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Speech phones are a replication code

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Abstract — Our ability to map sound into pronunciation — vocal imitation — is necessary for vocabulary learning, and so the existence of language. It is also unexplained. Here I show that speech is imitable due because of the brain's use of the innate sensitivities of the vertebrate auditory system for speech motor targets. Their public nature enables speech to transmit articulation information. These units I suggest closely link with phones, the minimal unit of speech segmentation. The conjecture that phones function as a replicative code removes five unexplained anomalies in language science: (i) why nearly eight hundred phones exist but any language uses only a tiny subset of them (evolutionarily this makes no sense); (ii) why newborn infants hear phones of all languages; (iii) why animals also hear them; (iv) why the Wernicke's and Broca's areas arose from homologous areas in primates which process imitation, and why (v) in humans these areas process nonspeech imitation.

Introduction

Humans show an extraordinary ability to copy the pronunciation of overheard words. For instance, most of us during language tuition can readily imitate unfamiliar foreign words and phrases. Even severely retarded people can do this: one otherwise verbally handicapped individual was reported at the end of the nineteenth century to repeat with perfect inflexion sentences made in nine languages (1).

This ability to imitate speech is remarkable given that it requires our brain to derive complex motor program sequences using, if need be, only overheard sound. As will be reviewed below, such imitation abilities play a transient but critical-path role in language acquisition (most notably in the rapid expansion of an infant's spoken vocabulary). Indeed, the existence of automatic verbal imitation is required for the continued cross-generational existence of language. Yet, in spite of its importance, how the brain manages to map sound into pronunciation is at present unknown.

Another loose end scientifically is why spoken words arose so that the smallest unit we can hear in them, phones (and their component features), link to articulatory not auditory-related invariants. For instance, [d], irrespective of vowel context, is normally made by placing the tongue against the alveolar ridge of the palate, but acoustically [d] varies with vowel context: for example, in [di] it involves a rise in F2 frequency but in [du] it involves a fall (2). This linkage is shown in several other ways: phoneticians classify and characterize phones nearly entirely in terms of how they are articulated not how they sound — for instance, in the columns and rows of the International Phonetic Association Alphabet. Phonetics courses and textbooks teach the identification and production of individual phones in terms of movements in a student's own vocal tract rather than in terms of their sounds — indeed research finds that

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instruction in the 'silent making' of phones results in better recognition of them than auditory-based instruction (3). Phones and articulation are also neurologically and experimentally linked: for instance, lesions which impair phone production impair their perception (4); and the repeated listening to a phone primes the pronunciation of phones containing the same articulatory features (5). At present it is unexplained why the smallest unit we can hear in speech should link to articulation.

Until now, phones have been studied in terms such as how they transcribe pronunciation, or their contribution through a 'motor theory of speech' to word identification. I review the literature related to imitation, and propose instead that phones should be viewed neurobiologically as the means by which speech transmits the articulation information used to map speech into pronunciation.

Speech needs to carry such information otherwise the brain would find turning overheard words into vocal movements hard, and possibly impossible. This is particularly so since vocal imitation imposes tough information processing constraints.

- First, it requires mapping auditory information not only into motor movements but movements which recognizably recreate the original speech.
- Second, this mapping needs to be possible for an extraordinary variety of potential articulations — the world's languages use phones that differ in 13 vocal tract 'places' (from the lips to the space between the vocal cords, the glottis) and do so through no less than 11 types of movements (nasals to lateral clicks).
- Third, on top of this variety of phones potentially needing to be imitated, infants (who must imitate to learn new vocabulary) face the problem that they must copy movements made by adults with very different shaped and sized vocal apparatuses.

