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Supplemental data

The Sound of Actions in Apraxia

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Supplemental Figures

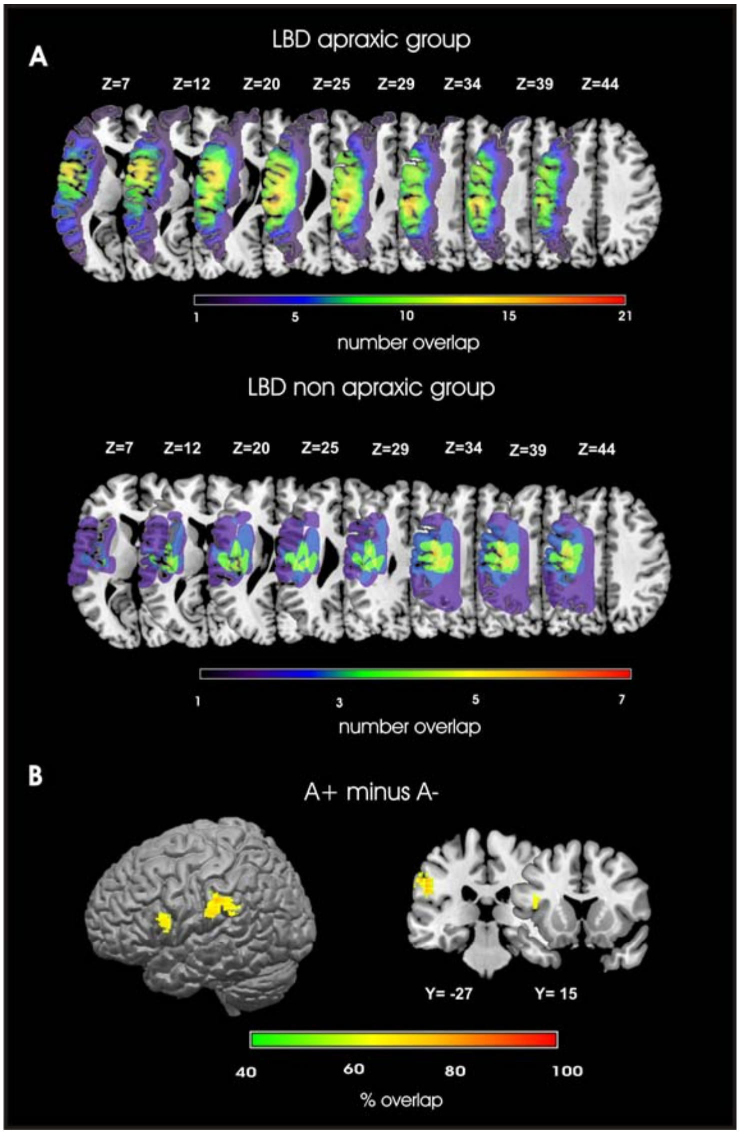

Figure S1 - **Comparison of lesion overlay for apraxic and non apraxic LBD patients**
(A) Overlays of regional lesion plots of the 21 patients with apraxia deficit (A+$_{(LBD)}$) and of the 7 patients without apraxia (A–$_{(LBD)}$).
(B) Subtraction image of the lesions in 7 left brain damaged (LBD) patients without apraxia (A–) and in the 21 LBD patients with apraxia (A+). Sagittal rendering and coronal views are shown in the left and the right part, respectively.

Region	MNI			Overlap	Voxels overlapping
	x	y	Z	number	percentage
7 $A+_{(B+L+)}$					
Precentral	-54	7	15	7	0.65
Frontal_Mid	-49	14	36	6	0.46
Frontal_Inf_Oper	-48	10	3	7	0.99
Frontal_Inf_Tri	-58	20	16	7	0.70
Rolandic_Oper	-51	0	3	7	0.99
Insula	-49	5	5	7	0.91
Postcentral	-52	-12	17	7	0.65
Parietal_Inf	-55	-34	37	7	0.80
SupraMarginal	-50	-27	24	7	0.99
Angular	-55	-51	33	5	0.94
Heschl	-44	-13	5	5	0.99
Temporal_Sup	-51	0	-2	6	0.93
Temporal_Pole_Sup	-54	8	-2	6	0.40
Temporal_Mid	-51	-20	-2	4	0.60
7 $A+_{(B+L-)}$					
Precentral	-54	7	15	6	0.36
Frontal_Mid	-38	10	34	4	0.27
Frontal_Inf_Oper	-42	9	8	7	0.97
Frontal_Inf_Tri	-36	11	24	6	0.88
Rolandic_Oper	-43	-2	11	7	0.86
Insula	-41	-1	5	7	0.69
Postcentral	-41	-1	5	6	0.33
SupraMarginal	-63	-27	23	4	0.37
Heschl	-41	-14	9	6	0.68
Temporal_Sup	-53	-8	3	5	0.59
Temporal_Pole_Sup	-60	7	-22	4	0.04
Temporal_Mid	-70	-39	-3	3	0.15
7 $A+_{(B-L+)}$					
Precentral	-50	-6	24	6	0.26
Frontal_Mid	-47	23	33	3	0.04
Frontal_Inf_Oper	-46	6	24	3	0.80
Frontal_Inf_Tri	-44	16	24	3	0.52
Rolandic_Oper	-50	-22	19	6	0.85
Insula	-37	-31	24	5	0.24
Postcentral	-52	-20	19	6	0.38
Parietal_Inf	-55	-38	37	7	0.62
SupraMarginal	-51	-29	23	7	0.95
Angular	-49	-51	26	6	0.63
Heschl	-51	-17	9	3	0.32
Temporal_Sup	-51	-45	23	7	0.55
Temporal_Mid	-57	-46	23	6	0.30

Table S1 - Damaged brain regions in each apraxic group. Quantitative estimates of the overlap of region lesion plots for each automated anatomical labeled in $A+_{(B+L+)}$, $A+_{(B-L+)}$ and $A+_{(B+L-)}$ groups. For each region, the local maxima Montreal Neurological Institute (MNI) coordinates, the maximum number of voxels overlapping, and the percentage of lesioned voxels overlapping and affected in at least 30% of the sample size are shown.

