be more concerned with more accurately characterizing the
1086 statistical structure of speech cues and learning the various factors that give rise to the
1087 observed data. For some sounds (e.g., non-native sounds), this may mean narrowing; but for
1088 other sounds, the representation may need to be enriched (Eilers & Minifie, 1975; Eilers et al.,
1089 1977; Narayan et al., 2010), and sensitivity may need to be improved to accurately account for
1090 contextual factors like talker. In fact, taking a lifespan approach (Figure 9D; McMurray et al.,
1091 2018), and using tools more sensitive to the structure of speech, we see that children actually
1092 improve in their ability to encode fine-grained, gradient detail over the first 18 years of life—the
1093 exact opposite of narrowing. In short, if speech perception is about harnessing variability to
1094 enable flexible behavior, we may need a new metaphor that moves us beyond narrowing.

1095 **4. *Toward a new direction.*** Together, these arguments suggest the need to think

differently about what it is that infants know, what they are trying to achieve developmentally and how we get there. This may require moving beyond categories – which we can't even measure in infancy. For example, Feldman et al. (2021) argues that early infancy may be a time in which infants largely organize the perceptual space (e.g., the middle layer of Figure 3), and that true categorization may not come until children are older and have access to more words, articulation, and richer information (see also McMurray, in press).

B. Development and Disorders in Older Children

CP—both as a theory and a set of methods—has been instrumental in understanding development and communication disorders in older children. In typical development, a small but growing number of studies has used speech continua along with 2AFC tasks to demonstrate changes in phonetic categorization over the school-age years and later (e.g., Figure 9C) (Bernstein, 1983; Hazan & Barrett, 2000; McMurray et al., 2018; Nitttrouer, 1992, 2002; Slawinski & Fitzgerald, 1998). These studies have typically not used a discrimination task to establish CP, but they nonetheless show changes in categorization. Moreover, a voluminous body of work has used similar tasks (often with a discrimination task to establish CP) in children with disorders such as dyslexia, developmental language disorder, or brain damage (e.g., Dial et al., 2019; Robertson et al., 2009; Serniclaes et al., 2004; Werker & Tees, 1987).

With respect to identification, such studies typically find that younger or impaired listeners show differences in the identification curve relative to typical or older listeners (Figure 10B). These take the form of either a shallower slope (gray curve) or asymptotes that do not reach 0 or 1. The question is what does this mean?

Consider the labeling function. The typical interpretation (assuming CP) is that listeners are striving for a discrete categorization. Consequently, a shallower slope must come from noise, specifically, in encoding the continuous cue. For example, if a VOT of 15 msec (a /b/) was misheard as 20 msec (a /p/) on some trials, this would cross the boundary, and result in a

different identification. However, if a VOT of 0 msec was misheard as 5 msec, it would still be a /b/ and yield no difference. In contrast, if cue encoding was not noisy, but there was noise at the level of categories, this should be fairly independent of the VOTs – all /b/'s are occasionally misperceived as /p/'s and vice versa. Consequently, if we assume CP, the interpretation is clear: a shallow slope is an unambiguous marker of noisy cue encoding, and a reduced amplitude is an unambiguous marker of a category-level difference.

But what if the categories are gradient? As described, gradient categories could be beneficial—not costly—in some circumstances. However, the mapping between a gradient underlying category and 2AFC performance is ambiguous. A shallower slope could indicate a more gradient category, which might be interpreted as a rational response to uncertainty (Clayards et al., 2008). However, it could also reflect a noisier system (much like the model assumed by CP). It's possible that both are occurring: shallower slopes in some children indicate greater noise, but in other listeners may indicate a useful adaptation! The 2AFC task cannot distinguish these possibilities (Apfelbaum et al., submitted). A critical issue is how listeners choose to map an underlying gradient representation to a response across trials: if a given token is heard as 60% /b/-like, do they attempt to match this probability (choosing /b/ 60% of the time), or do they always choose /b/ (winner take all) (Nearey & Hogan, 1986)? Understanding this linking function could radically change our interpretation.

Other studies attempt to pin a deficit specifically at the level of cue-encoding using discrimination tasks; for example, Serniclaes et al. (2004) has argued dyslexia can be linked to an inability to sufficiently ignore within-category detail, and Robertson et al. (2009) has argued that children with developmental language disorder show impaired between-category discrimination. However, given the arguments against CP at both theoretical and methodological levels, it is not clear what these claims mean. If the Pisoni and Tash (1974) model (Figure 5) is right and both category and auditory levels contribute to categorization, then perhaps these differences in discrimination simply reflect poorer phonological categorization.

Alternatively, the kinds of discrimination tasks used in such studies heavily tap working memory, cognitive control and phonological processing. All three skills likely co-develop with speech perception or are comorbid deficits in many communication or neurological impairments. Perhaps, then, these differences in discrimination don't reflect perception or categorization at all, but rather reflect differences in processes that are entirely external to speech categorization.

Minimally, it is clear that studies of communication disorders and development should better account for what is known about the memory and decision demands of discrimination tasks (Gerrits & Schouten, 2004). However, given the various cognitive comorbidities, as well as the uncertainty surrounding forced-choice categorization, it may be better to explore radically different methodological alternatives such as the continuous VAS tasks, eye-tracking in the VWP, or ERP components like the N1.

Beyond methodology, the implicit claim of CP is that steep categorization, and the suppression of within-category detail is the "goal" of normal development. That's what typical listeners should do; that's what children should learn to do; and that's what impaired listeners do not do as effectively. In light of more modern thinking in speech perception, that is clearly not the case. Gradiency is important—both for speech perception as classically defined and other functions (articulatory control, sociolinguistic marking). It is functionally beneficial for listeners and may be a crucial avenue by which people facing communicative impairments adapt (McMurray et al., 2016). It may be something that development or learning is attempting to achieve. In short, we need a new paradigm – both methodologically and theoretically – for thinking about these crucial real-world problems.

