

The Sound of Actions in Apraxia

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Summary

Studies in nonhuman and human primates have demonstrated that sound-producing actions are mapped on the same mirror circuits that are activated during the visual recognition and execution of actions [1–12]. However, no causative link between the auditory recognition and execution of actions has been provided thus far. Here, we sought to determine whether patients with apraxia, who are by definition impaired in performing specific gestures, are also impaired in recognizing sounds specifically linked to human actions. Twenty-eight left-hemisphere-damaged patients with or without limb and/or buccofacial apraxia and seven right-hemisphere-damaged patients with no apraxia were asked to match sounds evoking human-related actions or nonhuman action sounds with specific visual pictures. Hand and mouth action-related sound recognition were specifically impaired in limb and buccofacial apraxia patients, respectively. Lesional mapping revealed that the left frontoparietal cortex is crucial for recognizing the sound of limb movements. By contrast, the left inferior frontal gyrus and adjacent insular cortex are causatively associated with recognition of buccofacial-related action sounds. These behavioral and neural double dissociations indicate that a left-lateralized multimodal mirror network is actively involved in the body-part-specific motor mapping of limb and mouth action-related sounds, as well as in the execution of the very same actions.

Results

In the present study, we devised a novel test to explore the ability of brain-damaged patients with or without limb and buccofacial apraxia to recognize actions on the basis of the sound produced by them and to execute limb or buccofacial actions associated to the heard sounds. Apraxic patients who, by

definition, are impaired in intentional action execution [13–15] may be an excellent model for testing the active role of specific neural structures in performing actions, as well as in seeing them or listening to their sounds.

We combined behavioral results with lesion-mapping techniques to explore (1) whether apraxic patients present with a consistent association between difficulties in producing and recognizing actions by listening to the sound typically associated with these actions, an issue that has been addressed in a few visual studies [16–19] but never in the auditory domain; (2) whether body-part-specific gestural-production impairments (i.e., limb versus buccofacial apraxia) [20, 21] may parallel similar defects in gesture comprehension (in other words, we wondered whether patients with limb apraxia may show deficits mainly in recognizing “hand clapping” and whether patients with buccofacial apraxia may show deficits mainly in recognizing “whistles”); and (3) whether the action-sound recognition process associated with body-part-specific apraxia is associated with distinct lesion locations. This is also particularly important in view of the fact that the anatomical substrates of buccofacial and ideomotor apraxia are likely different [22, 23].

Thirty-five patients with unilateral left (LBD) or right (RBD) brain damage participated in the study. Twenty-one LBD patients performed below the cutoff in action-imitation tests specifically tapping limb apraxia [24] (LA, mean \pm standard deviation [SD] = 49.23 \pm 11.74) and/or buccofacial apraxia [25] (BA, mean \pm SD = 13.46 \pm 3.33) and were assigned to the Apraxia (A+) group. Seven out of these 21 LBD patients exhibited both BA and LA (A+[B+L+] group), seven exhibited only BA (A+[B+L-] group), and seven exhibited only LA (A+[B-L+] group). The remaining 14 patients, i.e., seven with LBD (A-[LBD]) and seven with RBD (A-[RBD]), did not show any signs of apraxia and were assigned to the A- group (see [Supplemental Experimental Procedures](#), available online, for additional demographic and clinical data). Lesion overlap of patients with or without apraxia confirmed the crucial role of frontal and parietal areas in apraxia (see [Figure S1](#) for lesion distribution). Lesions of the insula, the posterior pars opercularis of the inferior frontal gyrus (IFG), and the rolandic operculum were mainly associated with buccofacial apraxia, whereas lesions involving the inferior parietal lobe (IPL), the supramarginal gyrus (SMG), and the superior temporal gyrus (STG) were mainly associated with limb apraxia (see also [Figure S2](#) and [Table S1](#)).

Comprehension of Action Sounds

In the novel sound-picture matching test used in this study, each patient was asked to listen to a sound and then choose from among four pictures the one corresponding to the heard sound. The sounds used included limb-related action sounds (LRAS), buccofacial-related action sounds (BRAS), and nonhuman action-related sounds (NHARS). Examples of stimuli and event trials are shown in [Figure 1](#) (see [Supplemental Experimental Procedures](#) for a list of the auditory stimuli and information on the preliminary psychophysical studies). Correct sound-picture matching responses (mean and standard error of the mean [SEM]) for each category of sounds in the five patient groups are shown in [Figure 2](#). These values were entered in an analysis of variance (ANOVA) with group