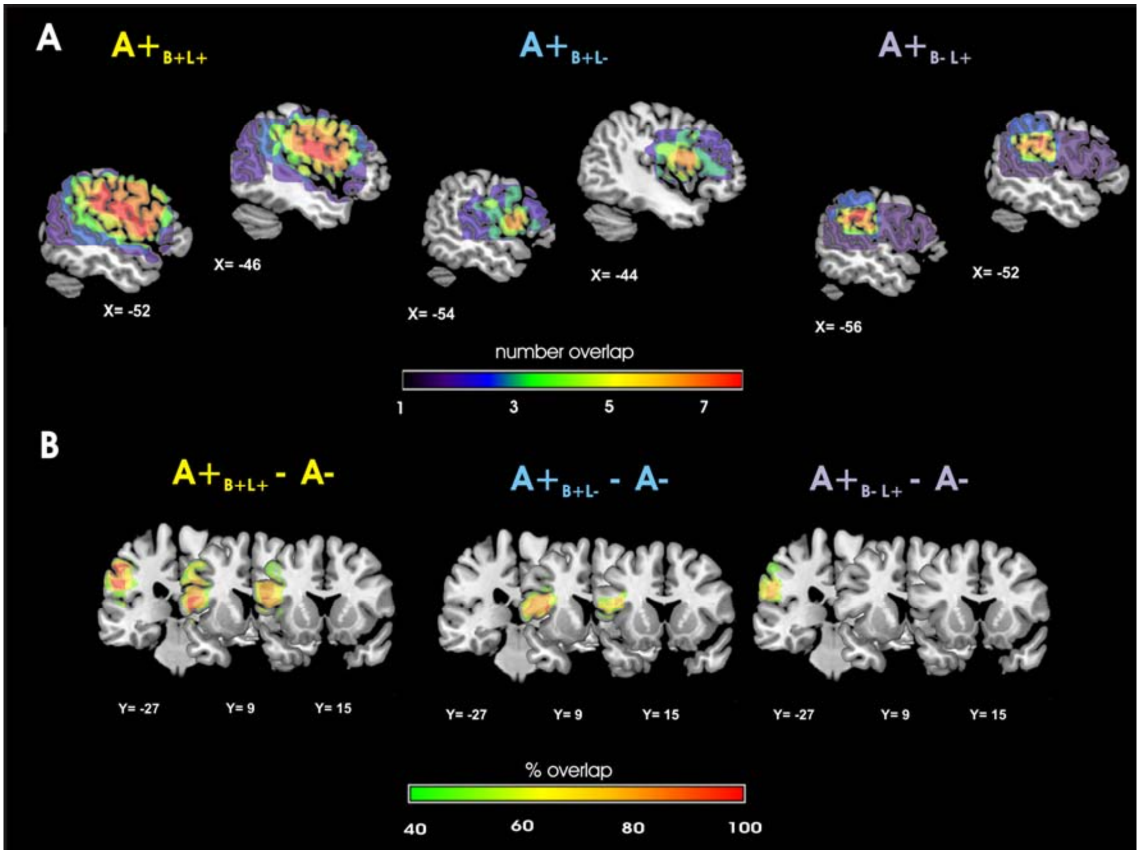

Figure S2- Lesion mapping in the apraxic patients.
(A) Overlays of regional lesion plots for the three groups of apraxic patients ($A+_{(B+L+)}$, $A+_{(B+L-)}$, $A+_{(B-L+)}$). The number of overlapping lesions is illustrated by different colors that code for increasing frequencies from black (lesion in one patient) to red (lesion in all the patients of the respective group). Additional details are provided in Table S1.
(B) Subtraction of lesions of the seven LBD patients without apraxia from each apraxic group [$A+_{(B+L+)}$ - $A–_{(LBD)}$], [$A+_{(B+L-)}$ - $A–_{(LBD)}$], [$A+_{(B-L+)}$ - $A–_{(LBD)}$]. Lesion subtractions show the highest difference in lesion density illustrated by different colors that code for increasing frequencies from green to red. Each color represents a 20% increment.

Supplemental Results

Lesion volume analysis

Using state-of-the-art technology (MRIcron software, see experimental procedure for details) we performed a lesion volume analysis that allowed us to explore the neural underpinnings of limb and buccofacial apraxia. Kruskal-Wallis test revealed a significant difference across the 5 groups (H = 12.12, $p < 0.016$). Post-hoc comparisons (Mann–Whitney U tests) demonstrated that the lesion volume was significantly greater in the $A+_{(B+L+)}$ group (mean ± SD, 96.2 ± 32.7 cm^3) than in the other 4 groups (mean ± SD, $A+_{(B-L+)}$= 55.20 ± 55.6); $A+_{(B+L-)}$ = 56.75 ± 31.9); $A-_{(LBD)}$ = 34.96 ± 15.5; $A-_{(RBD)}$= 41.22 ± 17.16; all *ps* < 0.05) which in turn did not differ from each other (all *ps* > 0.1).

Sounds associated with transitive and intransitive human actions

To explore whether the ability to perform transitive and intransitive actions can be reflected also in the sound-picture matching test we performed a mixed model ANOVA with group ($A+_{(B+L+)}$, $A+_{(B–L+)}$, $A+_{(B+L–)}$) as the between-subject factor and object or non-object related action sound (transitive and intransitive) and body-part related action sound (LRAS, BRAS) as the within-subjects factors. The main effect of Group was significant ($F_{(2,18)} = 22.65$, $p = 0.0001$) because $A+_{(B+L+)}$ performed worse than the other two groups (all *ps* < 0.002). The Group X body part related action sound ($F_{(2,18)} = 17.44$, $p < 0.0001$) was significant. Again, post-hoc analysis showed that $A+_{(B+L–)}$ patients were more impaired in matching buccofacial related action sounds ($p = 0.03$), and $A+_{(B–L+)}$ patients were more impaired in matching limb related action sounds ($p = 0.01$) with respect to all the other groups. Not surprisingly, the $A+_{(B+L+)}$ patients matched equally badly limb and buccofacial related action sounds. This result supports and extends the notion that the sound into action translation process takes place according to body-part specific coordinates. Interestingly, no main effect ($F_{(1,18)} = 0.45$, $p < 0.50$), or interactions [group x transitive/intransitive ($F_{(2,18)} = 0.50$, $p < 0.60$), and group x transitive/intransitive x body part ($F_{(2,18)} = 1.49$, $p < 0.25$)] related to transitive or intransitive action sounds were significant thus indicating that this variable did not play any major role in our task. Although there are studies showing a clear association between deficits in the production and discrimination of transitive and intransitive gestures in brain damaged patients [S1,S2] and in patients with cortical vs. subcortical lesions [S3], dissociations have been reported at single-case level [S4,S5]. Thus, we explored the interindividual variability in the transitive and intransitive actions of apraxic patients by using the Crawford procedure [S6,S7]. Bayesian Standardized Difference Test (BSDT) on the difference between the patients standardized scores on transitive and intransitive with respect to control patients indicate that only 3 apraxic patients meet the criteria for a dissociation. Two out of the three belonged to the $A+_{(B+L+)}$ group (patient 2, Transitive score: 7/20, Crawford t = -8.33 vs. Intransitive score = 9/20, Crawford t = -3.26; BSDT p=0.01;

patient 6, Transitive score: 8/20, Crawford t = -7.27 vs. Intransitive score = 9/20, Crawford t = -3.26; BSDT p = 0.04) and one to the $A+_{(B–L+)}$ group (patient 16, Transitive score: 11/20, Crawford t = -4.11 vs. Intransitive score = 13/20 , Crawford t = -0.9; BSDT p = 0.04).

Sounds associated with unimanual and bimanual limb actions

Half of the unimanual sounds implied movements of the left hand and half of the right hand. Of the eight sounds used also for the execution task, four were related to unimanual and four to bimanual actions. Note that the two control groups (non apraxic LBD and RBD patients) did not recognize differentially sounds related to the use of one hand or the other. Therefore, the laterality of the stimuli *per se* is unlikely to play any role in our study. Moreover, we performed an additional analysis to investigate any specific effect of matching sounds related unimanual vs bimanual actions. We performed a 5 (group: $A+_{(B+L+)}$, $A+_{(B–L+)}$, $A+_{(B+L–)}$, $A–_{(LBD)}$, and $A–_{(RBD)}$) X 2 (task: unimanual vs. bimanual) mixed-model ANOVA and found no significance of task ($F_{(1,30)} = 0.13$ $p = 0.72$) and the interaction ($F_{(4,30)} = 1.01$ $p = 0.41$). Therefore, in no group the matching performance was influenced by the fact that the sounds were related to unimanual vs bimanual actions.