C. Bilingualism and L2 Acquisition

Work on bilingualism and second language (L2) acquisition has been motivated by CP in multiple ways. This is a voluminous body of work, and I won't attempt a systematic review. Instead, I offer two observations.

1. Critical or Sensitive Periods.

First, there is a strong presumption of critical or sensitive periods for L2 acquisition. This has been motivated in part by work examining proficiency as a function of when a learner begins learning a second language (Johnson & Newport, 1989). However, this work has also been challenged by much larger-scale studies that account for not only when L2 acquisition begins, but also for the fact that language learning (both L1 and L2) is likely to be protracted (Hartshorne et al., 2018). This seems to show a much larger sensitive window (through age 18). The other argument for a sensitive period is the apparent rapid emergence of L1 speech categories in infancy (Werker & Tees, 1984), coupled with the struggles many adult L2 learners face in acquiring such categories (Strange & Shafer, 2008): if infancy is a special time for speech category learning, this can explain these difficulties (Werker & Hensch, 2015).

There are two problems with this presumption. First, as I described, without the assumptions of CP, it is challenging to conclude that infants truly have acquired speech categories so rapidly. While they are certainly attuning to their language, they may be doing other things (Feldman et al., 2021; McMurray, in press; Schatz et al., 2021), and development may be quite a bit slower (Hazan & Barrett, 2000; McMurray et al., 2018) (supporting the Hartshorne et al., 2018, analysis). Second, infant methods are radically different than from those used with adults; a typical infant study may present infants with multiple tokens of the two sounds to be discriminated, and any difference in listening time is used to support discrimination. In contrast, adults get one token/trial, and the criterion is accuracy. If adult L2 learners were tested with the relatively looser infant procedures, would they look just as good? This challenges the basic assumption that L2 learning adults struggle, while L1 learning infants “get it.” Both of these arguments undercut the premise of a critical period and call for more rigorous and direct empirical evaluation of this construct (Fuhrmeister et al., 2020) as well as new ways of thinking about critical periods (Thiessen et al., 2016).

2. What is the goal of bilingual speech perception?

1200 Most work on bilingual or L2 speech perception implicitly assumes CP as a framing. This could
1201 restrict interpretation along two dimensions. First, as with children and impaired populations, it is
1202 not warranted to presume that a sharp categorical boundary is desirable. Gradiency could be
1203 helpful in general, and, in a multi-lingual environment, *gradiency may be even more helpful*.
1204 When confronted with multiple languages or dialects (potentially changing from moment to
1205 moment), gradiency may be needed to be more flexible and to incorporate contextual
1206 information (about the language or dialect spoken). Thus, the question should not be how
1207 listeners attain sharp boundaries, but how they attain flexibility.

1208 Second, CP highly emphasizes boundaries. In a bilingual situation, that frames
1209 questions such as whether a Spanish/English bilingual puts their VOT boundary at 20 msec
1210 (English) or 0 msec (Spanish) and whether they can shift it rapidly. But no serious model of
1211 speech perception assumes boundaries anymore. Instead, prototypes (e.g., Figure 8) (or some
1212 functional variant of that) are the norm. But crucially, *prototypes need not be mutually exclusive*.
1213 A listener could have an English /b/ category centered at 5 msec, and a Spanish /b/ category
1214 centered at -60 msec. Thus, moving beyond CP may pose new questions for work on
1215 bilingualism and L2 acquisition.

1216

1217 **D. Other domains of cognition and perception**

1218 As I described, the extension of CP to domains beyond speech perception has been an active
1219 endeavor, and it has played an important role in debates about linguistic relativity (Franklin et
1220 al., 2008), modularity (McKone et al., 2001), and other fundamental issues. While it is beyond
1221 the scope of this review to fully address this problem, it is worth a few brief comments.

1222 First, for the most part, this literature outside of speech has assumed CP and made little
1223 contact with the literature specifically on CP within speech. There are exceptions, but often the
1224 deeper message is lost. Goldstone and Hendrickson's influential (2010) review does discuss
1225 some of this literature, but it does not appear to lead them to question the premise. Even the

original demonstration of categorical perception in color (Bornstein & Korda, 1984) explicitly adopts the Pisoni and Tash (1974) model (Figure 3), but fails to realize its deeper implications.

Second, the few studies that have addressed this issue head on suggest a story much more consistent with non-categorical perception. For example, Hanley and Roberson (2011) conducted a retrospective analysis of several studies of face and color CP and found that the order in which the stimuli were presented in the discrimination task had a major impact on performance, and when that was accounted for, results were well described by a model featuring the continuous encoding of the input, but in which categories could also impact discrimination (e.g., Pisoni & Tash, 1974). Similarly, Roberson et al. (2009) conducted a serious analysis of the discrimination tasks used to establish color perception (analogous to Gerrits & Schouten, 2004; Pollack & Pisoni, 1971), and identified a less biased task in which colors were presented immediately adjacent to each other. When this task was adopted, the CP effect disappeared. While these sorts of issues are still under active debate (e.g., Best & Goldstone, 2019), this suggests some movement in the broader field.

Third, a key argument here is that the claims of CP do not live in isolation from broader theories of speech perception—CP makes claims that the rest of the system must live with. In speech, throwing away fine-grained continuous detail may pose limits on the degree to which the system has access to this detail for other things like integrating cues over time, using the same cue for multiple purposes or identifying sociolinguistic properties. This kind of theoretical inconsistency may arise in other domains of cognition where CP is invoked.