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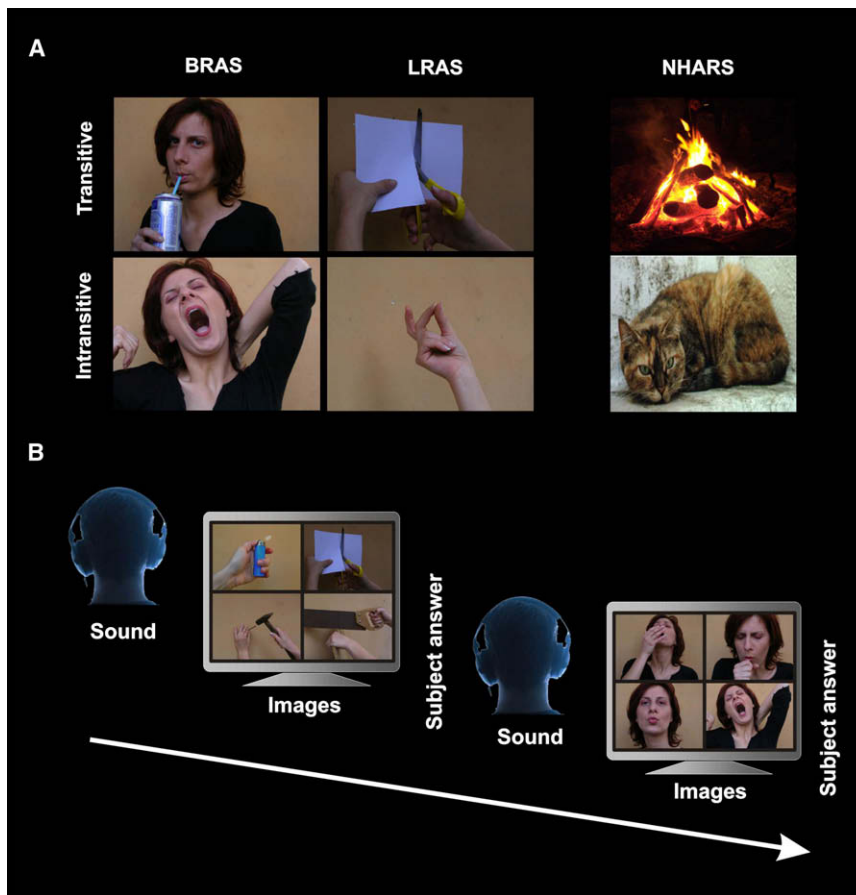


Figure 1. Experimental Design

(A) Examples of visual stimuli associated to buccofacial-related action sounds (BRAS), limb-related action sounds (LRAS), and nonhuman action-related sounds (NHARS).

(B) Schematic representation of two trial events related to hand and buccofacial actions, respectively. The patients heard a sound stimulus, lasting 2 s. A four-picture set appeared on the screen 100 ms after the end of the sound presentation, and the patients were required to select the correct picture associated with the heard sound. Sound stimuli were presented in a randomized order, and the spatial position of the correct target picture varied in each trial (see [Appendix S1](#)).

patients performed significantly worse in matching buccofacial-related sounds (mean hits = 11.85) with respect to limb-related (mean hits = 13.42, $p = 0.01$) and nonhuman action-related sounds (mean hits = 14.14, $p = 0.0007$).

Remarkably, between-group comparisons (performed with the Newman-Keuls post-hoc test) showed that whereas matching of buccofacial action-related sounds was significantly better in $A_{+(B-L+)}$ than in $A_{+(B+L-)}$ (mean hits = 13.85 versus 11.8, $p = 0.002$), the opposite was true for limb action-related sounds (mean hits = 12 versus 13.43, $p = 0.009$). Therefore, the translation code converting sounds into body

actions seems to follow body-part-specific mapping rules. Interestingly, a nonsignificant trend toward a better performance in matching nonhuman action-related sounds (mean hits for NHARS = 9.71) as opposed to human action-related sounds (mean hits for LRAS = 8.71 and for BRAS = 8.57) was observed in the most impaired group (i.e., the $A_{+(B+L+)}$ group; $p = 0.06$ and 0.08).

Studies indicate that the ability to perform transitive and intransitive actions may be double-dissociated in patients with apraxia [26]. However, no main effect or interactions related to transitive or intransitive action sounds were significant, thus indicating that this variable did not play any major role in our task (see [Supplemental Results](#) for details).

It has been reported that LBD patients with aphasia may exhibit impaired comprehension of both linguistic and nonlinguistic sound stimuli (e.g., action and environmental sounds), thus suggesting that these sounds may share a common neural substrate [27]. This raises the question of whether the deficits in processing action sounds exhibited by our apraxic patients may be related to language problems. However, we demonstrated that language-comprehension deficits do not covary out with sound-recognition performance (see [Supplemental Results](#)).

Deficits in Performing Limb and Mouth Actions and in Recognizing Them by Their Sounds

Studies in the visual domain demonstrate that deficits in viewing and performing actions are positively correlated [18, 19, 28]. However, it is worth noting that not only associations [16–19] but also dissociations between viewing and

($A_{+(B+L+)}$, $A_{+(B-L+)}$, $A_{+(B+L-)}$, $A_{-[LBD]}$, and $A_{-[RBD]}$) as the between-subjects factor and type of sound (LRAS, BRAS, and NHARS) as the within-subjects factor.

The main effect of the group was significant ($F_{[4, 30]} = 38.15$, $p < 0.0001$). Post-hoc test for multiple comparisons showed the following: The $A_{+(B+L+)}$ group performed (mean hits = 9) significantly worse than the other four groups (all $p < 0.001$); the two $A_{+(B-L+)}$ and $A_{+(B+L-)}$ groups (mean hits = 13.43 and 13.14) performed with comparable accuracy but significantly worse than LBD and RBD nonapraxic groups (mean hits = 14.8 and 14.6; all $p \leq 0.04$), which in turn did not differ from one another. This effect can be parsimoniously explained by the finding that the $A_{+(B+L+)}$ group presented with significantly larger lesions with respect to all the other groups (see [Supplemental Results](#) for details).