Sounds associated with upper and lower limb actions

One main aim of our study was to explore if the limb actions may be differently represented with respect to bucco-facial actions. Since two of the limb-related sounds were associated to lower limb actions, we performed an additional analysis that considered only the performance limited only to the upper-limb related sounds. Percent correct responses were entered in a 5 X 3 ANOVA, with group as between-subject and task (BRAS, LRAS without the two lower limb action related sounds, NHARS) as within-subject variable. In keeping with the results of the original analysis we found a significant main effect of group ($F_{4,30} = 37.95$, $p < 0.0001$). Newman-Keuls post-hoc comparisons showed that patients with both limb and buccofacial apraxia (Mean = 45%) performed worse than the other four groups (Mean $A+_{(B-L+)}$ = 66.87%, $A+_{(B+L-)}$ = 67.51 %, $A–_{(LBD)}$ = 75.50 % and $A–_{(RBD)}$ = 75.48%, $p < 0.0001$). The main effect of task was significant ($F_{2,60} = 3.9$, $p = 0.02$), suggesting a better performance in matching non human action (mean = 67.57 %) related sounds with respect to buccofacial (mean = 64%, $p < 0.02$) and limb- (mean = 66.67%, $p < 0.06$) action related sounds. Crucially, we found a significant interaction between task and group ($F_{8,60} = 5.07$, $p < 0.0001$). The Newman-Keuls post-hoc tests revealed the following: patients with only buccofacial apraxia had lower scores in the BRAS (Mean = 59.28%) than in the LRAS (Mean = 70.63%; $p < 0.002$). In contrast, patients with only limb apraxia performed with significantly less accuracy in the LRAS (Mean = 61.11%) than in BRAS task (Mean = 69.28%; $p < 0.007$). Furthermore, in the BRAS task patients with only buccofacial apraxia were impaired with respect to controls (ps < 0.0004), while the performance of patients with only limb apraxia was comparable to that of controls (all ps > 0.53). In contrast, in the LRAS task patients with only limb apraxia were impaired with respect to controls (ps < 0.0002), while the performance of patients with only buccofacial apraxia was comparable to that of controls (ps > 0.1). Moreover, patients with only buccofacial apraxia performed significantly better than patients with limb apraxia in matching sounds related to limb actions ($p = 0.006$); patients with limb apraxia performed significantly better than patients with buccofacial apraxia in matching sounds related to buccofacial actions ($p < 0.004$). Finally, matching the NHARS was significantly more difficult in the group with both limb and buccofacial apraxia with respect to the others 4 groups (that did not differ from each other).

These results showed that the analysis limited only to the upper-limb related sounds, provided the same results of the analysis including both upper and lower limb action related sounds.

Language comprehension does not influence the ability to match human action sounds

To assess whether language comprehension deficits influenced sound recognition tasks, we performed an analysis of covariance on sounds type (LRAS, BRAS, and NHARS) with scores in the Token comprehension test as a covariate and the 3 apraxic groups as the between-subjects factor. The Task X Group differences in sound recognition remained significant, ($F_{(4,34)} = 4.15$; $p = 0.007$) and the Task × language comprehension interaction remained not significant ($p = 0.59$) independent of language comprehension severity. This indicates that, in our study, language comprehension deficits are not crucial for the sound recognition performance.

Comprehension and execution of human action related sounds

Correct recognition and execution scores were entered into a mixed model ANOVA, with Group ($A+_{(B+L+)}$, $A+_{(B–L+)}$, $A+_{(B+L–)}$ as the between-subjects factor; body part (buccofacial / limb) and task (recognition / execution) as within-subject factors. The significance of the main effect of Group ($F_{2,18} = 9.23$, $p = 0.002$) is due to the impairment of patients $A+_{(B+L+)}$ compared to patients $A+_{(B–L+)}$ and $A+_{(B+L–)}$ (all *ps* < 0.003). The significance of the task ($F_{1,\ 18} = 41.36$, $p = 0.0001$) suggests that patients showed a better performance ($p < 0.004$) in the recognition (mean hits = 4.33) than in the execution (mean hits = 3.64) task. Importantly, however, we found a non significant interaction between task and group ($F_{2,\ 18} = < 1$**)** thus suggesting that apraxic patients who have deficits in acoustically mediated action recognition have parallel deficits in the execution of the very same actions.

We explored the relationship between sound-mediated action recognition and execution of the same gestures in apraxic patients by means of a correlational analysis in which Pearson coefficients were computed. Given our design, we were also able to analyze whether deficits in sound-mediated recognition of hand or mouth actions were correlated with deficits in actual performance of the very same body action (i.e., recognition of a clapping sound and execution of hand clapping). The results indicate that deficits in comprehending BRAS correlated with deficits in performing actions involving the buccofacial region (BRASexe) ($r_{(21)} = 0.63$, $t_{(19)} = 3.54$ $p = 0.002$) but not the limbs ($r_{(21)} = 0.15$, $t_{(19)} = 0.67$ $p = 0.51$). Similarly, deficits in recognizing limb-action sounds significantly correlated with deficits in executing actions involving the limbs (LRASexe) ($r_{(21)} = 0.68$, $t_{(19)} = 4.13$ $p = 0.005$) but not the buccofacial region ($r_{(21)} = 0.35$, $t_{(19)} =1.64$ $p = 0.11$).

To further assess the link between action recognition and execution we also correlated the ability to identify actions by their sound with performance in tests of buccofacial (BA) [S8], and limb apraxia (LA) [S9] that require subjects to view and then perform the actions shown by an examiner. This allowed us to test whether audiomotor mapping correlated with deficits in action execution *per se* or whether it was related to execution of the same gestures. BRAS recognition was correlated with the BA test ($r_{(21)} = 0.54$, $p = 0.01$), while LRAS recognition was correlated with LA test ($r_{(21)} = 0.50$, $p = 0.02$). In contrast, no significant correlation was found between BRAS recognition and the LA test ($r_{(21)} = 0.10$, $p = 0.66$) and between LRAS recognition and the BA test ($r_{(21)} = 0.15$, $p = 0.5$). Again, no significant correlation between performance in tests of BA ($r_{(21)} = 0.29$, $p = 0.19$) or LA ($r_{(21)} = 0.40$, $p = 0.07$) and deficits in the ability to discriminate NHRAS sounds was found .

Therefore, two different sets of correlational analyses hint at a body-part specific relationship between deficits in action execution and deficits in action recognition no matter whether this is mediated by either audition or vision. It is worth noting that the ability to discriminate non human action related sounds is not related to the apraxic patients' impairment in performing actions.

Single cases analysis

Using the modified t-test procedure [S6] and the Bayesian Standardized Difference Test (BSDT) [S7] designed to analyze single patient data, we compared the performance of each apraxic patient in matching action related sounds with the performance of non apraxic control patients. The performance of each apraxic patient in the different sounds matching is shown in Table S2. Adopting the suggestions of Huizenga et al., (2007) [S10], we applied the Bonferroni correction to control for multiple comparisons and we tested the directional (one-sided) hypothesis that patients perform worse than controls.

The results show that all the 7 patients with both buccofacial and limb apraxia (Cases Nos 1-7) performed significantly worse than controls in matching both human and non human action sounds. Six of 7 patients (cases Nos. 8-13) with only buccofacial apraxia performed significantly worse than controls in matching BRAS. Patient 14 (who exhibited buccofacial apraxia only), was better at matching LRAS and NHRAS than BRAS. However, the Crawford procedure shows that his performance in matching sounds related to buccofacial actions was in the normal range. Crucially, all the 7 patients with buccofacial apraxia only, matched limb and non human action sounds with accuracy in the normal range. All the patients with only limb apraxia matched NHARS within the normal range. Six of them were also normal in matching BRAS. Four patients (cases Nos. 15, 16, 18 and 20) were impaired in matching LRAS but the remaining 3 (Nos. 17,19 and 21) were not. Patient 20 was also impaired in matching BRAS. Finally, patient 19 was relatively more impaired in matching LRAS than BRAS. However, she was more impaired in matching LRAS than NHARS (BSDT $p < 0.02$) or BRAS (BSDT $p < 0.01$). Therefore, while in (LA+ $_{B+L+}$) and (LA+ $_{B+L}$) patients the performance was completely congruent at the individual and group level, in (LA+ $_{B-L+}$) patients there was some inter-individual variability.

