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Response time as an index for selective auditory cognitive deficits

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Abstract. The full or partial recovery of cognitive functions following brain lesions is believed to rely on the recruitment of alternative neural networks. This has been shown anatomically for selective auditory cognitive functions (Adriani et al. 2003b). We investigate here behavioral correlates that may accompany the use of alternative processing networks and in particular the resulting increase in response times. The performance of 5 patients with right or left unilateral hemispheric infarction and 6 normal control subjects in sound identification, asemantic sound recognition, sound localization, and sound motion perception was evaluated by the number of correct replies and response times for correct and wrong replies. Performance and response times were compared across patients and normal control subjects. Two patients with left lesions were deficient in sound identification and sound motion perception and normal in sound localization and asemantic sound recognition; one patient with right lesion was deficient in sound localization and sound motion perception and normal in sound identification and asemantic sound recognition; deficient performance was associated with increased response times. The remaining 2 patients (1 with left, 1 with right lesion) had normal performance in all 4 tasks but had significantly longer response times in some (but not all) tasks. Patients with normal or deficient performance tended more often than normal subjects to give faster correct than wrong replies. We propose that increased response time is an indication of processing within an alternative network.

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Key words: response time, sound identification, sound localization, parietal lesion, auditory "what" and "where" processing streams

INTRODUCTION

Several lines of evidence indicate that sound recognition and sound localization are processed in two at least partially independent processing streams. In non-human primates the non-primary auditory areas of the belt were shown to contain predominantly neurons responding to animal-cry like stimuli (area AL) or to the spatial location of the sound (area PL) (Rauschecker and Tian 2000). In man fMRI (Alain et al. 2001, Maeder et al. 2001) and electrophysiological investigations (Alain et al. 2001, Anourova et al. 2001) suggest a similar dichotomy. In particular the recognition of significant auditory stimuli activated selectively bilaterally regions on the temporal convexity and sound localization bilaterally parietal and frontal foci (Maeder et al. 2001). Relatively large lesions centered on either of these networks were shown to be associated in the chronic stage with the corresponding deficit both after right (Clarke et al. 2002, Fujii et al. 1990, Griffiths et al. 1996, 1997, Spreen et al. 1965), left (Clarke et al. 2000) or bilateral hemispheric lesions (Jerger et al. 1972, Rosati et al. 1982). Smaller lesions were shown to produce in the acute stage auditory cognitive deficits, but these deficits did not always correspond to the specialization of the damaged network, e.g., small lesions centered on the recognition network were found to be associated in the acute stage with a selective deficit in sound localization (Adriani et al. 2003a). Follow-up evaluations showed that most of the deficits associated with these small lesions recovered within the next months (Rey et al. 2003).

Activation studies on motricity (see Calautti and Baron 2003 for review) and language (Blasi et al. 2002, Cao et al. 1999, Karbe et al. 1998, Ohyama et al. 1996, Rosen et al. 2000, Warburton et al. 1999, Weiller et al. 1995) have shown that full or partial recovery of function following brain lesions relies on the recruitment of alternative neural networks. The processing within these networks is very likely to be less efficient than in normals and be associated thus with subnormal performance and/or increased processing times. The latter can be assessed by means of response times in specific cognitive tasks. Most neuropsychological studies characterize deficient performance by the insufficient number of correct replies as compared to the normal population and/or by excessively slow responses (Lezak 1995, Saygin et al. 2003). In online paradigms differences in response time between correct and wrong replies have been interpreted as an additional measure of performance (Buttet Sovilla and Grosjean 1997). This research seeks to investigate whether increasing response time is due to a general slowness in cognitive functions as proposed by Saygin et al. (2003) or can be interpreted as an additional measure of reorganization of a deficient processing in chronic patients. This is a first report using these two approaches to describe the performance of

Table I

Patients participating in the study

	Age (years)	Sex	Occupation	Education (years)	Lesion side	Lesion site	Etiology	Post onset
MF	53	M	civil engineer	16	R	Temp. Pariet. Thal.	Hemorrhagic Stroke	14 m
HA	60	M	army officer	16	L	Temp. Pariet.	Stoke	20 m
PA	47	F	bank manager	16	L	Front. Temp. Pariet.	Stroke	17 m
KH	50	F	housewife	12	R	Pariet.	Stroke	7 m
GT	48	M	aviator	14	L	Front. Temp. Pariet.	Embolic stroke	35 m

(M) male; (F) female; (R) right; (L) left, (m) month. Lesions have been assessed on CT scans.

brain-damaged patients in spatial and nonspatial auditory functions.