Face perception offers a useful illustration. In this domain, there has been rapid adoption of what's termed "norm-based" face coding (Leopold et al., 2001; Rhodes & Leopold, 2011). In this view, face perception is seen as dimensional, and frequent experience with classes of faces can shift the mean of this dimension—the same operation posited by C-CuRE in speech for talker compensation (McMurray & Jongman, 2011). Critically, this kind of dimensional shifting cannot occur if dimensions are collapsed into discontinuous regions. In a related issue, virtually

all domains of perception confront the problem identified by Mermelstein (1978): that the same continuous dimension may be needed for more than one distinction. It may make sense to minimize within-category differences in color if the only goal is accurate labeling. But people must also use subtle aspects of color to judge attractiveness, to compensate for ambient lighting, or many other things. In fact, color labeling may be one of the least important goals of color perception! Similarly, if variation within various exemplars of the same face is ignored, how can an observer use subtle differences in that face to judge facial emotion or health? One can argue that perhaps CP-like effects emerge in the context of a particular task, but this then is a far cry from everyday cognition and the radical warping posited by CP.

E. Summary

As the foregoing discussion reveals, in development, disorders, multilingualism and cognition more broadly, a strong presumption of CP has shaped many things, from the tasks used to assess perception and categorization, to the interpretation of the functional goals of the system. With the demise of CP within speech perception this has not been questioned. It needs to be.

In an influential critique of much of psychology, Meehl (1990) coined the term *Derivation Chain*, which refers to the inferential logic that allows one to generate predictions from a theory of cognition to an experiment or measure. In all of these domains, CP was an essential piece of the derivation chain. However, CP is now a part of the past; it makes problematic theoretical assumptions, and we better understand discrimination tasks. This undercuts the derivation chains used in these lines of work and calls for a new approach.

VII. Where do we go from here?

CP has been with us since before the cognitive revolution, and before I was born. Despite ample empirical evidence to the contrary, it remains. Despite the fact that it has no answer to

1278 fundamental facts about speech (like the fact that speech cues do multiple things), it remains.
1279 Despite the fact that its assumptions are inconsistent with most modern theories of speech
1280 perception, it remains. Why? What are we to learn? Where do we go from here? It helps to start
1281 by considering why it was (and remains) compelling.

1282
1283 **A. What made (and makes) CP so compelling?**

1284 When CP was discovered and promulgated, speech science was in a different place. While the
1285 early work identified many key sources of variability (Delattre et al., 1955), we had not identified
1286 the hundreds of phonetic cues we know of now, we did not have access to large corpora, and
1287 statistical tools for pooling “big data” were not in wide use. Speech perception for many was
1288 more of an analytic—rather than synthetic—process focusing on a small number of cues in
1289 isolated (simplified) syllables and so forth (thought see Blumstein & Stevens, 1979). And the
1290 problem was narrowly defined in terms of categorization (much as I’ve simplified here). In this
1291 light, it is easy to see how CP would be an attractive solution (see also Supplement S2).

1292 However, let’s look at this through the modern lens. What if we had encountered this
1293 problem for the first time now, with access to large corpora and tools for integrating dozens of
1294 measurements, with far more phonetic cues, with much more variable speakers and listeners
1295 under investigation, and with a richer understanding of related processes like word recognition
1296 and indexical perception? Would we ever have come up with CP? It’s not clear that we would
1297 have. Historical precedence is not an argument for retention.

1298 But, historical precedence alone does explain the persistence of CP. It also fits with our
1299 meta-expectations about language. Any ordinary person can tell you, there is nothing in
1300 between a *bunt* and a *punt*—these are distinct words. And for speakers of an alphabetic
1301 language, there may be nothing between a /b/ and a /p/. Arguably our over-reliance on the IPA
1302 as a tool for conceptualizing sound contributes as well—well before we had CP, field work in
1303 linguistics, speech pathology and developmental work was focusing on a symbolic

1304 representation of a fundamentally continuous signal CP matches these intuitions of
1305 discreteness. That is, we want to be able to talk about sound in terms of categories, and we
1306 even think we hear it in terms of categories. But this is an illusion—when we look closely with
1307 unbiased discrimination tasks or EEG we see a different story.

1308 People like to categorize—whether in terms of statistical significance, gender categories
1309 or color—and are uncomfortable with gradience and nuance as they are difficult to verbalize.
1310 CP would seem to take something that is quintessentially messy and nuanced—perception—
1311 and offers a comforting answer that it is not, that categories are just fine.

1312

1313 **B. What gives? Why is CP still with us?**

1314 The scientific community is generally more comfortable with nuance. And within the community
1315 of researchers working directly on CP, we have clearly known for a long time that speech is not
1316 perceived categorically. So how has this persisted? This is illustrated anecdotally by an
1317 experience I had as an early graduate student. When I submitted the first few papers arguing for
1318 gradiency for publication (McMurray, Aslin, et al., 2008; McMurray et al., 2002), the reviewers
1319 argued that my work was setting up a straw man, that CP was over, and we should move on.
1320 Clearly, the reviewers knew what was up. And yet this message did not appear to be true.
1321 Almost everyone outside of speech perception (e.g., in vision) was still assuming CP, and even
1322 within multiple areas of speech perception, it was still with us

1323 That's still true today, 20 years later. Work is building new theories of CP even in the
1324 field of speech perception (Kronrod et al., 2016), and in broader areas of cognition (Feldman,
1325 2021; Zhang et al., 2021). CP continues to be applied in a variety of subdomains of speech
1326 perception such as L2 learning and language/hearing disorders⁴. CP is not going away, despite

⁴ As evidence: A google/scholar search of (“categorical perception” AND “L2 learning”) led to 1170 hits since 2017, and (“categorical perception” AND “communication disorders”) led to 3020! Many of these papers may simply be using the phrase *categorical perception* to refer to categorization (not sensory discontinuities), but these impressive results suggest this idea is still omnipresent.

the fact that the small community of hardcore speech nerds who have worked directly on CP knows better. Bearing witness to this is the continual appearance of major reviews and large scale studies of CP (Goldstone & Hendrickson, 2010; Kronrod et al., 2016) that treat CP as a fundamental fact to be explained. While some of them do make contact with the literature reviewed here (e.g., Goldstone & Hendrickson, 2010), they do not question the premise.