Neural basis of the ability to recognize non-human action related sounds

The lesion-symptom mapping analysis concerning non-human action related sounds involved only recognition because no proper execution of non human actions is possible. Since the main aim of our study was to explore the recognition and execution of human actions in patients with apraxia and, therefore, with lesions centred upon parietal and frontal regions. However, neuropsychological [S11,S12] and neuroimaging [S13-S15] studies indicate that the processing of environmental stimuli is linked to temporal regions. We highlighted the possible role of temporal structures in processing non-human action-related sounds by using a conservative thresholding criterion (i.e. the Bonferroni correction). Figure S3 shows the statistical maps of the voxels significantly associated with BRAS, LRAS, NHARS. Notably, fronto-insular, parietal, and temporal clusters were significantly associated with deficits in matching mouth-, limb-, and non human related actions (upper, middle and lower parts of Figure S3 respectively).

Subject	**Group**	***t***			**BSDT**		
		BRAS	LRAS	NHARS	BRAS vs LRAS	BRAS vs NHARS	LRAS vs NHARS
1	AB+AL+	**-7.35**	**-3.78**	**-5.30**	0.03	0.25	0.25
2	AB+AL+	**-7.35**	**-5.13**	**-2.91**	0.19	**0.007**	0.08
3	AB+AL+	**-11.1**	**-3.78**	**-4.50**	**0.0004**	**0.003**	0.56
4	AB+AL+	**-9.86**	**-5.13**	**-3.71**	**0.02**	**0.002**	0.27
5	AB+AL+	**-8.61**	**-4.46**	**-3.71**	**0.02**	**0.01**	0.54
6	AB+AL+	**-7.35**	**-4.46**	**-4.50**	0.08	0.10	0.97
7	AB+AL+	**-3.59**	-1.10	**-2.91**	0.03	0.58	0.07
8	AB+AL-	**-3.59**	-1.10	1.09	0.03	**0.0003**	0.02
9	AB+AL-	**-4.84**	-1.10	0.29	**0.001**	**0.0002**	0.12
10	AB+AL-	**-3.59**	-0.43	-1.31	**0.01**	0.05	0.32
11	AB+AL-	**-3.59**	-1.10	0.29	**0.03**	**0.002**	0.12
12	AB+AL-	**-3.59**	-1.10	-1.31	**0.03**	0.05	0.82
13	AB+AL-	**-4.84**	-0.43	-1.31	**0.001**	**0.01**	0.32
14	AB+AL-	-2.33	-0.43	-0.51	0.06	0.09	0.92
15	AB-AL+	-2.33	**-2.44**	-0.51	0.92	0.09	0.05
16	AB-AL+	-2.33	**-2.44**	-0.51	0.92	0.09	0.05
17	AB-AL+	0.18	-1.10	-1.31	0.18	0.14	0.82
18	AB-AL+	-2.33	**-2.44**	1.09	0.92	**0.003**	**0.001**
19	AB-AL+	1.43	-1.10	1.09	**0.01**	0.73	**0.02**
20	AB-AL+	**-3.59**	**-2.44**	-0.51	0.32	**0.01**	0.05
21	AB-AL+	0.18	-0.43	-0.51	0.51	0.48	0.92

Table S2 - Single cases analysis. The performance of each apraxic patient compared against controls by means of t-test procedure [S6] and the Bayesian Standardized Difference Test (BSDT) [S7] is reported. Patients that are not in the normal range are shown in bold. Legend: A+$_{(B+L+)}$ = patients with both limb and buccofacial apraxia; A+$_{(B-L+)}$ = patients with only limb apraxia; A+$_{(B+L-)}$ = patients with only buccofacial apraxia; A-$_{(LBD)}$ = non apraxic patients, left brain-damaged.

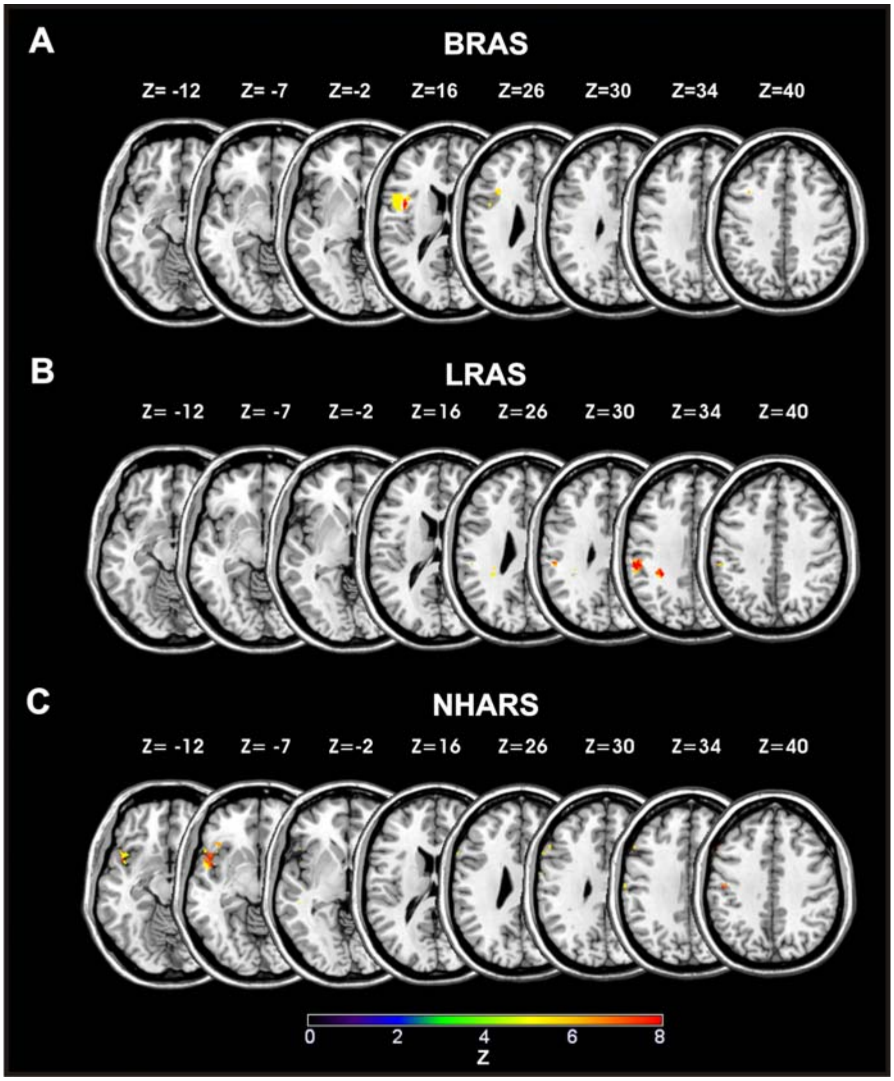

Figure S3 - Lesion loci associated with abnormal sound recognition
Voxel-based lesion-symptom mapping (VLSM) in the 28 left brain damaged (LBD) patients.
The behavioural measures are accurate matching scores for buccofacial- (BRAS), limb- (LRAS), and non-human (NHARS) action related sounds.
Z scores over 5.03 are significant after Bonferroni correction at $p < 0.05$ level.
Lesioned voxels in the:
(A) frontal, rolandic operculum, and insular region significantly correlate with deficits in matching mouth related action sounds; Montreal Neurological Institute [MNI] coordinates of the lesioned voxels: x = -37, y = 13, z = 17 for the pars opercularis, in the left inferior frontal gyrus; x = - 42, y = 5, z = 17 in the rolandic opercularis region; and x = - 37, y = 13, z = 13 in the insula;
(B) parietal cortex significantly correlate with deficits in matching limb related action sounds; MNI coordinates of the lesioned voxels: x = - 53, y = 30, z = 34 for the supramarginal gyrus and x = - 54, y = -29, z = 40 for the inferior parietal lobe in the inferior parietal cortex;
(C) temporal lobe significantly correlate with deficits in matching non-human action related sounds. MNI coordinates of this area of damage: x = - 49, y = 12, z = - 7 for the superior temporal gyrus.