In contrast, opportunities rather than constraints characterize the better-studied problem of how the brain maps overheard speech onto word identities. Recognizing words can use many varieties of clues — visual, auditory and contextual. Importantly words do not have to be specially tailored to contain this information to aid their recognition. Thus on informational grounds, even though imitation is transient and identification central to processing everyday speech, we would expect speech to have arisen to primarily carry information to aid word imitation and so be closely linked to articulation. (This information, of course, as it is associated with word identities, could then also be secondarily used to recognize them.) Below, I present the case that the articulatory information present in phones indeed does serve primarily as an imitation code.

Imitation

People are fluent verbal mimics whether immediately (echolalia and shadowing) or after internal short-term and long-term memory verbal storage.

This ability is independent of language skills and intelligence — nonlinguistic echolalia, for instance, dominates the interactions of many otherwise nonverbal autistic and some mentally retarded people (6). Mimicry is also prelinguistic: 18-week-old infants spontaneously copy vocal expressions provided the accompanying voice matches (7). Imitation of vowels has been found as young as 12 weeks (8). In both normals (9) (during shadowing) and in retarded individuals (10) (during echolalia) repetition of words can happen within 250–300 ms. Indeed, people start imitating the second phone in the syllable [ao] (out of the set [ao], [aæ] and [ai]) quicker than they start it as a fixed response to spotting the second phone when given it as a member of this same set (11). As Porter and Lubker note 'simply *executing* a shift to [o] upon detection of a second vowel in [ao] takes very little longer than does *interpreting and executing* it as a shadowed response' (11). As they further note, this suggests 'that the early phases of speech analysis yield information which is directly convertible to information required for speech production'. Such a fluent, automatic and prelinguistic ability to transform audition into vocal motor programming is unlikely to have arisen without reason.

Language learning

Functionally, the most obvious explanation is that human languages, given their large multi-thousand word vocabularies, need to be learnable. While language skills might be innate, language vocabulary is not, and so, if language is to continue to exist, needs to be propagated across generations to new speakers. This can only happen if infants from an early age can readily copy into their vocabularies the many thousands of spoken words they hear used around them.

Experimental, clinical and observational research shows that infants imitate and that this expands their vocabulary. At around 2 years of age, young children imitate between 5% and 45% of their words (12). On top of these percentages an unknown but significant number of delayed imitations exist which have been picked up and reused from several days or weeks earlier (13). This word copying (whether immediate or delayed) plays a key role in vocabulary expansion — children that are more imitative of new words (but not ones already in their vocabulary) at 13 months have statistically larger noun vocabularies, 4 months later, than those that are not (14). Consistent with this, in older children, the ability to repeat nonword phone sequences (a measure of mimicry and storage) predicts vocabulary increase (15). Moreover, clinically, defects in word imitation link to language acquisition impairment (16).

Constraints

Imitation neurobiologically is a difficult problem: not only has sound to be mapped quickly and automatically into vocal motor programming, and has to overcome the three constraints noted in the introduction, but if faces four other problems.

- It must copy motor programs across vocal apparatuses even though individuals, on top of age and gender differences, vary widely in their shape and size.
- It must copy speech even though vocal motor movements have often started several speech units before they are pronounced — coarticulation. For example, in saying the English word 'tulip' the mouth rounds for making the [u] vowel while making the previous [t] consonant.
- It must not be limited to a single form of physical pronunciation as speech articulation is surprisingly adaptive. For instance, intelligible words can be made when people bite pencils, clench their teeth (such as in ventriloquism), have a cold; and even in spite of oral deformations such as harelips, cleft palates or tongue tip amputations. Indeed, the intelligibility of pronunciation following partial-glossectomy links not to the amount of tongue removed but the degree of postoperative lingual movability able to make compensating articulations (17).
- It must be prelinguistic, otherwise children could not use it to learn to make their first steps into langauge.

Any theory linking the articulation information in phones and imitation should also account for three other phenomena.