I don't know how those of us who have worked on CP could make the truth more apparent. There are papers with titles like *The End of Categorical Perception as We Know it* (Schouten et al., 2003), *Categorical results do not imply Categorical Perception* (Hary & Massaro, 1982), and my favorite, *Categorical Perception of speech: A largely dead horse, surpassingly well kicked* (Crowder, 1989). Could speech perception researchers be any more direct? One does not even need to read the papers to know that something is up⁵.

Part of the problem is that CP is no longer just an empirical finding or a theory. It's part of the meta-narrative of speech, a scientific meme. It is easy to dismiss individual papers here and there, while at the same time treating them as exceptions to a general rule. I hope what this review has done is to show how there are simply too many inconsistencies to hold on to CP anymore. The question is where to go from here (see Box 2 for concrete steps).

C. Science Communication

Part of the solution has to be better communication. There are few, if any, reviews of CP in the speech literature (broadly construed) that wrestle with the more modern conception. The most comprehensive recent reviews that I've seen come from outside of speech (Goldstone & Hendrickson, 2010). We—speech researchers of all sub-domains—must take it upon ourselves to communicate outside our field. We can't expect textbook authors and people outside of our field to figure it out from more highly technical papers in the *Journal of the Acoustical Society of*

⁵ And here I've put the titles right in the text to save you the trouble of checking the references. Although since JASA puts notes at the end of the manuscript, you just did that too.

1351 *America* (yes, I get the irony). If my review was overly pointed, it was for this purpose—subtlety
1352 will not help make a dent in the rapid growth of CP (Figure 1).

1353 In fact, even the basic findings are not making it out of our field. Many people in use the
1354 term *categorical perception* to refer to any task in which people identify tokens from a
1355 continuum, whether or not discrimination is measured, and whether or not the researcher is
1356 making claims about the perception of the continuous space. People commonly refer to a
1357 sigmoidal identification function as a “categorical perception” curve – even without
1358 discrimination or any claim about perception. How do so many papers that mischaracterize or
1359 misapply CP continue to be published? Have speech researchers in the categorization
1360 community agreed to just let this pass? Are they not reviewing these manuscripts?

1361 A critical aspect of this issue is teaching. I recently surveyed most of the major
1362 psycholinguistics textbooks, and many phonetics texts. All treat CP uncritically. I suspect it's the
1363 same in other fields such as speech and hearing science or phonetics (when speech
1364 categorization is covered at all). Why is that? The easy response is that the alternative is too
1365 complicated for undergraduates. But this sells our students short. The debates around CP are
1366 an excellent opportunity to teach how science can be self-correcting, and how theories of
1367 speech perception need to account for fundamental properties of the speech signal. My
1368 suspicion is that many of us are making end runs around the texts to teach CP correctly with
1369 innovative demos and tools. If so, these should be shared. Moreover, too many textbooks treat
1370 speech perception as an interesting set of phenomena for students to share with their parents:
1371 Categorical Perception, the McGurk effect, Duplex Perception, the Cocktail Party Effect. That's
1372 important for raising interest, but it doesn't get our students closer to a deeper understanding of
1373 how speech and language works. We should be teaching students how the auditory system
1374 actually processes speech. The gradient alternative is not too complex: use multiple cues,
1375 engage in simple forms of compensation, maintain a prototype structure to be flexible, and
1376 constantly learn and update. This should be a message we can tell clearly.

1377

1378 **D. Throwing out prior results with the bathwater?**

1379 A question now is what to make of the voluminous findings that actually report the characteristic
1380 profile of between- and within-category discrimination that constitutes CP. It is tempting to
1381 dismiss them out of hand; but that's wrong. The data is real, even if the premise is problematic.
1382 So, we need some framework for understanding these prior results, and for making sense of
1383 differences in CP-like behavior across conditions and groups.

1384 Clearly, the wrong conclusion is that perception is warped by the presence of categories.
1385 That is a not tenable claim anymore. However, a not unreasonable claim – following Figure 5 -
1386 may be that once CP (empirically) is observed, categorization must be pretty robust (fast and
1387 strong) in order to contribute to the discrimination judgement—weakly represented or acquired
1388 categories are simply not engaged in discrimination. This accords well with the learning
1389 accounts—when CP is not observed in L2 learning (Miyawaki et al., 1975), listeners simply have
1390 categories that are represented or accessed less robustly. If we restrict ourselves to the idea
1391 that CP reflects robust categorization, this seems reasonable. However, perhaps we should just
1392 call it categorization (or perception of categories), not categorical perception (Holt & Lotto,
1393 2010). And perhaps future work should skip the discrimination tasks more generally—there are
1394 more informative ways to assess categorization.

1395 The alternative approach is to restrict the domain of interpretation. CP is not a paradigm
1396 for understanding perception of the auditory space, but it is a useful way to think about how
1397 people engage in discrimination judgements. Discrimination is an interesting human behavior
1398 and arguably important in its own right. Maybe CP is simply a way of probing the influence of
1399 higher-level knowledge on discrimination, and of probing various memory biases. If that's the
1400 question, perhaps AX and ABX task serve an important role. Again, this is defensible, but again
1401 it's not quite CP. Perhaps this is biased discrimination?

