LISTENER–SPEAKER PERCEIVED DISTANCE PREDICTS THE DEGREE OF MOTOR CONTRIBUTION TO SPEECH PERCEPTION

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Listening speech sounds activates motor and premotor areas in addition to temporal and parietal brain regions. These activations are somatotopically localized according to the effectors recruited in the production of particular phonemes. Previous work demonstrated that transcranial magnetic stimulation (TMS) of speech motor centers somatotopically altered speech perception, suggesting a role for the motor system. However, these effects seemed to occur only under adverse listening conditions, suggesting that degraded speech may stimulate listeners to adopt unnatural neural strategies relying on motor centers. Here, we investigated whether naturally occurring interspeaker variability, which did not affect task difficulty, made a speech discrimination task sensitive to TMS interference. In this paradigm, TMS over tongue and lips motor representations somatotopically altered the discrimination time of speech. Furthermore, the TMS-induced effect correlated with listeners’ similarity judgments between listeners’ and speakers’ speech productions. Thus, the degree of motor recruitment depends on the perceived distance between listener and speaker. This result supports the claim that discriminating others’ speech pattern requires the contribution of the listener’s own motor repertoire. We conclude that motor recruitment in speech perception can be a natural product of discriminating speech in a normally variable and unpredictable environment, not merely related to task difficulty.

Keywords: interspeaker variability, motor system, motor theory, speech perception, TMS

Introduction

Several influential theories of speech discrimination have assumed that a listener’s representation of a speaker’s articulatory gestures participates in speech perception (Liberman and Cooper 1967; Stevens and Halle 1967; Fowler 1986; Callan et al. 2010). In contrast, several competing theories have suggested that a purely sensory analysis is sufficient for classification (Diehl et al. 2004).

Sensorimotor theories predict that speech classification is achieved in part through the listener’s internal recapitulation of the phono-articulatory gestures produced by the speaker. In support of that, motor and premotor activations have been reported while listening to speech sounds (e.g. Fadiga et al. 2002; Watkins et al. 2003; Binder et al. 2004; Callan et al. 2004; Wilson et al. 2004; Pulvermüller et al. 2006; Shahin et al. 2009; Londei et al. 2010).

Transcranial magnetic stimulation (TMS) has been used to alter activity in different motor centers to demonstrate their localized causal involvement in speech discrimination tasks (Meister et al. 2007; Möttönen and Watkins 2009; Sato et al. 2009; D’Ausilio, Bufalari, et al. 2011). However, most of the prior TMS studies used artificially degraded speech. When stimuli were presented without noise, the effects found in noisy/degraded listening conditions were not replicated (D’Ausilio, Bufalari, et al. 2012).

This observation has led some researchers to argue that the role for the motor centers is only modulatory and appears only in extreme circumstances (Hickok et al. 2011). A more direct criticism is that the stimulation of motor centers affects speech perception because of the use of “unnatural stimuli, eliciting atypical strategies based on atypical motor activities” (see Gernsbacher in Gallese et al. 2011).

In response to these criticisms, it should be noted that, in nature, speech stimuli are almost always noisy and degraded, since in normal conditions many factors induce a significant variation in speech stimuli. These factors can be external to the speech signal, as noisy environments, for example, driving in traffic, traveling in an airplane, sitting in a tapas bar or walking next to the seashore. Features that stress the perceptual system can also be intrinsic to the signal itself, because of different acoustic/phonetic patterns unique to each speaker. For example, the gender of the speaker, age and other variations in the vocal tract shape are pervasive sources of these interindividual variations, along with the speed and regional accent of pronunciation (Dupoux and Green 1997; Floccia et al. 2006; Adank et al. 2009). Secondly, even if motor effects were experimentally observable only with degraded stimuli, it would not prove that the motor system plays a minor or exceptional role. Thus, even the existing studies leave open the possibility that motor activation occurs in all cases of speech discrimination, but difficult judgments are necessary to make it experimentally observable.