METHODS

Six healthy control subjects (4 male and 2 female, mean age 42) with no history of neurological or hearing disease and five right-handed patients with a first unilateral hemispheric stroke (Table I) were included in this study. The patients corresponded to consecutive cases from a speech therapy clinic that fulfilled the following criteria: (i) unilateral hemispheric stroke; (ii) no previous brain damage; (iii) normal hearing; and (iv) absence of major behavioral disturbances. Two patients sustained a unilateral right (MF and KH) and three a left lesion (PA, HA and GT). The onset of the lesion was between 7 to 35 months prior to the auditory cognitive testing reported here. They were evaluated for the neuropsychological and neurolinguistic deficits using a standard aphasia test (Nilipour 1993) as part of their neurorehabilitation program for speech-language therapy. Patients HA, PA and GT, but not MF and KH had a moderate general language deficit profile subsequent to the lesion and CVA history, but did not suffer from a major cognitive or motor deficit.

We presented two sets of auditory tasks in this experiment: two auditory spatial tasks and two auditory recognition tasks. The tasks were cultural adaptations of tasks used in previous studies (Bellmann et al. 2001, Clarke et al. 1996, 2000). The adapted auditory tasks were performed using Presentation® software (Version 0.51, www.neurobs.com) and were run on a Pentium III PC. The number of correct replies as well as the response times in each case was recorded.

The auditory spatial tasks included a localization task and a motion task. Previous studies of brain-damaged patients have tested the ability to localize sound sources either in free-field condition, i.e., with loudspeaker placed in different locations around the patient, or with simulations using interaural time (Altman et al. 1979, Bisiach et al. 1984) or intensity differences (Sterzi et al.1996). As in our previous studies, we have used here spatial simulations with interaural time differences (ITD) (Adriani et al. 2003a, Bellmann et al. 2001, Bellmann Thiran and Clarke 2003, Clarke et al. 2000, 2002). In the auditory localization task, a stationary auditory stimulus, a 2 second broadband bumblebee sound, shaped with 100 ms rising and falling times, was presented to the subject *via* headphones at five different locations: extreme right (0.6 ms ITD in favor of the right ear), right (0.3 ms), center, left (-0.3 ms), and extreme left (-0.6 ms) The subjects were asked to choose one of the five positions marked on a head drawing shown on the screen by indicating the location of the presented sound by pushing the proper key on the keyboard. The left and right Ctrl keys were assigned for the extreme left and extreme right positions respectively, left and right Alt keys for the left and right hemispace positions respectively, and the Space-bar key in the center for the stimuli presented in the center. Four samples were presented as training trials prior to the task.

In the motion task, the sound stimulus, 2.3 s "bumblebee" sound shaped with 100 ms rising and falling times, moved from one location to another using simulation with progressive changes of ITD. Four types of moving paths and two speed conditions were used in this task: extreme right to left, extreme left to right, right to center and left to center. The starting and finishing positions were defined by ITD as in the localization task. The extreme left to right and extreme right to left were presented with fast speed and the left to center and right to center with slow speed. The speed rate of the fast condition was 40 degrees/s and the slow condition 20 degrees/s. The subjects were asked to identify the direction and the trajectory of the moving sound they heard *via* the headphones by pushing the proper key. The left and right Ctrl keys were assigned for right to left and left to right stimuli respectively, left and right Alt keys for the left to center and right to center positions respectively. Four trials were presented prior to the task.

The sound recognition tasks included a sound identification task and an asemantic task with a similar design which have explained in previous research (Clarke et al. 2000). In the sound identification task, the auditory sound object lasted 7 s was presented on the headphones with a multiple-choice drawing presented on the screen simultaneously. The subject was asked to select the visual object corresponding to the sound from five drawings representing the target (e.g., hammer); a semantically but not acoustically related (saw); an acoustically but not semantically related (clock); a semantically and acoustically related (hatchet); and an unrelated object (ship). Five keys were labeled with 1 to 5 which would correspond to the number of the selected choices on the screen.

In the asemantic task, two consecutive non-identical environmental sounds were presented to the subject *via* headphones. The subjects were asked to decide whether the two consecutive sounds belonged to the same or different sound objects by pushing the key labeled "yes" or "no" on the keyboard. Four training trials were performed prior to the task.

Response times were measured from the offset of the stimulus (the second stimulus in the asemantic recognition task). The normal distribution of the response times for each test and each subject was tested with p-p plots. Since response times had normal distribution a parametric t-test was performed to compare response times in each case. The clustering of patients and normal subjects based on their response times in each task was performed using ANOVA test and Tukey HSD *post-hoc* analysis (Fig. 1).