Supplemental Discussion

Neural basis of non human action related sounds

Our study focussed on the relationship between action execution and the auditory recognition of human actions based on their audible output. Non-human action related sounds were mainly used as control stimuli. Therefore, it is no surprise that, clear deficits in matching non-human action related sounds were found only in the group with both limb and buccofacial apraxia and with a lesion size larger than other groups. The remaining four patients groups performed at comparable levels, and no behavioural dissociation in their performance was found. Importantly, deficits in the recognition of non-human action related sounds were independent from apraxia. The VLSM procedure allowed us to identify the neural network associated with defective performance in the recognition of non-human action related sounds. Neuropsychological studies using modern lesion mapping procedures have mainly tested the difference between processing language and environmental sounds [S11,S12]. While all these studies point to the fundamental role of the left superior temporal and infero-parietal regions in processing environmental sounds, sound stimuli related to human actions (e.g., a crying baby) were intermingled with non-human action related sounds (e.g., sea waves, cow mooing), and no inference could be drawn from their differential mapping. Therefore, this is the first patient study that identified the possible different neural substrates underlying human- and non human action related sound processing. Since our study focused on apraxia, four of the five patients groups presented with unilateral left hemisphere lesions. Therefore, our results concerning the set of cortical regions associated with deficits in processing environmental sounds can only be indirectly compared with the results of neuroimaging studies in healthy subjects reporting that a right-sided temporal, parietal, and frontal network is more activated by environmental sounds (e.g., boiling water) than by action sounds (e.g., hands clapping) [S13]. However, the left temporal involvement observed in our study is in keeping with the results of a left-sided increase in temporal activity during environmental sound processing [S13-S16].

Theoretical and translational implications of the present study

Being equipped with the mechanisms and neural machinery for the direct matching of auditory input with motor output has several possible functional advantages and adaptive implications. For example, a fine-tuned audiomotor recognition network may be essential for communication, as indicated by the presence in singing birds of audio-motor mirror neurons with precise auditory-vocal correspondence [S17]. Moreover, this network may be fundamental for language acquisition, a process which entails the constant matching of input-output processes [S18-S20]. Efficient mechanisms for matching audition with action may be crucial even at a more basic level because they may allow the survival of all hearing individuals. For example, in the dark of the primordial nights, our ancestors likely detected potential dangers (e.g., the footsteps of enemies) mainly by audition and thus implemented effective fight-or-flight behaviour. Studies on the visual domain suggest that direct matching may be stronger for actions that belong in the observers' motor repertoire [S21,S22]. In our study, the dissociation between human and non-human action related sounds supports the existence of a similar effect in the auditory domain. This would strengthen the notion that direct mirror matching has an inherently social role that allows one to understand others' sensory, motor and emotional states [S23]. For example, largely overlapping cortical premotor regions are activated during facial movements and auditory processing of affective nonverbal vocalizations, suggesting that audio-motor mirroring of others' emotional states may be at the root of cohesive interindividual bonds [S24].

Mounting evidence hints at a bi-directional link between action observation and execution. For example, studies in the visual domain not only indicate that viewing others' actions may strengthen the same motor representation in the self [S25], but also suggest that mere motor experience of a given action may improve the visual recognition of the same action performed by others [S26]. These findings led some of us to devise apraxia rehabilitation programs based on both visual observation and execution tasks [S27, S28]. Tasks aimed at assessing the visual comprehension of actions have also been used in apraxia research [S2, S29-S31]. However, even the most modern apraxia evaluation batteries [S31] do not include sound-into-action translation tasks, and no test for the assessment of auditory apraxia has been developed thus far. Yet, it is clear that action is a multimodal experience modulated not only by visual [S32] but also by somatic [S33], olfactory [S34], and auditory inputs [S35]. In view of this, the assessment of the ability to recognize human actions by their sound may be crucial for planning treatments as most rehabilitation techniques of perceptual, motor, and cognitive functions employ multimodal demonstrations of body actions. Therefore, we believe that the test devised in the present study may represent a novel neuropsychological tool, potentially useful for the diagnosis and rehabilitation of goal-directed action disorders in neurological patients.

Supplemental Experimental Procedures

Subjects

The study included 35 brain-damaged patients who suffered from ischemic or hemorrhagic stroke.

All the participants were right-handed [S36]. The criteria for inclusion in the study were as follows: (1) absence of auditory deficits; (2) single, unilateral brain lesion documented by magnetic resonance imaging; and (3) participation at least one month after the occurrence of stroke. The criteria for exclusion from the study were as follows: (1) history of previous neurological or psychiatric illness, dementia or confusional state; (2) impaired verbal comprehension preventing understanding of the experimental instructions, (3) presence of visual-field defects, and (4) presence of spatial neglect (assessed according to Pizzamiglio et al., 1989) [S37]. All the procedures were approved by the ethics committee at the IRCCS Fondazione Santa Lucia and were performed in accordance with the standards of the 1964 Declaration of Helsinki.

Assessment of praxic deficits

One important aim of the study was to explore the possible relation between impairment in performing actions with a specific body part and hearing the sound of action related to the same body part. Therefore, participants performed two standardized tests assessing the ability to imitate upper limb and mouth actions. In the LA test [S9], the patients were instructed to imitate 24 intransitive movements (12 involved hand movements and 12 involved finger movements) performed by the examiner by using their ipsilesional hands. Performance was scored by assigning 3 points for correct execution on the first attempt, 2 points for correct execution on the second attempt, and 1 point for correct execution on the third attempt (total score range, 0–72; cut-off score, 53). In the BA test [S8], the patients were instructed to imitate 10 buccofacial gestures performed by the examiner. Correct execution at the first attempt was scored as 2 and correct execution at the second attempt was scored as 1 (total score range, 0–20; cut-off score, 16). Patients who performed below the cut off score in at least one of the two praxis tests were considered apraxic (A+). Depending on whether their defective performance was in the LA, the BA tests or in both, the A+

patients were assigned to one out of three groups, hereafter indicated as $A+_{(B-L+)}$, $A+_{(B+L-)}$, and $A+_{(B+L+)}$. LBD and RBD patients who did not present deficits in performing limb or buccofacial actions served as the non-apraxic control groups ($A-_{(LBD)}$ and $A-_{(RBD)}$). Another major aim of the present research was to look for the neural correlates of deficits in executing actions and in recognizing them from their sound. Therefore, to perform lesion analysis on homogenous samples, care was taken to include the same number of patients in each group.

At the beginning of this study, 40 patients were recruited from the database at Neuropsychology unit, Fondazione Santa Lucia. Seventeen patients (seven RBD patients and ten LBD patients) met the inclusion criteria. All the patients had been tested by a clinical neuropsychologist (blind as to the aims of the study) for limb and buccofacial apraxia using standardized procedures. Based on the results of the buccofacial and limb apraxia tests in standard imitation tests, the LBD patients were assigned to one out of four groups. Note that our main aim was to explore the effect of body-part specific performance on body-part specific audio-motor mapping. Therefore, we tried to select a group with buccofacial apraxia and no limb apraxia and a group with the converse pattern of deficit. Moreover, to have a complete picture of the possible association and dissociation impairment, we aimed at recruiting a group of patients with both bucco-facial and limb apraxia and a group of patients with left hemisphere lesion and no apraxia at all. Five out of the 10 LBD patients recruited from the original data base did not show any sign of apraxia ($A-_{LBD}$). Three out of the same LBD patients presented with both bucco-facial and limb apraxia ($LA+ _{B+L+}$). One patient presented with only bucco-facial apraxia ($LA+ _{B+L-}$), and one with only limb apraxia ($LA+ _{B-L+}$). The seven RBD patients did not show any sign of apraxia and were considered as an additional (control) group. Having in mind to perform lesional mapping we set a 7 the number of patients in each group. It was comparatively easy to reach the pre-fixed number of patients in the $A-_{(LBD)}$ and in ($LA+ _{B+L+}$) by including in a consecutive way for the respective group all the patients who met the inclusion and the apraxia screening criteria (it took us four months and seven months respectively). However, it took us two years to reach the number of 7 in the $LA+ _{B+L-}$ and $LA+ _{B-L+}$ groups. A total of 21 A+ and 14 A- patients participated in the study.