In the present experiment, we introduced a common natural source of speaker variation, interindividual differences. Interindividual speech variability naturally increases the number of features not strictly relevant to the discrimination task, thus representing a possible confound without special degrading of speech. In this study, we applied online TMS to either lips or tongue motor representation while subjects discriminated syllables, with initial bilabial or dental consonants, spoken by 15 different speakers (following the method in D’Ausilio et al. 2009).
Our overarching goal was to develop evidence that an individual uses his/her own production system output as part of speech discrimination, matching it with the speaker’s input. If a perceivers uses an internal template based on his own production system, we expect to detect that the modulation on the motor system recruitment during perception is a function of the goodness of fit of the template of the perceiver with respect to the perceived speech features. Thus, similarities between the perceivers’ template and the speakers’ features should play a role in the degree of motor system recruitment during speech perception. To pursue this prediction, we measured subjective (perceptual judgments) and objective (acoustic measurement) distances between the experimental stimuli and the TMS subject’s own vocal productions. The goal was to verify whether interspeaker variability was a factor in the causal recruitment of the motor system and if the TMS-induced effects depended on subjective or purely acoustic distances between the stimuli and the subjects’ own vocal production.

**Materials and Methods**

**Subjects**

Twelve right-handed healthy subjects (6 males and 6 females, mean age and standard deviation: 27.8 ± 5.6 years) took part in the experiment. Subjects first participated in the TMS experiment and then in the multidimensional scaling (MDS) study. The 2 sessions were performed on different days. Participants were paid for their participation; the local ethics committee approved all procedures.

**Stimuli Database**

Audio recordings of 30 Italian native speakers (15 males; mean age: 29.1 ± 3.1 years) were collected. The speakers read the syllables presented one by one in a randomized order on a laptop screen using a PsychToolBox script running in Matlab (Mathworks, Inc.). Stimuli consisted of 8 different consonant-vowel (CV) syllables derived from the combination of 4 consonants ([b], [p], [t], [d]) and 2 following vowels ([a], [i]). Consonants were chosen with 2 different points of articulation (labials and dentals) and different voicing (voiced and voiceless) to match the experimental design of D’Ausilio et al. (2009). The 2 different vowels were included to give more variability to the stimuli. Each syllable was repeated 3 times. The stimuli were recorded with a professional microphone with the freeware program Audacity (http://audacity.sourceforge.net/). The recordings were processed to reduce background noise using Audacity’s built-in noise reduction tool (by a combination of noise reduction and frequency smoothing), down-sampled to 16 kHz, and segmented into 550 ms segments. Stimulus onset was aligned at 150 ms for every segment. Sound levels were then normalized using Vail’s normalization tool (available at http://normalize.sourceforge.net), and a second audio channel was parallel to each stimulus, with a sound spike 100 ms before stimulus onset. This channel was used to trigger TMS and was not heard by the subject.

**Stimuli Selection**

To find the subset of stimuli with maximum differences between speakers, we computed pairwise Euclidean distances between principal components of mel-frequency cepstral coefficients (MFCCs, widely used in speech research to analyze acoustic variability), and pairwise Euclidean distances between the formants f1 and f2 of the stimuli. For MFCCs, each segment was processed from 100 ms before the onset of the vowel to 50 ms after the onset of the vowel. This captured the voicing quality of the consonant together with its release and formant transitions. MFCCs were calculated using 16 ms windows with 5 ms overlap, resulting in 14 windows with 13 MFCCs each (a 182 dimensional vector for each segment). Calculating Euclidean distances between such large vectors leads to similar distances between every pair of tokens, limiting their usefulness (Beyer et al. 1999). To overcome this problem, we reduced the dimensionality of the MFCC vectors using standard principal component analysis (PCA), projected the data onto the first 15 principal components, and measured the Euclidean distances in the reduced space. The first 15 components accounted for 94.78% of the total variation in the MFCCs, which allowed for a reasonable approximation while avoiding the problems of high dimensionality. All calculations for MFCC, PCA, and Euclidean distances were performed using the SciKits library for Python (http://scikit.sappspot.com/).