The significance of the effect of type of sound ($F_{[2, 60]} = 7.2$, $p < 0.001$) is explained by better performance with nonhuman action-related sounds (mean hits = 13.51) compared to the buccofacial-related sounds (mean hits = 12.8) and limb-related sounds (mean hits = 12.69) ($p \leq 0.0038$).

Crucially, the group \times type of sound interaction was significant ($F_{[8, 60]} = 4.57$, $p < 0.0002$). The Newman-Keuls post-hoc test for multiple comparisons showed that whereas no differences in accuracy for different sound categories were found in RBD and LBD patients without apraxia, a different pattern of results emerged in patients with apraxia. Indeed, $A_{+(B-L+)}$ patients performed significantly worse in matching limb-related sounds (mean hits = 12) compared to buccofacial-related sounds (mean hits = 13.8, $p = 0.002$) and nonhuman action-related sounds (mean hits = 14.43, $p = 0.0005$). Moreover, $A_{+(B+L-)}$

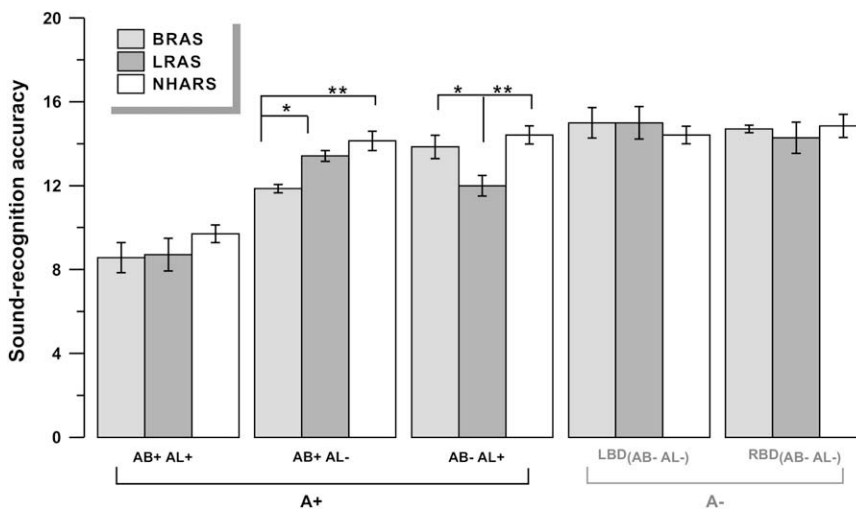


Figure 2. Accuracy in Action-Sound Recognition
Mean correct recognition responses for each category of sounds (LRAS, BRAS, and NHARS) in the five patient groups. Error bars indicate the SEM. Asterisks indicate significant post-hoc comparisons (* $p < 0.01$, ** $p < 0.001$). Note that sound-picture matching scores in non-brain-damaged subjects were as follows, presented as mean \pm SEM: BRAS = 17.8 ± 0.25 ; LRAS = 17.6 ± 0.32 ; NHARS = 18.1 ± 0.20 .

overlaps for (1) recognition plus execution tasks for BRAS and LRAS (lower row, left and middle columns, respectively), which reveal the lesional correlate of body-part-specific deficits independent of the process impaired, and (2) BRAS plus LRAS for recognition and execution tasks (rightmost column,

performing actions have been reported at both the group [29, 30] and single-case level [31, 32].

Moreover, causative evidence for the possible relationship between understanding actions by their sounds and executing the very same actions is lacking. To deal with this issue, we asked our patients to perform eight buccofacial actions and eight limb actions selected from those previously used for the sound-picture matching test. We chose the gestures so as to involve almost exclusively the buccofacial region or the upper limb (see Appendix S1). During execution of sound-associated actions, patients were allowed to look at pictures depicting the action to be performed.

Correct recognition and execution scores (raw values, mean, and SEM) for buccofacial and limb action sounds in the three apraxic patient groups are reported in Figure 3 (see also Supplemental Results). Whereas the body-part association between auditory mapping and action execution reported in the present study is clear at the group level, dissociations between these two abilities were found at the single-case level (see Table S2). This is in keeping with clinical studies [30–32] demonstrating that the range of possible dissociations between action execution and action comprehension that can occur in apraxia is quite multifarious and cannot be explained by simple perception-action mirroring mechanisms.

Lesion Analysis

To explore the neural underpinnings of defective recognition of action-related sounds and the execution of the action evoked by the same sounds, we analyzed the lesions in the four subgroups of patients with LBD by using a voxel-based lesion-symptom mapping (VLSM) procedure (see Supplemental Experimental Procedures). We determined the lesioned voxels that predicted ($p < 0.05$; Brunner-Munzel analysis) impairments in the recognition of sounds related to buccofacial, limb, and nonhuman actions (see Supplemental Results), as well as in the execution of buccofacial and limb actions evoked by specific sounds.