All the patients were also asked to perform limb or bucco-facial actions upon verbal request by using a task standardized in a large Italian population [S38]. Twenty symbolic gestures, ten for the limb and ten for bucco-facial regions, were used. Since 2 and 1 points are assigned for correct responses on the first or the second attempt, the maximal possible score is 20. The pattern of selective impairment was very similar to the one found in the imitation tests (see table S3). All the participants also performed a standardized test implying use of objects to assess for ideational apraxia (IA) [S39] . In the IA test, patients were required to perform seven complex actions that implied the actual use of real objects (hammer; toothbrush; scissors; pistol; pencil and eraser; padlock and key; candlestick holder, candle and matchbox). For each action, the correct execution was scored as 2; an inaccurate execution in which the action was recognizable but not entirely correct was scored as 1; and a completely incorrect execution was scored as 0 (total score range, 0–14; cut-off score, 14). Signs of ideational apraxia were found only in the $A+_{(B+L+)}$ group.

Additional neuropsychological testing

All the neuropsychological tests, including those assessing the praxic functions, were administered by an expert clinical neuropsychologist who was blinded to the aims of the study. Clinical and demographic data and the scores in the neuropsychological tests are reported in Table S3.

The presence of general non-verbal intelligence deficits was assessed by means of the Raven Colored Progressive Matrices test [S40]. An ANOVA on the scores in this test revealed a significant main effect of group ($F_{(4,30)} = 3.46$, $p < 0.019$) which was entirely accounted for by the defective performance of the $A+_{(B+L+)}$ group (all *ps* < 0.04) with respect to all the others.

The presence of non-contextual language comprehension deficits was tested by using the 36 item Token Test [S41]. An ANOVA on token test scores indicated a significant main effect of group ($F_{(4,30)} = 25.19$, $p < 0.0001$). The Newman-Keuls post-hoc analysis indicated that the three apraxic groups performed at a comparable level but were significantly more impaired (all *ps* < 0.02) with respect to the non apraxic LBD patients who in turn were less accurate than RBD patients ($p = 0.001$). Although deficits in non-contextual language comprehension tasks were higher in the apraxic groups, all of the patients understood and performed the experimental tasks.

Screening and object identification subtest tasks drawn from the visual object and space perception battery [S42] showed that no patient presented with any object identification deficits. That the performance was within normal limits has been ascertained by using the norms and statistical tools described by Crawford and Garthwaite (2002) [S6]. These tests allowed us to rule out that a possible deficit in recognizing the transitive action sound was due to object-recognition impairments.

Patients Group		A+			A-	
		BA+LA+	**BA-LA+**	**BA+LA-**	**LBD**	**RBD**
		(n=7)	(n=7)	(n=7)	(n=7)	(n=7)
Age	mean	65.7	53	60.3	54.3	60.4
	SD	9.6	11.1	10.7	14.7	15.3
	range	50 - 78	35 - 68	50 - 79	25 - 67	28 - 73
Education	mean	8.7	10.7	9.3	11.1	8.7
	SD	4.6	5.6	3.7	5.1	4.03
	range	5 - 18	5 - 18	5 - 13	5 - 18	5 - 13
Days since stroke	mean	35	42	37	39	48
	SD	10	15	18	20	11
	range	30 - 58	31 - 74	30 - 78	30 - 84	32 - 63
Raven	mean	21.14	25.6	25.9	26.8	24.6
	SD	0.89	3.2	2.1	4.8	3.2
	range	20 - 22	22 - 30	23 - 29	21 - 35	20 - 29
Token test	mean	16.4	20	19.1	25.6	33.8
	SD	2.5	4.6	4.2	4.5	1.1
	range	12 - 19	14 - 26	11 - 24	20 - 31	33 - 35
IA	mean	8.4	14	14	14	14
	SD	1.9	0	0	0	0
	range	6 - 11	14	14	14	14
LA (imitation)	mean	41.9	42.4	63.4	64.7	69.3
	SD	5.1	7.1	5.4	4.6	2.4
	range	32 - 47	31 - 48	58 - 70	59 - 70	66 - 72
LAvc (verbal command)	mean	10.1	11.7	17.6	19.3	19.7
	SD	4	2.9	1.1	1.1	0.5
	range	2 - 14	6 - 14	16 - 19	17 - 20	19 - 20
BA (imitation)	mean	10.9	18.8	10.7	19	20
	SD	4	1.2	3.3	1.1	0
	range	4 - 14	17 - 20	4 - 14	17 - 20	20
BAvc (verbal command)	mean	4.1	16.3	9.3	17.8	18.4
	SD	4	2.1	4.6	1.4	1.1
	range	0 - 10	13 - 18	2 - 14	16 - 20	17 - 20

Table S3 - Demographic and Clinical Data of the participants. Clinical and demographic data of the patients. Legend for the apraxic groups as in table S2. A-$_{(LBD)}$ = non apraxic patients, left brain-damaged; A-$_{(RBD)}$ = non apraxic patients, right brain-damaged. BA = buccofacial apraxia imitation test, LA = limb apraxia imitation test; BAvc = buccofacial apraxia on verbal command, LAvc = limb apraxia on verbal command test; IA = ideational apraxia test. Each cell reports mean, standard deviation (SD) and range. The different groups were comparable in age, education level, and days since stroke ($p > 0.05$).

Experimental tasks

Comprehension of action-related sounds

We devised a sound-picture matching task to assess the participants' ability to match sounds produced by human or non-human actions with specific visual stimuli.

Sounds stimuli

Each sound stimulus belonged to one out of the following three categories.
1) Human action sounds involving the use of the buccofacial region. Ten sounds were transitive, i.e., object related (e.g., inflating a balloon) and ten were intransitive, i.e., non object related (e.g., coughing).
2) Human action sounds involving the use of limbs. Ten actions were transitive (e.g., using a pair of scissors) and ten were intransitive (e.g., footsteps).
3) Sounds related to non-biological naturally occurring (e.g., sea waves, breaking) mechanical or electrical motion events (e.g., the noise of a helicopter), and animal vocalizations (e.g., dog barking) were used.
A list with the 60 sounds used in the study is reported in Appendix S1.
The sound stimuli were tape-recorded on a stereo (44.1 KHz, 16 bits) and compiled by a sound engineer. Each sound was modified using a specific editing software application (Cool Edit Pro Rel. 2.1; Syntrillium Corp., Phoenix, AZ), which set the duration of each sound at 2 seconds.

Visual stimuli

The visual stimuli for the sound-picture matching test was comprised of 240 pictures (400 × 300 pixel, 300 × 300 DPI resolution, 16.7 million colors, 24 bit, obtained using a Nikon Coolpix E3200 3.2 megapixel digital camera). The pictures depicting human actions were created with the help of an actress. The non-human action pictures consisted of colourful photographs, taken either by the authors or obtained, with permission, from photographic images available on the web. On each trial, after the sound presentation, 4 images were presented on a computer screen. Only one out of the four pictures was specifically related to the heard sound, one was semantically related to the target picture and two others were not related to the target picture or its sound. For example, for the recognition of an action-related sound, one image depicted the target action (e.g., sawing a piece of wood); one depicted an action that was semantically related to the target picture but that produced a different sound (e.g., strike of a hammer) and two other pictures depicted actions completely unrelated to the sound stimulus (e.g., a pair of scissors cutting or a lighter being ignited). Representative examples of visual stimuli corresponding to each sound category are shown in Figure 1 (Panel A).