The second measurement was related to formants, because they are strictly linked to dynamic configurations of the articulators. We used the first and second formant values measured at the midpoint of the vowel. Formant values were calculated automatically using the Forest Tool, which is part of the Emu Speech Database System (http://emu.sourceforge.net/). Formant distances and MFCC–PCA distances were each scaled to values between 0 and 1. For each stimulus, the formant and MFCC–PCA distances were summed to produce a final distance score. We then selected a subset of stimuli that maximized the combined distance scores of the subset. A set of 6 segments from different speakers was selected for each syllable type (including 3 female and 3 male speakers), by maximizing the distance scores between the 6 tokens (see Fig. 1). Maximization was done first by randomly choosing a segment as the point against which the distance scores would be measured. Segments were selected in order to maximize the sum of the distances from the previously selected tokens. This was repeated until the 3 tokens for each gender were selected, with only one token for each speaker. The selected set was saved together with the total distance score for all the selected segments. Thus, the final set of 6 segments was the set with the highest total distance score (Fig. 1). The entire procedure was repeated for each of the 8 syllables. The final set of stimuli consisted of 48 tokens (6 segments × 8 syllables). Since we did not constrain the selection of the speakers but only the maximization of the distance score, the final set of stimuli obtained comprised a subset of 15 (8 males) of the initial 30 speakers sample. We then ran a common PCA test (Flury 1988) to compare the covariance matrices of the 2 classes of stimuli. Using the “Jump-up” method described by Phillips and Arnold (1999) against unrelated/arbitrary structure we found that the 2 covariance matrices were proportional to each other ($\chi^2$, 253.02; degrees of freedom (DoF), 153; $P < 0.00001$), but not equal ($\chi^2 = 295.00$; DoF, 152; $P < 0.00001$), thus showing that the difference in covariance was statistically significant. This analysis was performed using Phillips’ CPC software (http://pages.uoregon.edu/philphil/programs/cpc/cpc.htm). Finally, we computed the Euclidean L1-norms for each covariance matrix (the maximum absolute column sum), showing that tongue-produced phonemes had larger variance than lips-produced ones (4.757 and 4.619). This fact comes to no surprise since the range of labial choices is much simpler than that of tongue possible configurations from a biomechanical point of view (Beaufremp et al. 2001), which, in turn, is reflected in a greater number of distinct places of articulation when considering the tongue with respect to the lips (Chomsky and Halle 1968; Clements 1985).

**General Procedures**

Participants were asked to listen to each audio trace presented through earphones and to identify the consonant in the CV syllable as fast as possible (ipsilateral to the stimulated hemisphere to avoid interference between hand response programming and TMS) by pressing on a 4-button response box the button corresponding to the consonant. Reaction times (RTs) and accuracy were recorded using the E-prime3 software (Psychology Software Tools, Inc.). The experimental session was divided into 2 blocks, one for each site of TMS administration (lips or tongue primary motor cortex). For each of the 2 blocks, the 48 audio files were repeated twice in a randomized order, with and without TMS, resulting in 96 trials for each block, with a total of 192 trials for each subject. The study lasted about 60 min (see TMS Specific Procedures section for more details). After the TMS study, all subjects were asked to record the 8 syllables with their own voices with the same PsychToolbox script and set-up used in recording the original stimuli (see Stimuli Database section above): This made it possible to subsequently measure the phonetic/articulatory distances between them and the heard stimuli.
In a second session (starting at least 60 days after the first TMS session), the same subjects were asked to complete the MDS experiment (see MDS Specific Procedures section). Subjects rated the similarity of pairs of stimuli (i.e. pairs of audio files) containing all combinations of the original TMS experiment stimuli and the newly recorded TMS subjects' vocal productions. Subjects never judged their own voice recordings. The presentation was performed by means of a Psychtoolbox function running under Matlab environment (Mathworks, Inc.).

**MDS Specific Procedures**

We used the MDS data to obtain similarity ratings between experimental subjects' voice recordings (recorded in the first experimental session) and the speakers' voice recordings (the auditory stimuli in the TMS study). The aim of the MDS experiment was to build maps of subjective distances between the speech characteristics of the experimental subjects and that of the stimuli. Indeed, the stimuli were selected with the objective to create a highly variable auditory space to test the hypothesis of motor recruitment under demanding conditions, thus leading to the possibility to test how the subjects perceived this space and how they fitted in this space. To build these (dis)similarity maps, a new superset of stimuli was assembled. The superset included all the syllables used in the TMS experiment (the subset of the original recordings) and the subject's own vocal productions. Pairs were created following certain constraints: The elements within a pair were always from speakers of the same gender and always involved the same syllable. The number of pairs of stimuli presented to the subjects was given by the calculation of all possible pairs of syllables irrespective of order by $\frac{n(n-1)}{2}$. This was adapted to the constraints described above, leading to the calculation of the number of possible pairs with male voices (10 male voices: 6 male voices obtained by recording the productions of the 6 male subjects in the TMS experiment, plus 3 male voices obtained from the recordings of the speakers—used as stimuli in the TMS experiment—plus 1 filler voice, which was not presented during the TMS experiment, leading to a total of 45 pairs) plus the number of possible pairs with female voices (10 female voices: 6 female voices from the recordings of the 6 female subjects in the TMS experiment, 3 female voices from the speakers, and 1 female filler voice = 45 pairs), multiplied by the number of syllables (8 syllables) leading to a total of 720 pairs. Each subject was presented with all pairs except those containing his/her own voice (72 pairs). These constraints resulted in 648 pairs. After listening to each pair, the subject reported the similarity by means of a visual analogue scale drawn on the computer screen, moving the mouse on a 100-step sliding cursor. Stimulus pair presentation was randomized for every subject and lasted approximately 90 min.

