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The role of Broca's area in speech perception: Evidence from aphasia revisited

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ABSTRACT

Motor theories of speech perception have been re-vitalized as a consequence of the discovery of mirror neurons. Some authors have even promoted a strong version of the motor theory, arguing that the motor speech system is critical for perception. Part of the evidence that is cited in favor of this claim is the observation from the early 1980s that individuals with Broca's aphasia, and therefore inferred damage to Broca's area, can have deficits in speech sound discrimination. Here we re-examine this issue in 24 patients with radiologically confirmed lesions to Broca's area and various degrees of associated non-fluent speech production. Patients performed two same-different discrimination tasks involving pairs of CV syllables, one in which both CVs were presented auditorily, and the other in which one syllable was auditorily presented and the other visually presented as an orthographic form; word comprehension was also assessed using word-to-picture matching tasks in both auditory and visual forms. Discrimination performance on the all-auditory task was four standard deviations above chance, as measured using d′, and was unrelated to the degree of non-fluency in the patients' speech production. Performance on the auditory–visual task, however, was worse than, and not correlated with, the all-auditory task. The auditory–visual task was related to the degree of speech non-fluency. Word comprehension was at ceiling for the auditory version (97% accuracy) and near ceiling for the orthographic version (90% accuracy). We conclude that the motor speech system is not necessary for speech perception as measured both by discrimination and comprehension paradigms, but may play a role in orthographic decoding or in auditory–visual matching of phonological forms.

1. Introduction

The discovery of mirror neurons in the monkey motor system, which are claimed by some to support action understanding (Rizzolatti & Craighero, 2004), has led to a resurrection of the motor theory of speech perception (D'Ausilio et al., 2009b; Fadiga & Craighero, 2006; Pulvermuller, Huss, Kherif, & Moscoso del Prado Martin, 2006). The motor theory of speech perception holds that recognition of speech sounds relies on mapping acoustic speech input onto motor speech representations in the listener (Liberman, 1957; Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967; Liberman & Mattingly, 1985). Despite the fact that a strong version of the motor theory has been all but abandoned by speech scientists (Galantucci, Fowler, & Turvey, 2006), some neuroscientists still promote such a view. For example, Fadiga and Craighero write, "Liberman's intuition. . . that the ultimate constituents of speech are not sounds but articulatory gestures. . . seems to us a good way to consider speech processing in the more general context of action recognition" (Fadiga & Craighero, 2006, p. 489). Consistent with this claim, recent functional imaging and transcranial magnetic stimulation (TMS) work has found that the motor speech system is indeed activated during speech listening (Watkins, Strafella, & Paus, 2003; Wilson, Saygin, Sereno, & Iacoboni, 2004) and TMS interference of motor cortex has been reported to modulate speech perception under some conditions (D'Ausilio et al., 2009b; Meister, Wilson, Deblieck, Wu, & Iacoboni, 2007; Watkins & Paus, 2004).

However, none of these studies provide a conclusive assessment of the causal role of the motor speech system in speech perception[1] (Hickok, 2009, 2010; Lotto, Hickok, & Holt, 2009). Functional neuroimaging is purely correlative, making it impossible to determine

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[1] "Speech perception" is an underspecified term that is variously used to refer to the ability to discriminate speech sounds, the ability to access phonological forms in the process of lexical access, or more generally to any operation involving the perceptual analysis of speech. It is empirical fact that the task used to assess "speech perception", e.g., discrimination vs. recognition/comprehension, not only affects performance, but in fact can double dissociate (Miceli, Gainotti, Caltagirone, & Masullo, 1980); for reviews see (Hickok & Poeppel, 2000; Hickok & Poeppel, 2004). Here we will use the term generically to refer to any task that involves analysis of speech signals and will qualify the term as needed to refer to specific operations or tasks.

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causality, and the TMS studies to date have demonstrated only very subtle effects on perception. For example, TMS induced modulations have only been reported for partially ambiguous stimuli (speech in noise or category boundary stimuli in a speech continuum) and the effect sizes are relatively small (~10% performance modulation); it is impossible to know whether this is a methodological limitation or an accurate reflection of the effect size.

Stronger evidence of a causal relationship between motor speech systems and the ability to perceive speech sounds is potentially available from lesion studies. Specifically, if the motor system is critical for the perception of speech sounds, then damage to the motor speech system should have a substantial impact on the ability to perceive speech. Research on aphasic patients conducted in the 1970s and 1980s appears to provide this critical evidence and is often cited by those promoting a critical role for the motor system in speech perception (D'Ausilio et al., 2009a; Wilson, 2009). For example, Basso and colleagues (Basso, Casati, & Vignolo, 1977) report that 74% of aphasics were impaired on a phoneme identification task and further that the incidence of impairment was greater for non-fluent aphasics (91% of patients) than fluent aphasics (72% of patients). However, another study of non-fluent Broca's aphasics reports only a mild deficit if any (~93% accuracy for the most difficult contrasts) on syllable discrimination[2] (Baker, Blumsteim, & Goodglass, 1981)[3]. However, these early studies did not have the benefit of modern neuroimaging methods and therefore could not reliably rule out cases with multiple or bilateral lesions, hemorrhagic stroke, and so on. In addition, these studies used percent correct as their dependent measure, which is subject to response bias, rather than a measure that controls for bias, such as d' (Green & Swets, 1966). It is therefore unclear whether the reported deficits are due to damage to the motor speech system and/or reflect perceptual discrimination or response bias.