The image paired with each human action sound stimulus showed a buccofacial or a limb action performed with (transitive) or without (intransitive) tools. The positions of the target and of the three distractors on the screen were counterbalanced. In particular, for each stimulus category, the non-related distractors were randomized so that they were not presented more than twice. Examples of the arrangement of the four visual stimuli are provided in Figure 1 (Panel B). A complete list of the pairings is provided in the Appendix S1

Procedure

The subjects were seated at a distance of approximately 60 cm from a 17-inch monitor (resolution: 1024 × 768 pixels). During each trial, the subjects listened to a two second sound selected from the 6 sound categories. Each sound was presented through Sennheiser™ PC165 earphones at a comfortable decibel level. The order of the different sounds was presented in a fixed randomized order (see Appendix S1). The four-picture set appeared 100 ms after the sound presentation and remained on until the patient responded. The presentation of the sound and visual stimuli was controlled using the Presentation software version 10.0 (Neurobehavioral Systems, Albany, NY).

Figure 1 (panel B) provides examples of two different trial events.

Each correct response was scored as 1; thus, an errorless performance corresponded to a score of 60 (20 for each sound category). Comprehension of the sound-picture matching test was preliminarily assessed in 10 practice trials where feedback on the performance was provided. The practice stimuli were different from those used in the experimental phase.

Execution of human action-related sounds

Participants were asked to listen to a sound and then to perform the action associated with that sound using their ipsilesional hand. The sounds were chosen so as to evoke 8 buccofacial actions and 8 upper limb actions (shown in grey in the sound description column in Appendix S1). An accurate performance scored 1 point; thus, an errorless performance corresponded to a score of 16. No feedback about performance in the recognition or the execution tasks was provided to the patients at any time. The sound-picture matching and the execution of sound evoked actions were performed on separate days. The sound-picture matching was administered first to avoid any priming effect from execution to recognition.

Creation of the sound-picture matching test and psychophysics results

In the phase of test creation, experimenters decided about the appropriateness of each sound-picture matching. However, this was controlled in two preliminary psychophysics studies. In the first, 20 healthy subjects (13 women, 22–35 years of age) were instructed to independently match a given sound to one of four pictures. The average identification accuracy was 88.6% for limb action sounds, 92.54 % for buccofacial action sounds and 89% for non-human actions related sounds**.** Ambiguous sound-picture pairs were replaced with new items. The items that were clearly matched in test creation study 1 were used in the test creation study 2, where 20 healthy elderly subjects (age 67.7, range 60-73 years, 6 women) matched sounds with pictures. Only the sounds matched correctly by at least 80% of the participants in test creation study 2 were included in the final test. Sound-picture matching scores were nearly identical in the three sound categories (mean ± SD, BRAS = 17.8 ± 1.15; LRAS = 17.6 ± 1.43; NHARS = 18.1 ± 0.91). There were no accuracy differences between the transitive and intransitive sound actions in BRAS and LRAS ($t_{39} = -0.50$, $p = 0.62$). Appendix S1 also reports the number of healthy participants who correctly categorized each specific sound.

Lesion analysis

MRI was performed using a 1.5-T system (Vision; Siemens Medical Systems, Erlangen, Germany). The acquisition protocol included the following sequences: (1) conventional T1-weighted turbo spin-echo images (TR/TE/excitations/flip angle = 650/14/2/70, matrix = 256 × 256, in-plane resolution = 0.9 × 0.9 mm) and (2) double-echo turbo spin-echo proton density and T2-weighted images (TR/TE1/TE2/excitations = 3800/22/90/1, matrix = 256 × 256, in-plane resolution = 0.9 × 0.9 mm). By using the MRIcron software available at http://www.sph.sc.edu/comd/rorden/mricron/index.html [S43], one experimenter mapped the lesions on slices of a T1-weighted template MRI scan from the Montreal Neurological Institute (http://www.bic.mni.mcgill.ca/cgi/icbm_view). This template is approximately oriented to match Talairach space [S44] and is distributed with MRIcron. The area of each patient's brain lesion was superimposed onto the T1 template to determine the total lesion volume (in cm^3) as calculated by MRIcron. Lesion volume analysis was performed using nonparametric statistics (Kruskal-Wallis and Mann–Whitney U tests).

By using the non-parametric mapping (NPM) software available with MRIcron, we computed Brunner-Munzel rank-order statistic analysis on the group of 28 patients with LBD using the continuous behavioral measures, i.e. accuracy in buccofacial and limb actions execution and in matching BRAS and LRAS and NHARS sounds as predictors. Since NHARS cannot be executed, only the lesion-symptom mapping analysis with recognition scores was performed. Therefore, 5 separate analyses were performed. Each statistical analysis was performed for each voxel of the brain [S43]. Colored VLSM maps were then produced that represent the Z statistics of the voxel-wise comparisons between patients with or without lesion on a given voxel. The maps indicate the voxels at which patients with a lesion in a given voxel performed worse than patients without lesion to that voxel on specific behavioral measures concerning limb-, buccofacial, and non-human action related sounds. The alpha level of significance was set at $p < 0.05$ and was corrected for multiple comparisons by using the false discovery rate (FDR) threshold [S45], or the Bonferroni correction. Only voxels lesioned in more than 3 patients were tested. We used this criterion to balance between the need to increase the statistical power by testing only voxels that were lesioned in a significant number of individuals and to detect the effect of regions that are reliable predictors of deficits but were lesioned in just a few patients [S43]. The correlations between anatomical maps were computed by means of the NIFTI toolbox in matlab (http://www.rotman-baycrest.on.ca/~jimmy/NIFTI/).

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Appendix S1 List of the sounds used in the sound-picture matching test.

S	Sounds	Category	Type	N	I	II	III	IV
1	**Lion, roaring**	NHARS		20	Lion	Ape	Panther	Cat
2	**Puffing** Explosive sound made by forcing air quickly through the lips	BRAS	IN	19	Puffing	Clicking tongue	Kissing	Sniffing
3	**Helicopter, flying**	NHARS		17	Helicopter	Shower	Airplane	Vacuum cleaner
4	**Water, pouring** The sound of water flowing from a jug into a glass	LRAS	TR	16	Turning a key in a lock	Water, pouring	Bell, ringing	Flushing a toilet
5	**Rain, pouring**	NHARS		16	Waterfall	Rain	Motorbike	Car
6	**Hammering** The loud sound produced by hitting a nail with a hammer	LRAS	TR	20	Tennis ball, hitting	Hammering	Sawing a wood piece	Coffee, stirring
7	**Boat, docking**	NHARS		16	Boat	Train	Sewing machine	Sea waves
8	**Turning the key in a lock** The loud sound produced by turning a key by hand fastening or by unfastening a lock	LRAS	TR	19	Pencil, sharpening	Bell, ringing	Turning the key in a lock	Cheese, grating
9	**Sea waves, breaking**	NHARS		18	Motorbike	Sea waves on a reef	Wind	Stormy sky
10	**Taking a photograph** Clicking sound produced by pressing a finger on the shutter button of a camera when taking a photograph	LRAS	TR	16	Turning on the radio	Typing on computer	Taking a photograph	Cheese, grating
11	**Train, running**	NHARS		19	Coffee maker	Boat	Blender	Train
12	**Knocking** A sudden brief sound made when a door is hit with the knuckles	LRAS	IN	20	Knuckles cracking	Slapping	Running	Knocking
13	**Wind, blowing**	NHARS		17	Rain	Fire	Wind	Waterfall
14	**Candle, blowing out** The sound produced when air is forced out of the mouth in order to put out a candle	BRAS	TR	17	Balloon, inflating	Candle, blowing out	Coffee cup, drinking	Breadstick, eating
15	**Water, boiling**	NHARS		17	Washing machine, whirring	Sports car	Blender	Water, boiling
16	**Apple, crushing** The sound produced when an apple is crushed loudly between the teeth	BRAS	TR	17	Pen, biting	Apple, crushing	Glass, drinking	Teeth, brushing
17	**Bells, ringing**	NHARS		20	Shower	Alarm clock	Van	Bells
18	**Straw, drinking** The sound produced by sucking a liquid into the mouth	BRAS	TR	18	Trumpet, playing	Potato crisps, eating	Straw, drinking	Smoking a cigarette