**MDS Experiment Analysis**

MDS was performed using the R statistical package (R Development Core Team 2008). First, a 2-dimensional solution was obtained for each syllable separately; the subject ratings were averaged and used to obtain a perceived distance map across speakers for each syllable type.
The cumulative sum of the first 2 eigenvalues divided by the sum of the absolute value of all eigenvalues for each solution was considered as a measure of goodness of fit of the 2-dimensional solution, and validated 2 dimensions as being sufficient for the representation of the subjective ratings (we do not discuss the 2-dimensional analysis further, since the aim of the analysis was not to explore underlying dimensions, but to obtain a simplified map of similarity distances). Maps of perceived distances were first obtained for each gender separately and were then merged together by centering the solution on the centroid given by averaging speakers’ position, resulting in a common 2-dimensional representation.

We then measured Euclidean distances between each subject’s recording coordinates and each speaker’s recording coordinates (in the common MDS 2-dimensional representation) to obtain a distance index. This index was used to investigate the relationship between the effect found in the TMS experiment and the subjective dissimilarity between subject-stimuli (speakers) individual characteristics. These Euclidean distances were then included in a correlational analysis with RT ratios data in R.

**Acoustic Distance Analysis**

Acoustic distances were calculated between the subjects’ own productions and the stimuli used during the TMS experiment, with the same method discussed above (cf. Fig. 1). MFCC vectors were calculated and PCA was performed to reduce the dimensionality of the vectors. Formant estimations together with the principal components of the MFCC vectors were used to calculate Euclidean distances between each token. These distances were then used to investigate the relationship between TMS effects and the acoustic interspeaker distances by applying correlational analysis in R.

**TMS Specific Procedures**

TMS was delivered through a figure-eight coil (50 mm) and a Magstim Rapid stimulator (Magstim Co., Whitland, UK). For each subject, the left primary motor cortex was first localized following standard procedures (Rossini 1994). Motor evoked potentials (MEPs) were recorded with adhesive Ag–AgCl electrodes (Digitimer 360 (Digitimer Ltd., Hertfordshire, UK); CED Power1401 (Cambridge Electronics, UK) acquisition board and Signal (version 4) software for data acquisition) from the right hand first dorsal interosseus (FDI) muscle. The motor threshold (MT) was identified as the lowest intensity of magnetic stimulation still able to elicit at least 50 µV MEPs (Rossini 1994). Lips and tongue stimulation sites were localized on the basis of FDI localization, and validated 2 dimensions as being sufficient for the representation of the subjective ratings (we do not discuss the 2-dimensional analysis further, since the aim of the analysis was not to explore underlying dimensions, but to obtain a simplified map of similarity distances). Maps of perceived distances were first obtained for each gender separately and were then merged together by centering the solution on the centroid given by averaging speakers’ position, resulting in a common 2-dimensional representation.

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**Results**

**TMS Experiment Results**

The direction of the TMS effect on behavioral measures (in this case, facilitation) depends on several factors, mainly represented by stimulation characteristics (frequency of pulses, timing with respect to stimulus) together with ongoing activity in the target area (Moliadze et al. 2003; Silvanto et al. 2008). Here, we adopted a stimulation procedure (see TMS Specific Procedures section), which in our previous studies led to similar facilitation effects (D’Ausilio et al. 2009; D’Ausilio, Bufalari, et al. 2011).