One clue regarding the possibility of bias in these early measurements comes from a study (Baker et al., 1981) in which the data were reported separately for same and different trials in a discrimination task. Reading from their first figure, it is clear that for the more difficult place contrast discrimination, Broca's aphasics are more than four times more likely to err on different than same trials, indicating a bias to say "same". From the graphed values it is possible to calculate d' and bias measures which indicate good discrimination performance (d' = 3.78) with a bias to respond "same" (c = .38).[4] A more recent study re-examined the speech perception ability in a set of five case studies of patients with lesions in Broca's area (Rogalsky, Love, Driscoll, Anderson, & Hickok, 2011). This study reported at or near ceiling performance (>95% correct) on a battery of word comprehension and syllable discrimination tasks in the two patients with lesions that included frontoparietal regions but spared the temporal lobe. The other three patients had lesions that included temporal cortex but still performed with better than 95% accuracy on the word comprehension tests. Although this study clearly shows that damage to motor speech systems does not cause significant deficits in receptive speech ability, the small sample size limits generalization.

Additional evidence supporting the possibility that frontal lesions and speech production deficits do not predict perceptual deficits comes from another early study that reported a dissociation between perception and production of the voice onset time feature in speech sounds (Blumstein, Cooper, Zurif, & Caramazza, 1977). In this study, 4 out of 5 Broca's aphasics exhibited normal ability to discriminate VOT despite deficits in producing VOT accurately. Specifically, in these subjects, good VOT discrimination did not correlate with the ability to produce VOT, as they frequently produced phonetic distortions (i.e., VOT values that fell in an intermediate voiced/voiceless range), and less frequently phonemic substitutions (i.e., sounds that were clear voiced <–> voiceless substitutions). But again, the small sample size limits generalization.

The present study sought to revisit the role of the motor speech system in speech perception in a larger series of patients with radiologically confirmed damage to the motor speech system defined minimally as damage involving Broca's area.

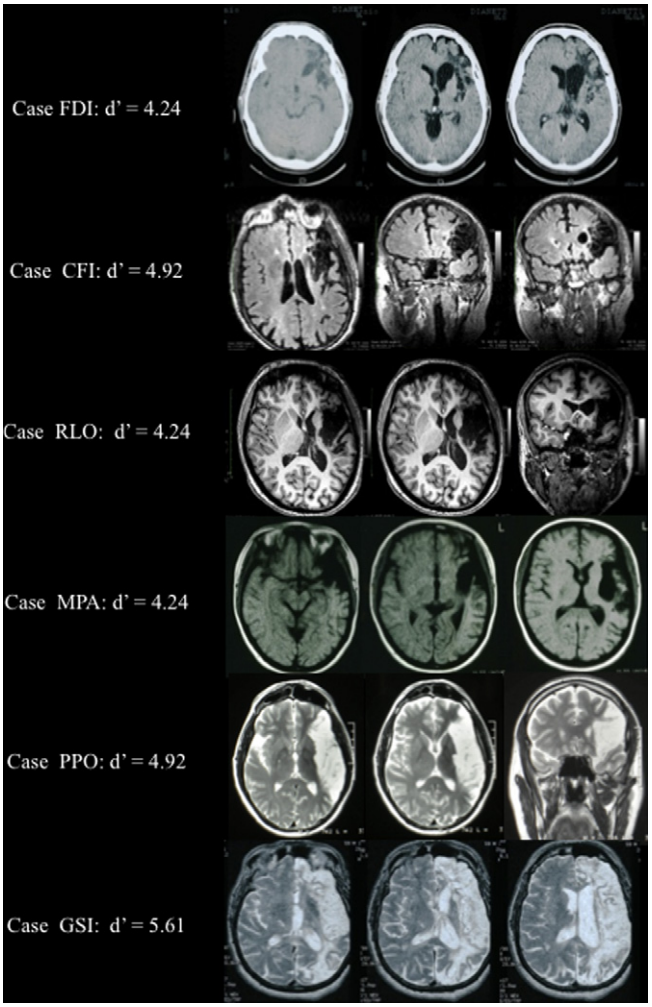

Fig. 1. Brain lesions in five participants showing damage to Broca's area and surrounding tissue. As is clear from these images, sometimes the lesions were quite extensive. Syllable discrimination performance (d') for each of these participants the auditory–auditory (A–A) task is also provided. Despite extensive lesions, performance was excellent: none of these subjects made more than two errors on the 60 item test and d' values were all 4.24 or better.

2. Methods

2.1. Subjects

All of 54 subjects in the patient registry of one of us (GM) were evaluated for damage involving at least a portion of Broca's region

[2] A reviewer pointed out that discrimination tasks may not require the participants to use categorical speech information, implying that such tasks may not be assessing normal speech processing systems as they are used in word recognition. We agree completely that discrimination and recognition do not involve identical operations (see Footnote 1), but do not agree that discrimination tasks, as they are typically used, do not involve analysis of or access to categorical information as is demonstrated by category boundary effects reported in many discrimination studies (see (Diehl, Lotto, & Holt, 2004) for review).

[3] This value is calculated from the raw mean error rates reported only in figure form for place contrasts. Note that this value of 93% differs from the value calculated by (Hickok, 2010), 85%, which was incorrect.

[4] Again the d' value differs from that calculated in (Hickok, 2010) which was incorrectly indicated as 4.8.