RESULTS

The performance of normal subjects in sound identification, asemantic sound recognition, sound localization and sound motion perception is summarized in Table II. None of the tests had a ceiling effect. Response times varied between 116 ms (mean response time to correct replies in the asemantic recognition tests) and 647 ms (mean response time to wrong replies in the sound identification test). The response times when giving correct versus wrong replies were significantly different for sound motion perception, almost significantly different for sound identification, and not significantly different for sound localization and asemantic sound recognition.

Three patients presented selective deficits as assessed by the number of correct replies. Patient MF was deficient in auditory spatial functions (i.e., his scores were significantly different from those of normal subjects), both in sound localization (P=0.022) and sound motion perception (P=0.006), while sound identification and asemantic sound recognition were within normal limits (P=0.816 and 0.667, respectively). His response times were significantly slower than those of normal subjects in the deficient domains, i.e., sound localization and sound motion perception, as well as in the apparently preserved sound identification, but not in asemantic sound recognition (Fig. 1). Within a given task, re-

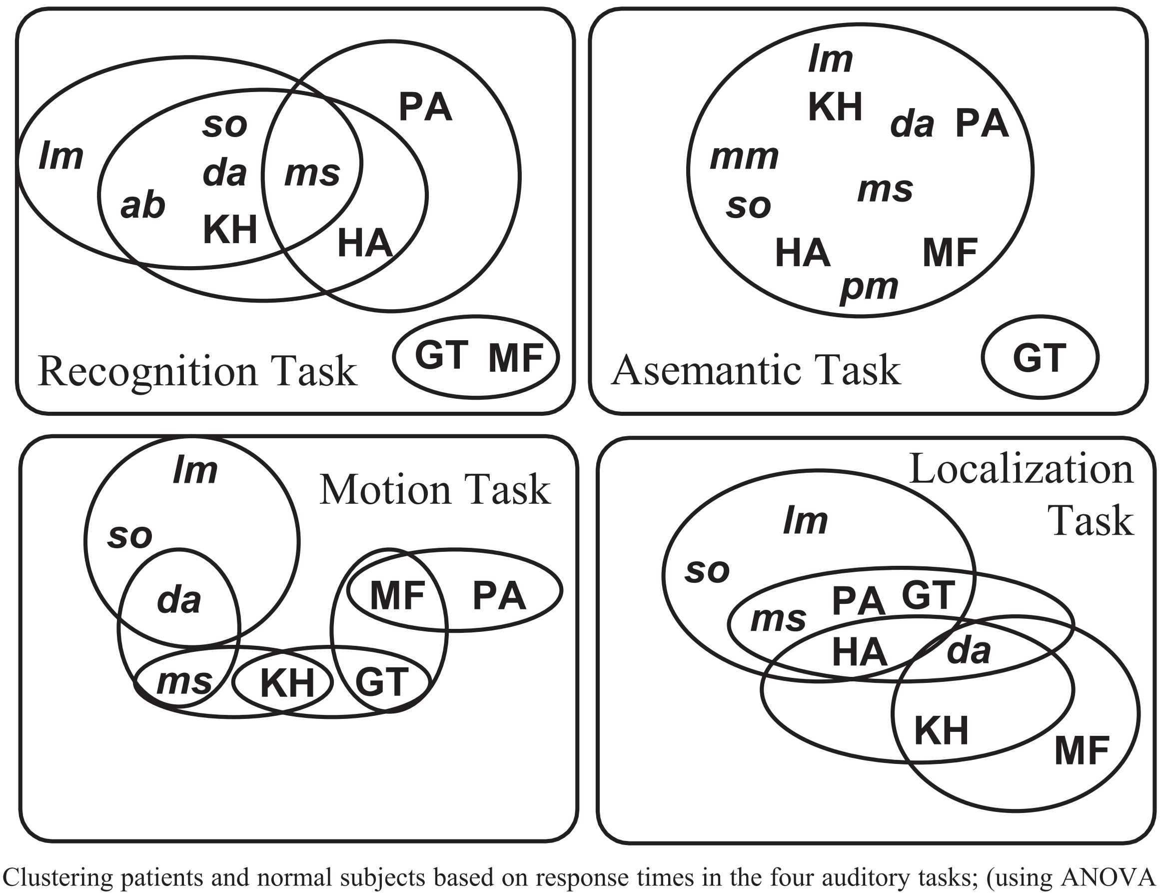

Fig. 1. Clustering patients and normal subjects based on response times in the four auditory tasks; (using ANOVA test and *post-hoc* Tukey HSD). Initials identify patients (upper case) and normal subjects (lower case). Normal subjects and patients entered the same contour are not statistically different from each other.

sponse times of correct and of wrong replies did not differ significantly (Table II). Detailed analysis of the type of errors in sound localization revealed a rightward shift which was not present in normal subjects.