- Whatever the basis of vocal imitation it must overlap in its processes with those that form the basis of sign-gesture languages of the deaf such as ASL (American Sign Language). It would be difficult to conceive of the human species evolving two separate language processes: one for speech language and another for sign-gesture language.
- Initially, infants imitate and make whole words, and only then as they increase the size of their vocabulary do they refine their speech segmentation. Moreover, as this happens, young children's pronunciations often pass through a stage of becoming less accurate copies than their earlier ones (18). Any account of speech imitation and its code should explain why.
- The minimal units of speech exist as two separate phenomena: phones (the minimal units in speech perception and production, and studied in phonetics); and phonemes (the minimal units which linguistically contrast words, and studied in phonology). Oddly, these units always link and are often the 'same' — for instance, /d/ is a phoneme while [d] is a phone (phones and phonemes both use the same alphabetic-derived symbolization with phonemes placed in slashes and phones in square brackets). Why two closely related forms, not one, of speech segmentation?

Existing work

In spite of the importance of the brain's ability to map overheard sound into vocal motor programs, the study of how we imitate words has received little attention. In 1992 and 1994, for instance, two seemingly thorough encyclopedias were published upon language and linguistics (four and ten volumes, respectively), the latter in its attempt at exhaustiveness included lengthy entries upon Bats, Dance Notation and even Quakerism. Yet in spite of this exhaustiveness, both encyclopedias ignore imitation (or any of its synonyms) (19,20). The speech-copying problem (perhaps because it is transient, with its importance hidden in infant vocabulary expansion) does not as a scientific problem exist for most linguists and phoneticians.

Not that the existence of a function for the articulatory information present in phones has been overlooked: 'the motor theory of speech perception' argues that listeners identify spoken words through using that information to access their speech motor system (21). The recognition of words in continuous speech, however, cannot depend upon articulation information.

- The phones of words are hard to hear in words even when specially focused upon. Normally this difficulty is hidden because our 'top-down' knowledge of words aids (or rather gives the illusion) of detecting phones (22). However, in foreign speech this cannot happen. In such circumstances, even the most skilled phone hearers, phoneticians (who are known to have a heightened awareness of them (23)), can identify in spoken sentences only 70% of their phones (24).

- Moreover, if phones were the basis of word identification, speech perception should be vulnerable to the removal of information characterizing them. However, speech perception is robust — it is possible to remove electronically the information in speech by which phones are acoustically characterized, such as formant frequency transitions, steady-state formants and fundamental frequency changes and replace them with a three-tone sinusoidal replica and preserve its intelligibility (25).
- The use of context information dominates word identification. One in five words are recognized after the word following them has started (26). Everyday speech, further, is so poorly articulated that even in laboratory recording conditions two in three words of some speakers can be so indistinct in pronunciation as to be unintelligible outside of their spoken context (27).

The articulation information in phones thus cannot exist to aid word recognition (at least in continuous speech). By default this suggests it might exist in regard of something else such as aiding imitation. Positive arguments exist for making this link.

The origins of vocal imitation

Let us look at the problem of how speech might have arisen to be imitable, in terms of what is copied. Spoken words are sequences of motor movements created in regard to motor targets (28). This can be seen in the robustness of their movements against perturbation: for instance the perturbation of lip articulation results in target corrected adjustment (29). This is not a peculiarity of speech: a knocked arm is automatically readjusted to fulfil its spatial–temporal target (30). Thus speech imitation requires the imitation of its motor goals.

The organization of vocal movements in terms of motor targets, however, if auditory, would enable them to serve also as units of imitation. While many motor targets are spatial–temporal or in other ways private to the individual making them, if they aim at some acoustic parameter they are public. The motor targets of speech can therefore serve not only to organize vocal movements but serve to make them imitable.

Motor targets and imitation

Using motor targets compatible with imitation leads to robust speech imitation.