19	Alarm clock, ringing	NHARS		18	Alarm clock	Police car	Broken plate	Bells
20	Bottle, gurgling The sound made by drinking from a bottle	BRAS	TR	16	Pineapple, eating	Smoking a cigarette	Drinking from the bottle	Soup, eating
21	Fireworks, bursting	NHARS		16	Stormy sky	Car	Bells	Fireworks
22	Balloon, inflating Filling air inside a ballon by blowing in air through the mouth	BRAS	TR	18	Balloon, inflating	Glass, drinking	Breadstick, eating	Coffee cup, drinking
23	Drumming fingers The sound produced by hitting a surface repeatedly with the fingers	LRAS	IN	15	Finger cracking	Rubbing one foot against the other	Drumming fingers	Snapping finger
24	Ambulance siren, hooting	NHARS		20	Coffee maker	Ambulance	Fountain	Police car
25	Footsteps The sound produced by walking on the paving	LRAS	IN	17	Drumming fingers	Going down the stairs	Finger snapping	Footsteps
26	Fire, crackling	NHARS		18	Fountain	Fire	Fireworks	Water, boiling
27	Hands, clapping The noise produced by hitting the hands together	LRAS	IN	20	Stamping foot	Finger flicking	Hands, clapping	Rubbing one hand against the other
28	Horse, whinnying	NHARS		18	Donkey	Sheep	Hen	Horse
29	Going down the stairs Sound made by the feet when climbing down a set of steps	LRAS	IN	15	Rubbing one foot against the other	March	Going down the stairs	Finger flicking
30	Coughing	BRAS	IN	18	Spitting	Coughing	Speaking	Puffing
31	Cat, meowing	NHARS		20	Dog	Cat	Ape	Lion
32	Rubbing one hand against the other The sound made by pressing the hands together with a circular or repeated up and down movement	LRAS	IN	15	Rubbing one hand against the other	Scratching	Slapping	Hitting one fist against the hand
33	Lighting a lighter The typical sound made by striking a device with the hand, which produces a small flame	LRAS	TR	16	Lighting a lighter	Striking a match	Coffee, stirring	Velcro fastener
34	Hands, washing The sound made by rubbing the hands together with a circular repeated movement	LRAS	IN	20	Stamping foot	Rubbing one hand against the other	Hands, washing	Running
35	Sawing a piece of wood The crude sound made by sawing wood using a metal tool	LRAS	TR	16	Lighting a lighter	Sawing a wood piece	Hammering	Scissors, cutting
36	Whistling	BRAS	IN	16	Whistling	Chattering teeth	Singing	Clicking tongue
37	Snapping A brief noise made by pushing the second finger hard against the thumb and then releasing it suddenly	LRAS	IN	18	Knocking	Snapping finger	Footsteps	Finger kracking

38	**Striking a match** The sound made by a short thin stick made of wood when it is rubbed firmly against a rough surface by a quick movement of the hand, which results in the stick being lit	LRAS	TR	18	Water, pouring	Sandpapering	Knife, cutting	Striking a match
39	**Scratching** Sound produced when the fingernails are moved across the skin	LRAS	IN	16	Finger flicking	March	Clapping	Scratching
40	**Whistle, blowing** A high sound made by forcing air through a special device held to the lips	BRAS	TR	17	Whistle, blowing	Straw, drinking	Candle, blowing out	Apple, crushing
41	**Knuckles, cracking** A sudden, brief sound produced by pulling the joints of one's fingers	LRAS	IN	19	Knuckles cracking	Hands, washing	Hitting one fist against the hand	Rubbing one foot against the other
42	**Nose, blowing** The sound produced by blowing one's nose in a handkerchief	BRAS	TR	19	Ice cream, eating	Glass, drinking	Candy, crunching	Nose, blowing
43	**Typing on computer** The sound produced by pressing one's fingers on a computer keyboard	LRAS	TR	20	Turning on the radio	Typing on computer	Tennis ball, hitting	Taking a photo
44	**Yawning**	BRAS	IN	18	Singing	Sneezing	Yawning	Spitting
45	**Projector, operating**	NHARS		16	Radio	Projector	Ambulance	Refrigerator
46	**Blowing a raspberry** A rude sound made by sticking the tongue out and blowing	BRAS	IN	18	Sticking out tongue	Snoring	Hiccupping	Blowing a raspberry
47	**Washing machine, whirring**	NHARS		18	Refrigerator	Sewing machine	Water, boiling	Washing machine, whirring
48	**Kissing**	BRAS	IN	16	Blowing a raspberry	Yawning	Kissing	Coughing
49	**Sheep, bleating**	NHARS		20	Donkey	Bear	Sheep	Cow
50	**Snoring**	BRAS	IN	19	Snoring	Hiccupping	Biting lip	Sticking out tongue
51	**Closing a zip fastener** The sound produced by closing a fastener with one's hand	LRAS	TR	17	Zip fastener, closing	Velcro fastener	Sandpapering	Flushing a toilet
52	**Crying**	BRAS	IN	19	Biting lip	Laughing	Speaking	Crying
53	**Teeth, brushing** The sound produced when a toothbrush comes into contact with the teeth	BRAS	TR	20	Teeth, brushing	Flute, playing	Candy, crunching	Pineapple, eating
54	**Laughing**	BRAS	IN	16	Sniffing	Singing	Laughing	Chattering teeth
55	**Airplane, flying**	NHARS		18	Clock	Broken plate	Helicopter	Airplane
56	**Cutting with a scissors** The sound produced by cutting paper using a scissors	LRAS	TR	19	Knife, cutting	Pencil, sharpening	Scissors, cutting	Zip fastener, closing

57	**Soup, eating** **The sound produced by slurping soup noisily from a spoon**	**BRAS**	**TR**	**20**	**Straw, drinking**	**Soup, eating**	**Flute, playing**	**Pen, biting**
58	**Potato crisps, eating** **The crunching sound made in the mouth while eating potato chips**	**BRAS**	**TR**	**19**	**Whistle, blowing**	**Ice cream, eating**	**Drinking from the bottle**	**Potato crisps, eating**
59	**Dog, barking**	**NHARS**		**20**	**Hen**	**Cow**	**Dog**	**Horse**
60	**Sneezing**	**BRAS**	**IN**	**16**	**Sneezing**	**Whistling**	**Sniffing**	**Crying**

Appendix S1 - **List of the sounds used in the sound-picture matching test.** Each sound could evoke transitive or intransitive, limb (LRAS) or buccofacial (BRAS) related human actions or non-human actions (NHARS). The sounds were chosen on the basis of two psychophysics studies, the second of which used 20 elderly, healthy participants matched in age to the patients groups of this study. The appendix reports: i) the order of the stimuli, ii) their description, iii) the sound categories (BRAS, LRAS, and NHARS); iv) the types: whether they can be associated to transitive (TR) or intransitive (IN) actions; v) the score of non brain damaged control subjects; vi) the four pictures shown on each trial (one target -in light blue- and three distracters) and their spatial arrangement (I, II, III, IV refer to the upper left, upper right, lower left and lower right quadrants of the screen, respectively). The items in grey (in the sound description column) indicate the sounds used for both action recognition and execution in the apraxic groups.