Patient HA was deficient in sound identification and sound motion perception (P=0.000 for both), while sound localization was within normal limits (P=0.256) and asemantic sound recognition at the lower limit of normal performance (P=0.074). His response times were significantly slower than those of normal subjects in the deficient domain (sound identification; response times for motion perception have not been assessed), but not in the preserved sound localization and the relatively preserved asemantic sound recognition (Fig. 1). Within a given task, response times of correct and of wrong replies did not differ significantly for sound localization, sound motion perception and asemantic sound recognition. For sound identification correct re-

Table II

Performance of patients and normal subjects and related response times (RT)

	Sound identification	Asemantic sound recognition	Sound localization	Sound motion perception
Mean of normal subjects				
Number of correct replies	36.8/44	23.4/25	16/25	30/40
RT of correct replies	434 ± 357 ms	116 ± 151 ms	152 ±2 88 ms	125 ± 126 ms
RT of wrong replies	647 ± 630 ms	134 ± 79 ms	199 ± 312 ms	237 ± 304 ms
Difference RT correct vs. wrong	P=0.057	P=0.700	P=0.419	P=0.025#
Patient MF				
Number of correct replies	30/44	21/25	7/25*	17/40*
RT of correct replies	1,797 ± 1,202 ms*	239 ± 240 ms	564 ± 325 ms*	641 ± 229 ms*
RT of wrong replies	2,029 ± 814 ms*	235 ± 74 ms	645 ± 244 ms*	742 ± 320 ms*
Difference RT correct vs. wrong	P=0.517	P=0.980	P=0.501	P=0.272
Patient HA				
Number of correct replies	19/44*	17/25	11/25	3/40*
RT of correct replies	712 ± 260 ms*	111 ± 51 ms	110 ± 71 ms	122 ± 102 ms*
RT of wrong replies	961 ± 302 ms*	116 ± 68 ms	376 ± 521 ms	92 ±54 ms*
Difference RT correct vs. wrong	P=0.007#	P=0.830	P=0.093	P=0.399
Patient PA				
Number of correct replies	33/44*	18/25	9/25	13/40*
RT of correct replies	1,060 ± 979 ms*	98 ± 83 ms	417 ± 283 ms	-
RT of wrong replies	997 ± 614 ms*	231 ± 209 ms	363 ± 209 ms	-
Difference RT correct vs. wrong	P=0.801	P=0.147	P=0.147	-
Patient KH				
Number of correct replies	36/44	25/25	18/25	10/12
RT of correct replies	449 ± 345 ms	197 ± 208 ms	530 ± 663 ms*	331 ± 208 ms*
RT of wrong replies	884 ± 701 ms	-	537 ± 642 ms*	265 ± 45 ms*
Difference RT correct vs. wrong	P=0.115	-	P=0.982	P=0.158
Patient GT				
Number of correct replies	32/44	17/25	13/25	26/40
RT of correct replies	1,285 ± 1,019 ms*	464 ± 720 ms*	143 ± 76 ms	502 ± 262 ms*
RT of wrong replies	2,382 ± 1,361 ms*	654 ± 637 ms*	201 ± 160 ms	601 ± 463 ms*
Difference RT correct vs. wrong	P=0.006#	P=0.531	P=0.276	P=0.391

(#) statistically significant differences in response times associated with correct vs. wrong replies; (*) deficient performance or significantly slower response times in brain-damaged patients as compared to normal subjects plies were significantly faster than wrong replies. Detailed analysis of the type of errors in the sound identification task revealed a specific weakness in the semantic domain. This patient gave 25 wrong replies of which 9 were semantically but not acoustically related to the target, 3 acoustically but not semantically, 9 semantically and acoustically and 4 unrelated (the range of these errors in normal subjects was, respectively, 0-2, 0-1, 3-8, and 0-2). Furthermore, he gave wrong replies which were never given by normal subjects and which revealed confusion between acoustic and semantic categories: e.g., when he heard a "hammer" he chose a "saw" as the target.

Patient PA was deficient in sound identification and sound motion perception (P=0.003 and 0.000, respectively), but normal in asemantic sound recognition (P=0.138) and at the lower limit of normal performance sound localization (P=0.089). Her response times were significantly slower than those of normal subjects in the two deficient domains (sound identification and sound motion perception), but not in the preserved asemantic sound recognition and the relatively preserved sound localization (Fig. 1). Within a given task, response times of correct and of wrong replies did not differ significantly for sound identification, asemantic sound recognition and sound localization. For sound motion perception, correct replies were significantly faster than wrong replies (Table II).