Cortical Regions Causatively Associated with Recognition and Execution of Human Action-Related Sounds

Figure 4 shows the VLSM threshold at voxel-wise $p < 0.05$ (false-discovery-rate correction) for the recognition of buccofacial and limb action-related sounds and the execution of actions related to the same sounds. Figure 4 also shows lesion

upper and middle rows, respectively), which reveal the lesional correlate of recognition and execution deficits independent of the topography of the deficit. Lesions associated with deficits in the recognition of sounds related to buccofacial actions primarily involved regions including the left IFG and insula and the nearest lateral anatomical region of the precentral gyrus and rolandic operculum. Two main lesional clusters were associated with deficits in matching sounds related to limb actions. One cluster involved the SMG and the IPL and extended to the underlying parietal white matter and the STG. The other cluster involved the IFG and insula and extended to the rolandic opercularis region. This lesional pattern indicates that whereas deficits in matching LRAS seem to be related to both frontal and parietal lesions, those in matching BRAS seem to be related to frontal lesions. The insula appears to be affected in both cases, although its involvement in matching buccofacial action-related sounds is higher than in matching limb action-related sounds (highest Z score for BRAS is 7.62 [MNI coordinates $-37, 13, 13$] and for LRAS is 4.32 [MNI coordinates $-47, 11, -7$]).

An impaired performance in the execution of actions related to buccofacial sounds was significantly associated with lesions of the rolandic operculum and pars opercularis of the IFG as well as of the insula, and it was associated to a lesser extent with lesions to the inferior parietal cortex. An impaired performance in the execution of actions related to limb sounds was associated with lesions involving the entire inferior parietal cortex as well as the IFG and extending to the rolandic operculum.

The correlations between anatomical maps shown in Figure 4 were computed by means of the NIFTI toolbox in Matlab (<http://www.rotman-baycrest.on.ca/~jimmy/NIFTI/>). Such correlations indicate that the lesioned voxels actively associated to deficits in execution tasks also play a role in gesture-comprehension deficits. The relationship between damage to these regions has a fundamental, predictive value, as indicated by the comparisons between recognition and execution related to the same effector (r [exeBRAS, recBRAS = 0.78] $>$ r [exeBRAS, recLRAS = 0.71] and r [exeLRAS, recBRAS = 0.63] $<$ r [exeLRAS, recLRAS = 0.74]).

Discussion

The ability to infer and describe others' actions from the sound they produce is fundamental in the absence of visual

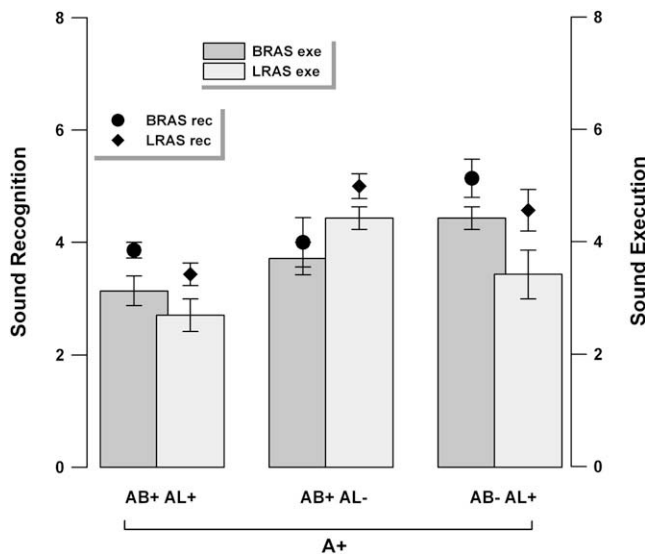


Figure 3. Accuracy in Comprehension and Execution of Human Action Sounds

Mean correct responses in recognition and execution of the eight LRAS and eight BRAS in the three apraxic groups. Error bars indicate the SEM. Note that mean correct responses in nonapraxic groups were as follows, presented as mean \pm SEM: recognition in LBD patients: BRAS = 7.86 ± 0.14 ; LRAS = 7.86 ± 0.14 ; recognition in RBD patients: BRAS = 7.86 ± 0.14 ; LRAS = 7.71 ± 0.18 ; execution in LBD patients: BRAS = 7.71 ± 0.18 ; LRAS = 7.86 ± 0.14 ; execution in RBD patients: BRAS = 7.71 ± 0.18 ; LRAS = 7.71 ± 0.18 .

information concerning the same actions. Humans, for example, are able to infer from the doorbell sound that the postman is ringing twice or even to attribute precise identity to others simply by hearing their footsteps. Therefore, relevant aspects of social actions are acquired not only through sight, but also through hearing. By combining a psychophysics paradigm based on a novel sound-picture matching test with lesion-mapping procedures, we obtained three main findings concerning audio-motor mirroring in humans. The first is that audition-mediated human action-recognition and action-execution abilities are closely linked at the behavioral level. The second is that the frontoparietal regions that underpin action-sound recognition largely overlap with the regions that underpin action execution. Importantly, no such overlap between non-human action-sound recognition and action execution was found. The third is that audio-motor mirroring is inherently embodied and is likely to take place according to body-part-specific coordinate systems.

Hearing and Doing in Apraxia

The notion of parity between the motor and perceptual aspects of action processing is based on neurophysiological and neuroimaging studies in monkeys and humans, which show that merely viewing others' actions triggers an automatic, simulative mapping of observed actions onto specific regions of the onlooker's brain [33–35]. This action mirroring, which is likely to be fundamental to understanding what the observed agent is doing [36], has been mainly demonstrated in the visual domain [33]. Important studies in monkeys [1, 2, 37] and humans [3, 6, 7, 38] hinted at a close link between auditory input and action mirroring. Recent studies demonstrate that hearing sounds associated with intransitive [4, 5] or tool-use-related human actions [6] activates not only cortical areas

related to auditory processing, but also a set of left-lateralized frontotemporoparietal areas that are also linked to action execution. Even highly complex properties of the sounds heard, such as phonetic [7] or semantic features [8, 9], as well as their emotional qualities [10] can be mapped in the mirror motor system. Electrophysiological [4] and functional magnetic resonance imaging (fMRI) [3] investigations provided correlational evidence that the motor mapping of heard actions occurs according to body-part-centered mapping rules. Moreover, motor mapping of heard actions may be plastic and linked to expertise [11, 12]. However, no evidence of an active role of specific brain structures in modulating hear-do mirroring processes has been provided thus far.