A global ANOVA showed a significant interaction between the point of articulation of the speech stimuli and the site of TMS (condition × stimulation site: $F_{1,11} = 7.123, P = 0.021$). Post hoc comparison using Holm’s adjustment for type 1 errors revealed that the difference in the RT ratio between labial and dental conditions was significant during tongue M1 stimulation ($P = 0.006$) but not during Lips M1 stimulation ($P = 0.19$). On the other hand, RT ratios for the identification of dental stimuli showed a significant difference between the 2 stimulation sites ($P = 0.049$), while labial stimuli showed almost as much difference ($P = 0.052$). Generally speaking, RTs were shorter for dental syllables ([l], [l]) during stimulation of Tongue M1 (ratio of RT TMS/no-TMS 0.94 ± 0.2) compared with Lips M1 stimulation (0.99 ± 0.2). Labial syllables ([l], [l]) were more rapidly discriminated during Lips M1 stimulation (0.95 ± 0.3) than during Tongue M1 stimulation (1.01 ± 0.2). Therefore, stimulating the primary motor cortex of the effector involved in the production of a heard syllable speeds up the discrimination of that syllable in a specific and congruent manner (Fig. 3). This result is in agreement with those in D’Ausilio et al. (2009).

That tongue motor area stimulation is more effective than that of the lips was already observed in our previous study (D’Ausilio et al. 2009). This might be due to several reasons: (1) The larger variability in the tongue stimuli dataset (see Stimuli Selection section); (2) the use of the first 2 formants (describing more tongue position) to compute distances in the
involved in speech discrimination not only in conditions of de-

The present study shows that the motor system can be critically

Discussion

of motor involvement during speech discrimination was

stimuli set; (3) the inclusion of vowels [a] and [i] which vary cri-

cically the tip of tongue position and only to a minor degree

(Chomsky and Halle 1968), and (5) the differences in the exten-

Correlations Between TMS Data and Distance Measures

The MDS procedure measured the subjective distances be-

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Discussion

The present study shows that the motor system can be critically

dependency on the difficulty of the task caused by acoustic inter-

Humans are extremely efficient in understanding speech
despite distortions of many different kinds (Mattys et al. 2009).
Distortions can be grouped according to their origin. External
distortions are those related to environmental factors, such as
background noise or signal filtering (Davis and Johnsrude
2003). Internal distortions are instead related to the specific
characteristics of the speaker, such as vocal tract differences,
rate, accent, or style of speaking (Dupoux and Green 1997;
Floccia et al. 2006; Adank et al. 2009).

Neuroimaging research on the processing of altered speech
typically investigates stimuli with external background noise
(Davis and Johnsrude 2003; Scott et al. 2004; Wong et al.
2009). These studies usually report noise-related activity in the
bilateral superior temporal gyrus (STG) and in the left inferior
frontal gyrus (IFG). While it is likely that the posterior STG
is part of a pathway for processing comprehensible speech
(Poldrack et al. 2001; Davis and Johnsrude 2003), the role of
IFG activation is less clear. A similar pattern of bilateral STG
and left IFG activation has been shown while listening to
speech pronounced with an unfamiliar accent (Adank, Davis,
et al. 2012), and a further study showed that bilateral IFG acti-

In the present study, interspeaker variability determined a
causal contribution of the motor system to the syllable dis-

The present result is particularly relevant for 2 main
reasons. First, it answers the concern that the motor system in-

Secondly, our findings confirm the previous evidence that
the listener’s brain actively compares others’ speech voices
with its own motor production template. In the present study,
we asked to rate the similarity between each experimental
stimulus and each TMS study participant’s voice. In this way,
by using a MDS procedure, we could extract a subjective map
of perceptual distances between listeners and speakers. Corre-
lation between MDS effect on RTs and these distances showed
that, the facilitation related to Tongue TMS was stronger for
those participants whose mean perceptual distance was
shorter from the TMS speakers with respect to the those whose
mean distance was greater, thus showing a gradient of motor
recruitment during perception, as evidenced by the cor-

Figure 3. TMS results. Bar plots represent mean RTs (TMS/no-TMS ratio) for the
syllable identification task. In the abscissa are shown the 2 sites of TMS (Lips M1 and
Tongue M1). Dark grey bars represent the dental syllables ([da], [di], [ba], [bi]) and in
light grey, the labial syllables ([pa], [pi], [ba], [bi]). Corrected P-values are shown for
each post hoc comparison.
modulatory role in perception of the motor system (Hickok et al. 2011), can hardly be reconciled with the somatotopically related, specific motor activity, modulated by the perceptual self-other distances, shown in our present study.