- It gets around the problem that vocal apparatuses anatomically differ. Our vocal apparatuses may vary but they can use, in spite of this, the same motor targets. Thus a code using targets allows children, in spite of their different sized and shaped vocal apparatuses, to imitate adults.
- It allows speech movements to be copied even though they can be done in many ways such as when clenching teeth, or after glossectomy. What is important to speech is not its actual articulation but the targets its articulators seek to achieve.
- Speech can articulate several speech movements at the same time — coarticulation. Nothing stops the preparation of one target while articulators are engaged in producing other ones. It is not the sequentiality of movements which matters (they can blend together) but the sequentiality of their targets.
- Moreover, it explains why human language can also be nonvocally mediated through visual-gesture signs, since both types of language can be organized around public targets (auditory and spatial–visual) and so use common neurobiological processes.

It is unlikely that such motor targets would have gone unnoticed by phoneticians. Phones and their features are an obvious candidate since their articulatory information links them closely (but as we see not exactly) with motor goals. To establish the details of this relationship we need to review the nature of 'acoustic targets': where they come from, how they link to the neurobiology and the cognitive development of speech.

Vocal targets

Targets which can be imitated must use appropriate acoustic parameters. Two informational constraints apply. First, imitable pronunciations must be producible by vocal tracts of different sizes and shapes. That rules out 'template' type acoustic invariants — the differing pitches of longer and shorter vocal apparatuses would prevent the mimicry of exactly similar sounds. However, sounds can be duplicable in regard to higher-order characteristics such as rates and shape of modulations (31) and rates and shape of frequency shifts. The production of these would be independent of anatomy. While simple sound resemblances between phones have not been detected, higher-order ones have: for instance, Delattre, Liberman and Cooper found with synthesized [d] + vowel syllables that while the second formant transitions of [d] in the syllables varied with their following vowel, they all pointed upwards or downwards to the same frequency locus (2). (I use this only as an illustration: the abstract acoustic properties linking [d] phones must be considerably more complex than this — for instance, evidence exists that acoustic invariants for place of articulation in stop consonants also occur in their onset bursts (32).)

A second constraint upon targets is that they must be perceptually discrete — either being perceived as one target or another. Abstract parameters that could blend between each other would require the imitation of degrees of blending and so would be difficult to copy. Discrete targets, in contrast, would enable imitation even when their perception was ambiguous (but weighted in one direction). One of the important characteristics of phone perception is that it is categorical — in a synthesized continuum between two phones, you either hear one phone or another, never a blend (33).

Abstract targets with these qualities exist in the auditory system's sensitivities to resonance and aerodynamic acoustic properties. As noted by the speech scientist James Abbs:

> 'For speech motor actions, the individual articulatory movements would not appear to be controlled with regard to three-dimensional spatial targets, but rather with regard to their contribution to complex vocal tract goals such as resonance properties (e.g., shape, degree of constriction) and or aerodynamically significant variables. ...Thus, for speech, the significant goals are the aerodynamic and acoustic response properties of the vocal tract (or respiratory system) which only in limited situations correspond to movements of a single structure.' (34)

This suggestion raises a problem, however: how could young children (unless they knew it somehow already) learn something as complex and abstract, for instance, that some speech sounds are the same because they share second formant transitions which point to a common frequency locus? Thus the use of acoustic properties as targets could only arise if humans were born prepared already to hear them. This makes a striking prediction: children should be able to overhear the phonetic distinctions of *all* languages, not just those spoken around them. No child, after all, could be born innately prepared to hear only its own surrounding language. For the phonetic distinctions which have been tested this has indeed been found (35). Infants are innately sensitive to the articulation of languages they have never heard (though this sensitivity is lost around 10 months) (36).