Here, we provide this evidence by showing that (1) deficits in comprehending human action-related sounds parallel deficits in performing the same actions and (2) audio-motor mirroring seems to be causatively linked to a left-sided frontoparietal network, a result in keeping with fMRI studies showing that the human auditory mirror system is correlationaly linked to a left-hemispheric temporo-parieto-premotor circuit [3]. Our results also expand on some of the few studies conducted in apraxia demonstrating that impairments in the visual recognition of actions paralleled deficits in performing these actions [16–19, 28].

Audio-motor mirroring is fundamental when visual information is absent. However, it is worth noting that during daily life conditions, action mirroring is inherently multimodal, and it is hardly possible to rule out that vision plays a role. Indeed, single-cell recording studies clearly reported the existence of trimodal, triple-duty mirror neurons that are activated when acting, seeing an action, and hearing the sound associated with that action [1, 2]. Moreover, visual and mental imagery may be at play both in audio-motor [3] and olfacto-motor mapping [39] studies. Thus, it is entirely plausible that although primarily auditory, the matching process requested by our task may also have tapped resources of visual and mental imagery. More generally, the suggestion is made that patients with specific action deficits may have problems in the multisensory mapping of the very same actions. Moreover, the dissociations at the single-case level indicate that motor execution deficits do not necessarily account for all the possible instances of action-recognition deficits. Therefore, although strong forms of the motor theories of action recognition are not supported by our data, the suggestion is made that motor production modulates perceptual action recognition no matter whether it is mediated through visual, auditory, or multimodal sensory inputs.

Body-Part-Centered Matching of Mouth- and Limb-Related Human Action Sounds in Patients with Buccofacial and Limb Apraxia

We designed the present study to explore, at the behavioral and neural levels, effector-specific relations between action execution and the recognition of the same actions by listening to their audible output. It is relevant that the results of the sound-picture matching test go hand in hand with those of the lesion-mapping analysis. Patients with deficits in performing limb and buccofacial actions were impaired in matching limb and mouth action-related sounds, respectively. It is relevant that hand-action observation in subjects with limb apraxia brought about the activation of mouth and foot representations, i.e., the effectors these subjects use to achieve the goal that typically developed individuals achieve using the hands [40]. Therefore, we can speculate that our body-part-specific impairment in audio-visuo-motor mapping may not simply be