Two patients had normal performance in all four auditory cognitive functions (patient KH; P<0.05 for all four functions) or in all except asemantic sound recognition, which was at the lower limit of normal performance (patient GT; P=0.074 for asemantic sound recognition, P<0.05 for the other three functions). The response times of patient KH were significantly slower than those of normal subjects in sound localization and sound motion perception, but not in sound identification and asemantic sound recognition (Fig. 1), suggesting a weakness in the auditory spatial processing. Within a given task, response times of correct and of wrong replies did not differ significantly (Table II).

The response times of patient GT were significantly slower in sound identification, asemantic sound recognition and sound motion perception, but not in sound localization (Fig. 1), suggesting a main relative weakness in sound recognition processing. Within a given task, response times of correct and of wrong replies did not differ significantly for sound localization, sound motion perception and asemantic sound recognition. For sound identification, correct replies were significantly faster than wrong replies (Table II).

DISCUSSION

Our results demonstrate that deficient performance in terms of correct replies tends to be accompanied by increased response times. A similar inverse relationship between the number of correct replies and response time has been recently described for both verbal and non-verbal auditory recognition in aphasic patients (Saygin et al. 2003). In this study poor performance in verbal and non-verbal domains tended to be associated, an observation which was interpreted in terms of shared processing networks for the two functions. In our study, three out of five patients presented selective deficits in auditory spatial tasks (patient MF) or in sound identification and sound motion (patients PA and HA), confirming previous findings of such dissociations in other patients (Adriani et al. 2003a, Clarke et al. 1996, 2000, 2002). Response times were significantly slower, as compared to normal subjects, in deficient domains. Each of the three patients had at least one domain in which normal performance in terms of correct replies was associated with response times within the normal range, speaking against a general slowness.

For some tasks in a given patient, normal performance was, however, also associated with increased response times. We argue that this profile reflects less efficient processing within an alternative network. The use of alternative cortical networks for sound recognition and sound localization in cases of brain lesions has been demonstrated both in the ipsi- and contralesional hemispheres (Adriani et al. 2003b) Two out of five patients in this study had normal performance in all domains, as assessed with the number of correct replies. The statistically significant increase in their respective response times suggested, however, a relative weakness in auditory spatial processing (patient KH) or in sound recognition (plus sound motion perception; patient GT). The interpretation of the increase in response times as a measure of reorganization of the corresponding processing stream has additional support from the fact that patient KH sustained a right parietal lesion, known to disrupt mainly processing within the auditory "where" stream (Clarke et al. 2002). This interpretation is in agreement with previous studies by others. The crossed visuo-motor task of the Poffenberger paradigm, i.e., motor response to a visual stimulus executed with the hand which is contralateral to the visual hemifield which has been stimulated, can be successfully performed by callosotomized patients, but their reaction times are significantly longer than those of normal subjects; activation studies have shown that callosotomized patients execute this task with different neural networks than normal subjects (Marzi et al. 1999).

The relatively faster response time associated with correct than wrong replies occurred in normal subjects for sound motion perception. In patients this phenomenon was associated with deficient performance in sound identification (patient HA) or in sound motion perception (patient PA) or with normal performance in sound identification (patient GT). We argue that this additional increase in reaction time associated with wrong replies reflects the additional processing load which is put on alternative networks in presence of difficult items. Differences in response times for correct and wrong replies have been described previously for covert face recognition in a prosopagnosic patient (Landis et al. 1988) and covert target detection in hemineglect (Laeng et al. 2002). In both studies, wrong negative replies (i.e., the incorrect detection of an absent stimulus or its incorrect identification) have been significantly faster than wrong positive or correct replies. This observation was interpreted as correct pre-attentive processing followed by a faulty and early aborted attentional processing. Our data, showing a reverse pattern, cannot be interpreted in this way.

CONCLUSIONS

Sound recognition, sound localization and sound motion perception were investigated in patients with focal unilateral hemispheric lesions. In terms of number of correct replies selective deficits were observed in 3 patients, in agreement with previously published studies. Deficient performance was associated with increased response times. Two patients had normal performance in all auditory cognitive functions, but presented increased response times in some of them. Anatomo-clinical correlations suggest that increased response times reflect processing in alternative networks, which occurs when the specialized networks have been damaged.

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ABBREVIATIONS

AL - anterolateral auditory area in macaque monkeys
ITD - interaural time difference
PL - posterolateral auditory area in macaque monkeys
RT - response time

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