The direct relationship between the amount of motor recruitment and interspeaker subjective distance was limited to tongue-produced consonants. This may, in part, be explained by the relatively larger variance in the dental stimuli set. However, such differences in the stimuli set have been driven by other deeper characteristics of lips and tongue motor control. Tongue control has, indeed, been considered more complex from a biomechanical point of view. In fact, the tongue is believed to have 6 degrees of freedom, whereas the lips only 3 (Beautemps et al. 2001). Moreover, on a more linguistic ground, the Distinctive Feature Theory (Chomsky and Halle 1968; Clements 1985) suggests that only 2 features are unique to lips positions, whereas 10 are unique to the tongue. In other words, tongue control is far more complex, and thus, reconstructing others' tongue configurations from an acoustic signal may prove computationally more difficult.

Therefore, the motor system may better show its contribution when discriminating sounds associated with complex motor control, as opposed to any other motorically simple discrimination. Here, we confirm that the motor contribution to speech perception is stronger when the task poses some difficulties to the perceiver, ranging from the presence of noise in the signal (D'Ausilio, Bufalari, et al. 2012) to the presence of different speakers, as in the present experiment. In fact, the amount of motor recruitment may not be related to the signal-to-noise ratio in the auditory information, but rather to the complexity of the motor control of that specific motor gesture. In line with this idea is the fact that the RT TMS/no-TMS ratios and

Figure 4. Correlation analyses. Correlation analyses between TMS effect on RTs (ratio between RTs in TMS and no-TMS trials) and the distance measures. Upper panel (A) shows the correlation with the subjective distances (MDS procedure), whereas the lower one (B) shows the correlation with the objective acoustic measures. On the left side of both panels are represented the correlations during the stimulation of the Lips M1 and the labial syllables. On the right side instead are shown the correlations with the stimulation of Tongue M1 and dental stimuli.
objective distances based on acoustic features did not correlate. This latter result suggests that the motor system does not take into account variance in the acoustic features of other’s speech. Interestingly, subjective distances did not match the results of acoustic distances, and in fact, these measures did not correlate themselves ($r = 0.39$, $t_{6} = 0.26$, $P = 0.79$). This is an interesting result by itself, since it shows that when subjects are asked to rate similarity between 2 speech segments they eventually map them in a space of features that are not necessarily acoustic only. Indeed, it is possible that participants were referring to a prototypical phonemic representation during the similarity judgment task, which, according to the theoretical framework of motor theories of speech perception, would be the participants’ own production-to-perception mapping (Stevens and Halle 1967). By this view, the perception of others’ speech features would be grounded on an internal representation, that is, a template, formed by nonlinear combination of features, which magnifies instances close to the prototype and represents distant speakers in a more coarse detail, thus giving rise to greater or smaller motor simulations.

Taken together, all these findings are in favor of an active synthetic process (Kilner et al. 2004; Fadiga et al. 2006) more than a passive resonant mechanism. Active perception can be conceived as a model-based exploration of our environment. Although we do not perform explicit discrimination tasks in our daily activities, the brain is always building inferences on the external world, actively rather than passively receiving data to classify. Indeed, coping with motor stimuli that are distant from our own motor repertoire may require an active search for specific motor invariants to enable classification. In agreement with such a predictive account, we have recently shown that the motor system activity anticipates incoming articulatory events by exploiting probability of phone occurrence and extracting subtle coarticulatory features from past signals (D’Ausilio, Jarmolowska, et al. 2011). These results are in line with recent computational models of motor control (Friston 2011) and mirror-neuron mechanisms (Friston et al. 2011). According to these models, both action and perception try to minimize surprise and the mirror-neuron mechanism may therefore implement a Bayesian-optimal perceptual processing of others’ action.

Finally, the present results may have also some practical implication for automatic speech recognition (ASR). The issue of speech variability (as well as that of background noise) has always been a well-known problem for ASR (Huang et al. 2001). As a matter of fact, variability is to be considered the main unresolved and weakest point in any computational model of speech processing. In our opinion, understanding why and how the brain copes with input variability and noise in such a robust manner could provide new insights for a new generation of automatic speech processing systems by incorporating the principle of active motor matching. In this direction, are some attempts to acknowledge the beneficial role of articulatory features in improving phoneme/word classification (King et al. 2007). Very recently, our group has shown that the inclusion of articulatory knowledge during training of an artificial system for speech classification significantly increases classification accuracy, particularly in noisy conditions (Castellini et al. 2011). Epistemologically speaking, describing if, when and how, the variance of a specific motor feature determines better accuracy in ASR systems could be extremely informative on the relevant features used by the brain to solve similar tasks (Badino et al. forthcoming).

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**Notes**

*Conflict of Interest:* None declared.

**References**