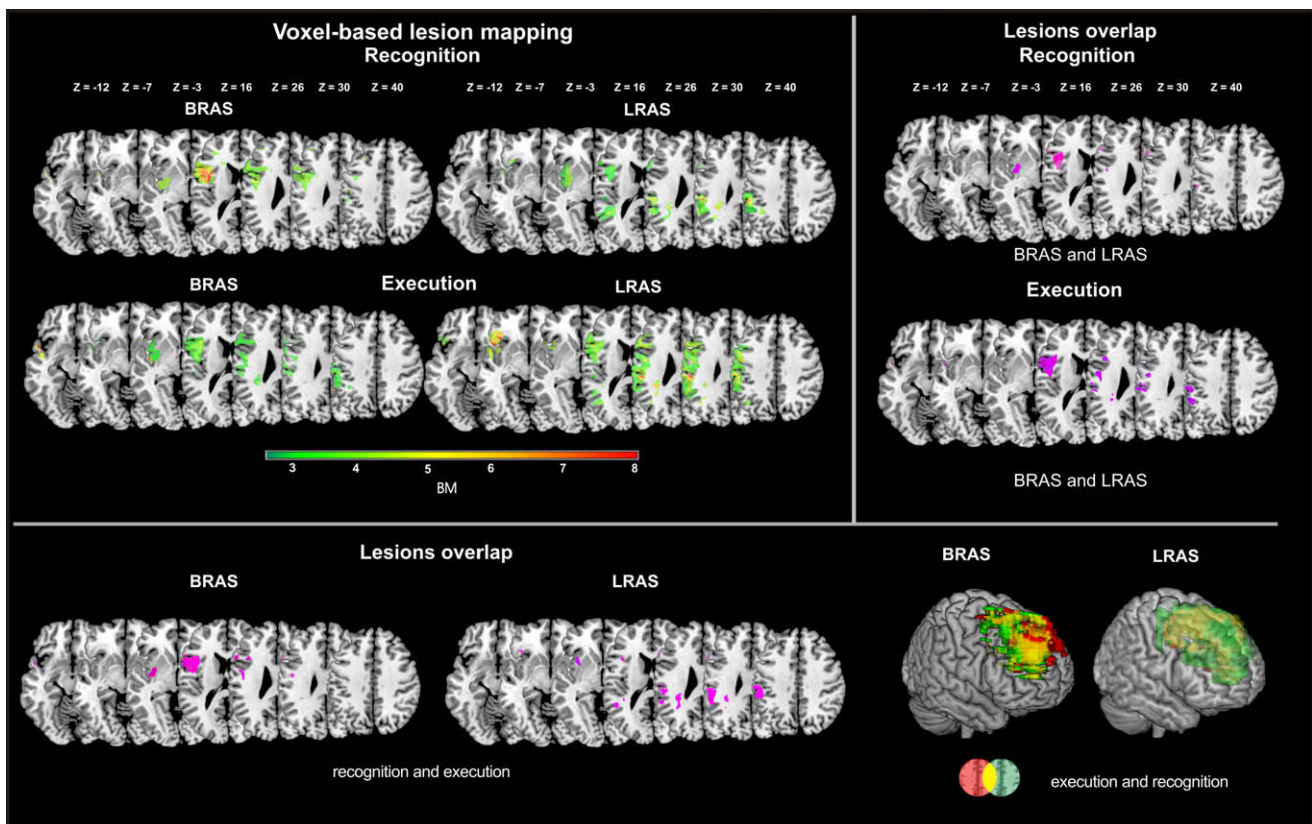


Figure 4. Voxel-Based Lesion-Symptom Mapping for Buccofacial and Limb Recognition and Execution of Human Action Sounds

The maps show the Z statistics corresponding to the nonparametric Brunner and Munzel rank-order statistic test comparing the behavioral performance of lesioned and intact patients on a voxel-by-voxel basis. The behavioral measures were the patients' accuracy scores in (1) matching BRAS and LRAS to the corresponding visual images and (2) executing the actions related to the BRAS and LRAS. A false discovery rate (FDR)-corrected alpha level of $p < 0.05$ was used. Comparisons were conducted across all the voxels that were lesioned in at least 3 out of the 28 LBD patients. The results of the voxel-based lesion-symptom mapping (VLSM) for BRAS and LRAS recognition are reported in the upper row, left and middle columns, respectively. The results of the VLSM for execution of actions related to buccofacial and limb sounds are reported in the middle row, left and middle columns, respectively. Lesion overlaps in the BRAS and LRAS recognition plus execution are shown in the lower row, left and middle columns, respectively. Lesion overlaps for recognition and execution of BRAS plus LRAS are shown in the rightmost column, upper and middle rows, respectively. Renderings of the maximal overlap lesion for recognition and execution of BRAS plus LRAS are shown in the extreme right part of the figure.

due to the observation of the effectors used by the model for performing a given action, but also to the listener's difficulty in achieving the goal of the heard action because of the specific execution deficit.

Remarkably, the impaired recognition and performance of buccofacial action-related sounds were associated with left anterior lesions (e.g., mainly in the IFG and insula), but not with posterior lesions (e.g., in the inferior parietal region). In contrast, the recognition of sounds related to limb action was predominantly associated with lesions mainly involving the IPL, SMG, and angular gyrus, but also extending as far as the IFG. Therefore, whereas lesions to frontal areas may be causatively linked to audio-motor mirroring of buccofacial actions, lesions centered upon parietal areas and involving frontal regions may be associated to deficits in audio-motor mirroring of limb actions. This behavioral and neural double dissociation may have to do with differences between the two types of movements. Buccofacial actions comprise a limited set of uniform elements, mainly differing in their serial position, and require precise selection, coordination, and timing of sequences. Moreover, these movements are restricted to a fixed number of planes, can vary along a limited set of degrees of freedom, and typically do not rely on online visual feedback. In contrast,

limb actions involve multiple degrees of freedom and spatial planning, and they are typically performed under visual control that codes the limb-body relationship and integrates various sensory inputs according to different allocentric and egocentric coordinate systems [41–43]. Studies in monkeys seem to suggest that the IFG and IPL are neurally equipped for such a division of labor [44]. Thus, our findings significantly expand on studies showing that the parietal cortex is crucially involved in hand and leg apraxia [18, 45], whereas the IFG, insula, and periventricular white matter are linked to buccofacial apraxia [46, 13]. Moreover, our findings complement and extend the results of the first fMRI study that provided correlative evidence of somatotopic audio-motor mirroring in healthy subjects [3]. The authors of that study reported that that neural activity in dorsal and ventral clusters in the left premotor cortex were associated with hand and mouth actions, respectively. Relevant to the present study is that the inferior parietal region showed more intense audio-motor mirroring for limb actions than for mouth actions [3]. This finding further highlights the notion that audio-motor mirroring due to very fine-grained mechanisms enables listeners to rapidly acquire precise information on what other individuals are doing, possibly as effect of hebbian learning [47].

Supplemental Data

Supplemental Data include three figures, three tables, Supplemental Results, Supplemental Discussion, Supplemental Experimental Procedures, and an appendix describing the sounds used in the sound-picture matching test and can be found with this article online at [http://www.current-biology.com/supplemental/S0960-9822\(08\)01339-0](http://www.current-biology.com/supplemental/S0960-9822(08)01339-0).

Acknowledgments

This work was supported by the Ministero Istruzione Università e Ricerca (PRIN), the Fondo Investimenti per la Ricerca di Base (FIRB), and the Italian Ministry of Health.