This, however, raises an evolutionary conundrum. A sample of 317 languages all together used 757 different phones (37). How could such variety arise when only a small subset (roughly one in twenty to one in forty) is used in any particular language? It offers no advantage. This situation, however, would be expected, rather than paradoxical, if speech reused the acoustic sensitivities already present in the vertebrate auditory system. This predicts that the potential for discriminating phones will exist widely in animals. Where the perception of features and phone contrasts has been tested in animals it has (much to the surprise of linguists) been found. The variety of animals involved ranges from chinchillas (38), dogs (39) and includes some birds such as Japanese quails (40). Indeed, paralleling the human auditory cortex sensitivity to phone invariants, direct recordings of the auditory cortex in monkeys finds that, in spite of their not hearing or making phones, they process the various parameters — fundamental frequency, voice onset time, place of articulation and voiced formant transition duration — needed to perceive them (41).

Phones, imitation and the brain

If phones link to imitation we would expect to find that phones and imitation share brain circuits. Consistent with this, electrical simulation studies of the human brain find 81% of areas showing that disruption of phone identification disrupted also the imitating of oral movements and vice versa (42). Further, lesions in the speech areas show a 0.9 correlation between those causing impairments to the copying of oral movements and those impairing phone production and perception (43).

Further, if phones arose from imitable motor targets, we would expect phone processing in the human brain to use areas in the primate brain specialized in the perception of motor targets and those linking movements perceived in others with their motor execution. The receptive aspect of phone detection takes place in the Wernicke's speech area — roughly the left superior temporal cortex — while the motor expression of phones takes place in part of the left inferior premotor cortex, the Broca's speech area (44). The homologous areas in nonhuman primates should therefore be specialized, respectively, in (i) motor target perception and (ii) the linking of perceived movements and their execution.

(i) Neurons responsive to motor targets have been found in the monkey superior temporal cortex (45). Input to provide auditory targets exists in adjacent areas of the temporal lobe, which as noted above has neurons responsive to the acoustic parameters characterizing phones (41). Thus the primate area homologous to Wernicke's speech area contains the neurons with the potential to perceive phones as motor targets.

(ii) Neurons activated both by actions seen in others and the same actions when performed by the animal itself have been found in the monkey inferior motor cortex area F5 homologous to the human Broca's speech area (46).

Consistent with these findings, functional imaging studies show both the Wernicke's and Broca's speech areas activate in the nonspeech activity of observing motor movements (47).

Acoustic targets, phones and phonemes

The reuse of innate acoustic sensitivities as vocal motor goals links but does not make them equivalent to phone features. Any language uses only a subset of the potential articulatory features with which speech can be copied. While the brain is born open to detect all of them, once the appropriate ones have been detected it can restrict itself to just that subset. This enables the neural networks in the brain to modify their processing (without changing their role as a replicative code).

- First, they can sharpen their detection by distorting the perceptual boundaries between them — the 'magnetic effect' (48).
- Second, they can systematize them in units shared across words. Initially, word pronunciations will be imitated and learnt independently of each other as whole pronunciation units rather than in terms of a series of units also present in other words — simply by virtue of the limited size of a child's vocabulary. Thus we would expect early pronunciation to be 'whole word' and unorganized with various phonetic inconsistencies. Later, as a small vocabulary is learnt, these pronunciations can be 'ironed out' around units found to be shared between words. Thus children would be later expected to reorganize, sometimes with a period of loss of accuracy, their first pronunciations in terms of their later pronunciation skills. The development of child speech indeed undergoes such a period of whole-word pronunciation followed by phonetic reorganization (18).
- Third, the set of pronunciation units used in any language is often redundant at the word level. For instance clear [l] (slightly palatalized) and dark [l] (slightly velarized) phones exist in English which do not differentiate word meanings. This gives many of the neural networks in the brain the freedom to ignore the difference between these phones when processing word meanings. Therefore, a linguistic level of word segmentation would be expected to arise which focuses upon the minimal contrastive units between words, in addition to those developed around pronunciation. As noted, linguistics makes such a distinction between phonemes and phones.

Thus in conclusion, neurobiologically, speech is organized around an imitation code which undergoes various neural network changes to yield us the observed speech units studied in phonetics and phonology.

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