1402 In both approaches, the key is to have a clear understanding of what we're actually

1403 studying in CP paradigms so we know what can be concluded. What does not seem reasonable
1404 to me is to stretch this concept in every conceivable direction to try to preserve the name.

1405

1406 **E. Methods?**

1407 The debates over CP and the development of this line of work clearly point to the need for a
1408 stronger understanding of methods. The limits of discrimination tasks are clearly highlighted
1409 (Pisoni & Lazarus, 1974; Schouten et al., 2003) and researchers need to be aware of these
1410 limits. The basic properties and concerns about discrimination tasks should be well known in
1411 any field that relies on them.

1412 But the 2AFC task is not without its issues either. As our brief discussion about
1413 development reveals, there are limits of interpretation to this task: is a shallow slope a natural
1414 reflection of a gradient system, or the result of a noisy but categorical system? These things
1415 cannot be known from this task alone. In fact, even if listeners have an underlyingly gradient
1416 boundary, they could still show a steep slope if their response on each trial always reflects the
1417 more likely of the two alternatives (Nearey & Hogan, 1986). We simply do not understand the
1418 derivation chain (Meehl, 1990) linking an underlying category mapping to people's behavior in
1419 this highly simple task. But even if we did, this task may simply be underdetermined.

1420 More sophisticated measures are needed. But these need not be technically
1421 sophisticated (e.g., eye-tracking or ERPs). As Massaro, Miller and Kapnoula have shown
1422 (Kapnoula, 2015; Massaro & Cohen, 1983; Miller, 1997), even something as simple as a
1423 continuous rating task (Figure 6), can dramatically open up new possibilities for understanding
1424 categorization. More sophisticated tools like eye-tracking and ERPs are not going to be a
1425 panacea. The most common ERP measure of speech, for example, the mismatch negativity
1426 (see Phillips, 2001, for an example applied to CP), is in fact a measure of discrimination, with all
1427 the caveats to interpretation that apply to any discrimination task. Techniques like ERP and the
1428 VWP are useful, but they need to be deployed in ways that are linked to the underlying cognitive

and perceptual operations, and that take advantage of their own unique properties. That is, they need to be deployed in ways that respect the derivation chain. For example, the ability to condition analysis of ERPs or eye-movements on the overt response offers the unique ability to ensure that one is examining within-category variation; or the fact that the N1 is tied to early auditory cortical regions offers an ability to isolate processing of continuous acoustic encoding.

Third, CP also introduced to us the notion of a speech continuum. This is arguably the most valuable and defensible methodological innovation. Nothing in the foregoing review invalidates this approach, and the fact that it can span an ambiguous region can highlight subtle but theoretically meaningful effects that cannot be seen elsewhere. However, we can improve it. It would be helpful to standardize how continua are reported and used (see Supplement 1). This can help ground arbitrary step numbers to real acoustic measurements. Such standardization can help compare effects across different contrasts and could be crucial for the currently fashionable meta-analytic approaches. But as the tools for constructing continua become better and easier, we must also be careful that continua are phonetically realistic—they span neighboring phonemes (not passing through a third phoneme or a dead space) and manipulate cues in ways that reflect the variation that real articulators are capable of. And this is not a panacea, nor is it the only way to study speech (note to self).

We should also consider moving beyond continua. In the era of big data and large-scale statistical models, one can (for example) simply record dozens of naturalistic exemplars, measure their phonetic properties, and give them (unmanipulated) to listeners to categorize. Then, logistic models can sort out which phonetic properties are contributing to a given percept or how that changes across experimental conditions (McMurray & Jongman, 2011). This could provide a powerful—and phonetically grounded—complement to continua.

The last methodological concern is the biggest. Many experiments are predicated on some notion of what kind of processing is typical, efficient, optimal, or ideal. This is perhaps the most serious impact of CP, by biasing researchers to expect sharp categorization and poor

within-category discrimination as the ideal. Instead, modern theories of speech suggest a system that is much more gradient, flexible, and complex, and our thinking needs to adapt.

F. Conclusions

CP have long lived. In some ways, it is easy to work around many of the points raised here individually. I've argued that CP is incompatible with the kind of rich compensation needed to account for talker and coarticulatory variation. An easy counterargument that could preserve CP would be that listeners do all this *before* they do CP (or maybe these processes are how one becomes categorical). But if that's the case, what's the point of adding CP to the system (and in that case, is this really perception)? In fact, attempting to salvage CP in this way ignores the fundamental claim of CP that the system is attempting to suppress variation – instead, it seems to be harnessing it. One could also attempt to account for the myriad discrimination results by claiming that there's an early categorical representation alongside a linear one. But is that really any different than the Pisoni and Tash (1974) model?

The point is, if one contorts oneself, we can salvage CP from many of these attacks. But at some point, we have to look at the bigger picture: CP as an empirical finding or a theory is just not logically consistent as a whole. It is not a coherent account of the extant data nor of speech perception, and its theoretical claims are incommensurate with theories of speech that use the fine-grained detail that CP would discard to do useful work for listeners. Given the wealth of empirical evidence against CP and the strong theories of speech that either do not require it or conflict with it, CP no longer adds to the greater coherence of our understanding of speech perception. Can we be done?

Acknowledgements

The author would like to thank Keith Apfelbaum, Joe Toscano, Joan Sereno and Allard Jongman for helpful comments on this manuscript; Ethan Kutlu for engaging ideas about multilingualism, and Effie Kapnola for ideas regarding individual differences. He would particularly

1482 like to thank Ben Munson whose thoughtful review of this manuscript led to a rethinking of
1483 crucial issues around the relationships among fields, and the importance of social and other
1484 functions of speech. This project was supported by DC008089.
1485

Inset Boxes

Box 1: What counts as steep? And what is a step?