Received: May 27, 2008

Revised: September 14, 2008

Accepted: September 21, 2008

Published online: November 13, 2008

References

- Kohler, E., Keysers, C., Umiltà, M.A., Fogassi, L., Gallese, V., and Rizzolatti, G. (2002). Hearing sounds, understanding actions: Action representation in mirror neurons. *Science* 297, 846–848.
- Keysers, C., Kohler, E., Umiltà, M.A., Nanetti, L., Fogassi, L., and Gallese, V. (2003). Audiovisual mirror neurons and action recognition. *Exp. Brain Res.* 153, 628–636.
- Gazzola, V., Aziz-Zadeh, L., and Keysers, C. (2006). Empathy and the somatotopic auditory mirror system in humans. *Curr. Biol.* 16, 1824–1829.
- Hauk, O., Shtyrov, Y., and Pulvermüller, F. (2006). The sound of actions as reflected by mismatch negativity: Rapid activation of cortical sensory-motor networks by sounds associated with finger and tongue movements. *Eur. J. Neurosci.* 23, 811–821.
- Pizzamiglio, L., Aprile, T., Spitoni, G., Pitzalis, S., Bates, E., and Di Russo, F. (2005). Separate neural systems for processing action- or non-action-related sounds. *Neuroimage* 24, 852–861.
- Lewis, J.W., Brefczynski, J.A., Phinney, R.E., Janik, J.J., and DeYoe, E.A. (2005). Distinct cortical pathways for processing tool versus animal sounds. *J. Neurosci.* 25, 5148–5158.
- Fadiga, L., Craighero, L., Buccino, G., and Rizzolatti, G. (2002). Speech listening specifically modulates the excitability of tongue muscles: A TMS study. *Eur. J. Neurosci.* 15, 399–402.
- Tettamanti, M., Buccino, G., Saccuman, M.C., Gallese, V., Danna, M., Scifo, P., Fazio, F., Rizzolatti, G., Cappa, S.F., and Perani, D. (2005). Listening to action-related sentences activates fronto-parietal motor circuits. *J. Cogn. Neurosci.* 17, 273–281.
- Galati, G., Committeri, G., Spitoni, G., Aprile, T., Di Russo, F., Pitzalis, S., and Pizzamiglio, L. (2008). A selective representation of the meaning of actions in the auditory mirror system. *Neuroimage* 40, 1274–1286.
- Warren, J.E., Sauter, D.A., Eisner, F., Wiland, J., Dresner, M.A., Wise, R.J., Rosen, S., and Scott, S.K. (2006). Positive emotions preferentially engage an auditory-motor “mirror” system. *J. Neurosci.* 26, 13067–13075.
- Lahav, A., Saltzman, E., and Schlaug, G. (2007). Action representation of sound: Audiomotor recognition network while listening to newly acquired actions. *J. Neurosci.* 27, 308–314.
- Bangert, M., Peschel, T., Schlaug, G., Rotte, M., Drescher, D., Hinrichs, H., Heinze, H.J., and Altenmüller, E. (2006). Shared networks for auditory and motor processing in professional pianists: Evidence from fMRI conjunction. *Neuroimage* 30, 917–926.
- Koski, L., Iacoboni, M., and Mazziotta, J.C. (2002). Deconstructing apraxia: Understanding disorders of intentional movement after stroke. *Curr. Opin. Neurol.* 15, 71–77.
- Leiguarda, R.C. (2005). Apraxias as traditionally defined. In *Higher-order Motor Disorders: From Neuroanatomy and Neurobiology to Clinical Neurology*, H.J. Freund, M. Jeannerod, M. Hallet, and R. Leiguarda, eds. (New York: Oxford UP), pp. 303–337.
- Petreska, B., Adriani, M., Blanke, O., and Billard, A.G. (2007). Apraxia: A review. *Prog. Brain Res.* 164, 61–83.
- Heilman, K.M., Rothi, L.J., and Valenstein, E. (1982). Two forms of ideomotor Apraxia. *Neurology* 32, 342–346.
- Rothi, L.J., Heilman, K.M., and Watson, R.T. (1985). Pantomime comprehension and ideomotor Apraxia. *J. Neurol. Neurosurg. Psychiatry* 48, 207–210.
- Buxbaum, L.J., Kyle, K.M., and Menon, R. (2005). On beyond mirror neurons: Internal representations subserving imitation and recognition of skilled object-related actions in humans. *Brain Res. Cogn. Brain Res.* 25, 226–239.
- Pazzaglia, M., Smania, N., Corato, E., and Aglioti, S.M. (2008). Neural underpinnings of gesture discrimination in patients with limb Apraxia. *J. Neurosci.* 28, 3030–3041.
- Marquardt, T., and Sussman, H. (1984). The elusive lesion-apraxia of speech link in Broca’s aphasia. In *Apraxia of Speech: Physiology, Acoustics, Linguistics, Management*, J.C. Rosenbek, M.R. McNeil, and A.E. Aronson, eds. (San Diego: College-Hill Press), pp. 91–112.
- Basso, A., Capitani, E., Della Sala, S., Laiacona, M., and Spinnler, H. (1987). Recovery from ideomotor apraxia. A study on acute stroke patients. *Brain* 110, 747–760.
- Rothi, L.J.G., Raade, A.S., and Heilman, K.M. (1994). Localization of lesions in limb and buccofacial apraxia. In *Localization and Neuroimaging in Neuropsychology*, A. Kertesz, ed. (San Diego: Academic Press), pp. 407–427.
- Raade, A.S., Rothi, L.J., and Heilman, K.M. (1991). The relationship between buccofacial and limb Apraxia. *Brain Cogn.* 16, 130–146.
- De Renzi, E., Motti, F., and Nichelli, P. (1980). Imitating gestures: A quantitative approach to ideomotor apraxia. *Arch. Neurol.* 37, 6–10.
- De Renzi, E., Pieczuro, A., and Vignolo, L.A. (1966). Oral apraxia and aphasia. *Cortex* 2, 50–73.
- Dumont, C., Ska, B., and Schiavetto, A. (1999). Selective impairment of transitive gestures: An unusual case of apraxia. *Neurocase* 5, 447–458.
- Saygin, A.P., Dick, F., Wilson, S.M., Dronkers, N.F., and Bates, E. (2003). Neural resources for processing language and environmental sounds: Evidence from aphasia. *Brain* 126, 928–945.
- Negri, G.A., Rumiati, R.I., Zadini, A., Ukmar, M., Mahon, B.Z., and Caramazza, A. (2007). What is the role of motor simulation in action and object recognition? Evidence from apraxia. *Cogn. Neuropsychol.* 24, 795–816.
- Halsband, U., Schmitt, J., Weyers, M., Binkofski, F., Grützner, G., and Freund, H.J. (2001). Recognition and imitation of pantomimed motor acts after unilateral parietal and premotor lesions: A perspective on apraxia. *Neuropsychologia* 39, 200–216.
- Cubelli, R., Marchetti, C., Boscolo, G., and Della Sala, S. (2000). Cognition in action: Testing a model of limb apraxia. *Brain Cogn.* 44, 144–165.
- Bartolo, A., Cubelli, R., Della Sala, S., Drei, S., and Marchetti, C. (2001). Double dissociation between meaningful and meaningless gesture reproduction in apraxia. *Cortex* 37, 696–699.
- Rumiati, R.I., Zanini, S., Vorano, L., and Shallice, T. (2001). A form of ideational apraxia as a selective deficit of contention scheduling. *Cogn. Neuropsychol.* 18, 617–642.
- Rizzolatti, G., and Craighero, L. (2004). The mirror-neuron system. *Annu. Rev. Neurosci.* 27, 169–192.
- Buccino, G., Lui, F., Canessa, N., Patteri, I., Lagravinese, G., Benuzzi, F., Porro, C.A., and Rizzolatti, G. (2004). Neural circuits involved in the recognition of actions performed by nonconspecifics: An fMRI study. *J. Cogn. Neurosci.* 16, 114–126.
- Molnar-Szakacs, I., Iacoboni, M., Koski, L., and Mazziotta, J.C. (2005). Functional segregation within pars opercularis of the inferior frontal gyrus: Evidence from fMRI studies of imitation and action observation. *Cereb. Cortex* 15, 986–994.
- Rizzolatti, G., Fogassi, L., and Gallese, V. (2001). Neurophysiological mechanisms underlying the understanding and imitation of action. *Nat. Rev. Neurosci.* 2, 661–670.
- Ferrari, P.F., Maiolini, C., Adessi, E., Fogassi, L., and Visalberghi, E. (2005). The observation and hearing of eating actions activates motor programs related to eating in macaque monkeys. *Behav. Brain Res.* 161, 95–101.
- Aziz-Zadeh, L., Iacoboni, M., Zaidel, E., Wilson, S., and Mazziotta, J. (2004). Left hemisphere motor facilitation in response to manual action sounds. *Eur. J. Neurosci.* 19, 2609–2612.
- Rossi, S., De Capua, A., Pasqualetti, P., Olivelli, M., Fadiga, L., Falzarano, V., Bartalini, S., Passero, S., Nuti, D., and Rossini, P.M. (2008). Distinct olfactory cross-modal effects on the human motor system. *PLoS ONE* 3, e1702.