CP is often colloquially defined as a “sharp” categorization function across a continuum that varies in some number of small steps. However, this can be illusory and subjective. If a researcher restricts the range of a continuum to a narrow region around the boundary (and then uses a small step size), the function might look quite gradient; while an artificially expanded range could make a relatively gradient function look step-like (c.f., McClelland & Elman, 1986, p. 46). The field has not converged on standards for continuum generation that would allow any kind of objective statement.

Here, I propose a simple solution. It is tempting to try to equate steps at a psychophysical level – much like the Munsell scale has done for color. That is, could we use psychophysical discrimination thresholds to decide how many msec of VOT equals 10 Hz of F1? However, speech contrasts are often highly multi-dimensional (Jongman et al., 2000; Lisker, 1986; Repp, 1984), and individual cues may be nonlinearly represented. Instead, I suggest a top-down approach, starting from the phonetic data.

- 1) Start with the actual words or strings that will be “morphed” into the continuum.
- 2) Generate recordings of multiple exemplars of each of them. These could be from the same talker or from a representative group of talkers.
- 3) Identify the relevant cues from the phonetic literature and measure them in the recordings.
- 4) Use the mean of those cue values as the prototype “locations” in a high-dimensional space.
- 5) Generate the continuum based on some subset of the recordings.
- 6) Finally, measure the cue values for the generated stimuli – these can be projected onto the line connecting the two prototypes to convert step number to a proportion of distance between the phonetic prototypes. Values more extreme than the endpoints (e.g., a super long VOT) could be treated as greater than 100% or less than 0%.

It may be helpful for labs to begin standardizing how they report continua in this way. This would permit meta-analyses, as well as more objective measures of steepness (e.g., change in proportion responses / step is now constant across all studies), which could eventually be used to establish criteria. See Online Supplement for equations and a worked example.

Box 2: Speech perception in a Post-CP world

CP has shaped the field for so long that it is unclear what the field will look like without it. To start that conversation, here are some concrete (but not exhaustive) recommendations.

Science Communication

- Textbooks should be revised to reflect the modern view.
- Pithy review articles are needed to communicate to speech-adjacent fields.
- Reviewers need to be more pointed in challenging appropriate uses of CP.

Methods

- Small differences in discrimination tasks can lead to different memory demands and different levels of bias. We cannot conclude CP from discrimination tasks, and they should be used very carefully.

- Forced-choice identification tasks may be problematic when studying the slope of the identification function (e.g., over development) (Apfelbaum et al., submitted). For this issue, a continuous VAS task may be better.
- Forced-choice identification tasks are not problematic for assessing boundary shifts (e.g., trading relations, perceptual learning paradigms).
- Measures that allow researchers to simultaneously measure the category label and the underlying activation on the same trial (e.g., specific VWP or ERP paradigms McMurray et al., 2002) are valuable.
- Speech continua are valuable when they are constructed on the basis of phonetic insight (not arbitrary morphing). It would help to standardize them across dimensions.
- Speech continua should be complemented with more naturalistic methods in which actual recordings are measured along multiple dimensions to relate categorization to actual acoustic variance.

Theory and Interpretation

- The focus should be on theories of perception not theories of categorization along a speech continuum.
- We need stronger theories of the problems highlighted by modern ideas: how do listeners achieve flexibility? Where do individual differences come from? How do listeners use fine-grained acoustic variability?
- Theoretical accounts of development, bilingualism, and clinical populations should abandon the premise that the goal of speech perception is discrete categorization and ignoring within-category detail, and instead ask how these listeners achieve a gradient, flexible and efficient categorization.

Figure Captions

Figure 1: Number of new citations in consecutive 5-year periods starting in 1955. Search was conducted on Google/Scholar with the term “categorical perception”

Figure 2: Canonical results of a categorical perception experiment. On the X axis, step refers to step from a speech continuum, where step 1 might be a prototypical /b/ and step 10, a prototypical /p/. Identification (dashed line, left axis) is coded as the proportion of responses that match one of the endpoints. Here, 0 is /b/ and 1.0 is /p/, so that 0% responding indicates the participant consistently heard /b/. Discrimination is assessed between neighboring points (e.g., between step 1 and 2, 2, and 3, and so forth). The peak indicates that discrimination is better between steps 5 and 6 (spanning the boundary shown by the identification results) than between steps 1 and 2 (both /b/).

Figure 3: A rough conceptual model of the speech chain assumed by CP. Speech input is first mapped to a continuous auditory encoding that represents something like continuous cue-values. This space is then carved into categories.

Figure 4: A) Spectral mean and F2 onset frequencies for /s/ and /ʃ/ from Jongman et al. (2000). The line represents a linear discriminant analysis that can separate the categories at about 92%. B) A simulation of CP generated by assuming the linear boundary in A, and then doubling the distance between tokens on each side of the boundary and halving the variation within each side of the boundary; C) A simulation of CP generated by only increasing the distance, without adjusting within-category variation. D) Same data after compensating for talker and vowel differences using the regression approach of C-CuRE (McMurray & Jongman, 2011); the discriminant analysis achieves 96.6% accuracy.

Figure 5: The Pisoni and Tash (1974) model of discrimination. Speech is transduced to a continuous perceptual space, then to categories and words (left branch). Discrimination, however, can use either the perceptual or category representation (right branch). Under these assumptions, between-category contrasts should almost always be more discriminable than within (embedded table), even if the perceptual encoding is continuous.

Figure 6: Distribution of rating scale responses for individual subjects as a function of continuum step (each row) from Massaro and Cohen (1983) (estimated from their Figure 7). A) Under a categorical model, listeners should use only the ends of the scale, and should only vary in how frequently they choose the /b/ or /p/ ends. B) Under a continuous model, the mean rating should shift with step. C) Estimated data from a typical listener.

Figure 7: Results from (Toscano et al., 2010). A) Voltage at front-central channels as a function of time and VOT. The large negative deflection at 100 msec is the N1 and its depth is related to VOT. B) Mean N1 amplitude as a function of VOT.

1599 Figure 8: Typical results of phoneme goodness rating experiments of Miller and colleagues
1600 (data estimated from Miller & Volaitis, 1989). A) /p/ goodness as a function of VOT and
1601 speaking rate (the length of the following vowel). B) Phonetic measurements showing the
1602 distribution of VOT as a function of speaking rate.

1603

1604 Figure 9: Results of VWP experiments documenting gradient within-category sensitivity to fine-
1605 grained detail. A) Fixations to the competitor as a function of time, and distance from the
1606 category for tokens on the voiced side of the continuum from McMurray et al. (2002). B)
1607 Average fixation from 200 to 2200 msec as a function of relative VOT in that study. C) 2AFC
1608 labeling function for children in McMurray et al. (2018); here, identification becomes steeper
1609 (more categorical) with development. D) In contrast, competitor fixations as a function of relative
1610 VOT show increasing sensitivity with development.

1611

1612 Figure 10: A) Schematic results of a typical trading relations experiment examining voicing
1613 categorization (/b/ vs. /p/) as a function of VOT (x-axis) and F0 (separate curves). B) Schematic
1614 results of an experiment examining voicing categorization in younger and older children, or in
1615 disordered and typical children.

1616

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The Myth of Categorical Perception

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S1: Standardizing Speech Continua

Despite decades of work using speech continua there are no attempts to standardize how these are reported or used across studies. This is a challenging problem for many reasons. First, the acoustic dimensions are often incommensurate – how many msec of VOT equals a 20 Hz shift in F0? Second, the approach to continuum generation is highly variable: some approaches would vary a single cue (Klatt, 1980), while others “morph” one natural recording into another (Kawahara et al., 1999).

However, standardizing how these manipulations are reported could yield two benefits. First, it could help understand similar effects applied across different speech sounds. For example, some perceptual learning effects appear to work differently across different speech contrasts (e.g., voicing vs. fricative place). However, without a standard unit these cannot really be compared. Second, it would allow rigorous quantitative standards—such as how big of a boundary shift is meaningful, or how steep is a slope—that can be applied across papers. Both are essential for meta-analyses.

One way to solve this problem is to rely on the phonetic measurements. If we assume that speech contrasts are coded as prototypes (not as a “boundary”), we know what a /b/ and a /p/ look like. We can measure a large set of cues for a /b/ in a set of recordings or in a corpus and use these to scale the continuum steps in terms of a proportion of the distance between the two prototypes.

Here, I work out an example of how this would work. I do this for several progressively more complex cases that range from a simple case of synthesizing a continuum along a single cue, to one that uses a more naturalistic morphing process (ala STRAIGHT).

S1.1 A single cue continuum

In this example, we consider constructing a VOT continuum for English. Typical approaches would start from 0 msec (canonically a /b/) and vary in 10 msec steps to maybe 50 msec (a /p/) (I’ve kept the continuum small to ease exposition). Let’s presume one has already made this continuum. How can this be standardized?

First, start by recording some tokens of /b/ and /p/. Since VOT is affected by the neighboring vowel, talker, speaking rate etc. these things should be roughly matched to your stimulus (e.g., use the same word, the same gender of the talker). If one is doing a form of copy synthesis (e.g., based on original recordings), one should use the same talker. However, even in this case, since individual tokens will vary from utterance to utterance, the experimenter should record multiple tokens of each endpoint.

Second, measure the VOT (or whatever cue is being manipulated) and compute the average for the endpoints. That becomes your prototype for each category.

Third, measure the VOT of each continuum member (if not already known from the synthesis parameters).

Finally, recompute the VOTs that were present in the continuum as the distance between the endpoints using equation 1.

$$\text{Step} = (\text{VOT}_{\text{actual}} - \text{VOT}_B) / (\text{VOT}_P - \text{VOT}_B) \quad (1)$$

For various assumptions, this would give something like the table below.

Fit of continuum to prototypes	Original VOT	0	10	20	30	40	50
Match	B: 0 msec P: 50 msec	.00	.20	.40	.60	.80	1.00
Continuum inside prototypes	B: -3 msec P: 58 msec	.049	.213	.377	.541	.705	.868
Continuum extends beyond prototypes	B: 5 msec P: 45 msec	-.125	.125	.375	.625	.875	1.125

This works equally well for a **log scaled continuum** (which is common for many temporal cues or frequency cues that are in the lower end of the scale such as F0 or F1). Here, the mapping from the original VOT to the proportion is still linear (to aid interpretation across studies, but the underlying continuum is logarithmic).

Fit of continuum to prototypes	Original VOT	0	1.2	3.84	9.65	22.42	50.5
Match	B: 0 msec P: 50 msec	.00	.024	.077	.193	.448	1.01
Continuum inside prototypes	B: -3 msec P: 58 msec	.049	.069	.112	.207	.416	.877
Continuum extends beyond prototypes	B: 5 msec P: 45 msec	-.125	-.095	-.029	.116	.436	1.138

S1.2 Multiple related continua

What about the case in which there are multiple VOT continua which vary in factors that may affect the prototypes? For example, consider an experiment which tested *beach/peach* and *back/pack*. Here the height of the vowel could affect the VOT. Or consider an experiment with a *beach/peach* continuum, but spoken by a male and female talker.

One should start by recording (as usual) multiple exemplars for each word and measuring the corresponding VOT. At this point there are two options. First, one could use slightly different prototypes for each continuum. This will result in different steps for each continuum. It may make it difficult to plot, but statistical analysis should not be problematic, since logistic mixed models can treat step as a continuous variable. Alternatively, one could average the prototypes and apply the same prototypes to both.