40. Gazzola, V., van der Worp, H., Mulder, T., Wicker, B., Rizzolatti, G., and Keysers, C. (2007). Aphasics born without hands mirror the goal of hand actions with their feet. *Curr. Biol.* *17*, 1235–1240.
41. Andersen, R.A., Snyder, L.H., Bradley, D.C., and Xing, J. (1997). Multimodal representation of space in the posterior parietal cortex and its use in planning movements. *Annu. Rev. Neurosci.* *20*, 303–330.
42. Chapman, H., Gavrilescu, M., Wang, H., Kean, M., Egan, G., and Castiello, U. (2002). Posterior parietal cortex control of reach-to-grasp movements in humans. *Eur. J. Neurosci.* *15*, 2037–2042.
43. Culham, J.C., Danckert, S.L., DeSouza, J.F., Gati, J.S., Menon, R.S., and Goodale, M.A. (2003). Visually guided grasping produces fMRI activation in dorsal but not ventral stream brain areas. *Exp. Brain Res.* *153*, 180–189.
44. Fogassi, L., and Luppino, G. (2005). Motor functions of the parietal lobe. *Curr. Opin. Neurobiol.* *15*, 626–631.
45. Leiguarda, R.C., and Marsden, C.D. (2000). Limb apraxias: Higher-order disorders of sensorimotor integration. *Brain* *123*, 860–879.
46. Daniels, S.K. (2000). Swallowing apraxia: A disorder of the Praxis system? *Dysphagia* *15*, 159–166.
47. Keysers, C., and Perrett, D.I. (2004). Demystifying social cognition: A Hebbian perspective. *Trends Cogn. Sci.* *8*, 501–507.