How one chooses to do this may matter. For example, if the goal was to capture differences between the two continua (e.g., do males have a different boundary than females), the first option will not work: by normalizing each continuum to separate male or female prototype values, you would be eliminating the differences you want to study. Here, using pooled estimates would make the most sense. Alternatively, if this is nuisance variance (you don't care about these differences), then separate prototypes would help control this and give you a more precise estimate of where each step lay along that continuum.

S1.3 Multiple cues in a continuum

Other times, one might simultaneously vary two cues, for example VOT and F0. Similarly, algorithms like STRAIGHT may simultaneously manipulate dozens of cues as it essentially morphs between two recordings.

Conceptually, we can use the same general procedure, but we have to do a little linear algebra. First, we need to identify each token of the continuum in a multi-dimensional cue space. For the VOT/F0 example, that's easy – those were decided in advance. For a case like STRAIGHT, one would need to identify the relevant cues and measure them for each token.

Next, we convert each of those cues to its relative location along each dimension using the formula defined above.

Original Values	VOT	0	10	20	30	40	50
	F0	140	144	148	152	156	160
Prototypes (from phonetic data)	VOT	-3					58
	F0	135					150
Relative Location	VOT	.049	.213	.377	.541	.705	.868
	F0	.2	.36	.52	.68	.84	1
	Combined	.124	.287	.449	.610	.772	.934

In this relative space, we can now visualize the prototypes located at <0,0> (/b/), and <1,1> (/p/). Each token has a coordinate in that space. The first step of the continuum, for example is at .049 on the VOT dimension, and 0.20 on the F0 dimension.

Next, we simply need to project that token onto its closest point along the diagonal. That will give us the relative location of that point *between* the two prototypes. This can be done with a little linear algebra (but actually, it turns out that you don't).

Start from a vector notation in which $\vec{s}$ stores the coordinates of that step $\begin{pmatrix} VOT \\ F0 \end{pmatrix}$. We need to project that point onto the closest point of a line defined by the vector, $\vec{v}$. Since we've relativized the distance, this vector is $\begin{pmatrix} 1 \\ 1 \end{pmatrix}$. We now apply the standard formula for projecting $\vec{s}$ onto $\vec{v}$

$$projection_{\vec{s}}(\vec{v}) = \frac{\vec{s} \cdot \vec{v}}{\vec{v} \cdot \vec{v}} \vec{v} \quad (2)$$

However, since $\vec{v} = \begin{pmatrix} 1 \\ 1 \end{pmatrix}$ this equation simplifies dramatically: $\vec{v} \cdot \vec{v} = 2$, and since the first half of the equation will be a constant (not a vector), multiplying it by $\begin{pmatrix} 1 \\ 1 \end{pmatrix}$ does nothing. Moreover, the dot product of $\vec{s} \cdot \begin{pmatrix} 1 \\ 1 \end{pmatrix}$ is the sum of the elements of $\vec{s}$. As a result the coordinates of the projection are now the sum of the two relative cues divided by two—the average! This can be done with any number of cues.

S.1.4 Summary

The procedures explained here share the goal of locating each step of a continuum along a line defined by two endpoints that are grounded in phonetic measurements of a real set of utterances. That is, 20 Hz of formant frequency change may be incommensurate with 5 msec of VOT; however, by converting both to 20% of the difference between the two endpoints, we now have a common scale. Adopting such procedures uniformly could help standardize and compare effects across different continua, and it could lead to standards (how big of a boundary shift is meaningful).

Critically, if one adopts this procedure, one should report (in a supplement) the details of the corpora on which the prototypes are based, the mean and variance of the prototypes, the specific prototypes used for each continuum, and both the raw (measured) continuum steps and the relative ones.

S2. Informal Observations about the History of Speech Perception

Categorical perception predates my birth by almost a decade. So, it is hardly my place to comment on the nature of the field at the time. And yet, I've been trained by folks who were there; I've [politely] fought with some them; and I've closely read much of that seminal work in a way that is not always done today. At the same time, I've also been involved in modern approaches that embrace more naturalistic samples, big datasets and sophisticated modeling, that admit more variability in speakers and listeners (though many younger readers may argue I don't go far enough), and that take advantage of much richer and more sophisticated phonetic analyses. So, as a sort of bridge, I'm in an interesting position to comment (classic Generation X, I suppose).

Figure S1 shows a photograph I took on my last visit to the Haskins laboratory. On the wall of their historical archives are original printouts¹ from Al Liberman and Franklin Cooper's seminal investigation of the phonetics of consonants (Delattre et al., 1955). Somewhat amazing is the breadth – every consonant of English in every vowel context. These are people who deeply appreciated what's in the signal and the way it varies across utterances.

Figure S1: Photographs of the original sound spectrograms posted on the wall of the Haskins Laboratory.

¹ Actually, “printout” is not the right word as it implies that there is some copy (digital or otherwise) that is reproduced on paper; at the time, this would have been the only available rendering of the spectrogram.

But at the same time, the more modern scientist in me can't help but notice what's missing. These are all spoken by the same person. They are all in a single syllabic frame (CV), and all spoken in isolation. Only three formants are present in most, and other cues that now know are important (e.g., duration, bandwidth, nasal zeros) may be difficult to measure. There is only one recording of each utterance. There was no way to pool these images for any kind of sophisticated statistical analysis. And the pattern playback generated utterances used to test these hypotheses are even simpler.

If this is where you were coming from, you can see the attraction of CP. However, if we had approached the problem with fresh eyes – appreciating the enormous variation of speech, the variable functions it must serve (phonological, sociolinguistic and others), and with the tools of big data would we have ever reached the same conclusion? It's not clear to me that we would have.

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