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Pitch and Timing Abilities in Adult Left-Hemisphere-Dysphasic and Right-Hemisphere-Damaged Subjects

Katherine. J. Alcock,* Derick Wade,† Philip Anslow,‡ and Richard E. Passingham*

**Department of Experimental Psychology, University of Oxford, Oxford, United Kingdom; †Rivermead Rehabilitation Hospital, Oxford, United Kingdom; and ‡Radcliffe Infirmary, Oxford, United Kingdom*

The production and perception of pitch and rhythm were tested in patients with acquired unilateral left-hemisphere (LH) lesions (and subsequent motor dysphasia, $n = 13$), patients with unilateral right-hemisphere (RH) lesions ($n = 14$), and normal age-matched controls. While the LH dysphasic subjects were not generally impaired on the production or perception of pitch, they were grossly impaired on the production and perception of rhythm. The RH subjects, in contrast, were impaired on measures of pitch perception and production, including the discrimination and production of single notes and of melodies. It is concluded that the two hemispheres differ in their specialization for the perception and production of pitch and rhythm.

INTRODUCTION

The lateralization of pitch and rhythm processing (musical abilities) has been a topic of interest for many years (Jackson, 1871; Botez & Wertheim, 1959). In studying the effects of brain lesions on pitch and rhythm, we had two aims. The first was to determine whether it was possible to dissociate the effects of left-hemisphere (LH) and right-hemisphere (RH) lesions on the processing of pitch and rhythm. Until recently, such studies were limited to single-case studies of brain-damaged individuals, generally professional musicians. Furthermore, the results were not consistent; for example, Ravel experienced deterioration of musical abilities resulting from degenerative disease of the left perisylvian area (Henson, 1988), whereas Shebalin, who suffered from a dominant hemispheric stroke and resultant aphasia, was able

Address correspondence and reprint requests to Katherine J. Alcock, Department of Psychology, City University, Northampton Square, London EC1V 0HB. E-mail: k.j.alcock@city.ac.uk.

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to continue conducting and composing (Luria et al., 1965). In addition, professional musicians may differ from the general population in their cerebral representation of musical processing (Benton, 1977). There is thus a need for studies of groups of patients, specifically nonmusicians, so as to provide a sounder basis for conclusions as to which musical abilities are impaired following unilateral hemispheric damage.

The second aim was to throw light on the impairments shown by the affected members of the KE family. This is a family with a severe inherited development dysphasia (Vargha-Khadem et al., 1995). The same tests were given to adults with acquired lesions as were given to members of the KE family. Thus it was possible to compare the performance of the developmental and acquired aphasics. The results of this comparison are discussed in a companion paper (Alcock et al., submitted-a, -b).

It has been claimed that patients with a nonfluent aphasia can still sing. Yamadori et al. (1977) found that when patients ($n = 24$) suffering from a nonfluent aphasia were asked to sing a well-known tune, 87.5% produced at least a satisfactory rendering of the tune, half produced flawless words, and a remaining 12.5% made only one paraphasic error on the words of the song. This is remarkable for patients whose main speech characteristic is poverty of output and paraphasias. Case studies have also shown that professional musicians who have become aphasic through focal or diffuse brain damage, due to acute or chronic neurological disease, can still express themselves through music and perceive music in the same way that they did previously (Basso & Capitani, 1985). In contrast, patients have been found with focal deficits of musical ability (amusias) who do not necessarily have any aphasia (Hachinski, 1989).

These observations might be taken to suggest that music and language have separate neural representations and that just as the left hemisphere subserves most language functions, so the right hemisphere is responsible for musical processing. However other reviews of this area have concluded that most patients suffering from amusia are also aphasic (Benton, 1977). Gates and Bradshaw (1977) suggest that differing strategies for processing musical stimuli may lead to differing cerebral representations. These strategies may depend on individuals and their experience, the stimulus, and the type of processing required.

In addition, a distinction should be drawn between the processing of pitch and other aspects of musical processing. Several group studies have compared the perception of music in patients with acquired left- and right-hemisphere lesions. Zatorre (1984) summarizes earlier research by saying that the discrimination of pitch patterns, particularly unfamiliar ones, is impaired following right-cortical damage. By contrast, if a preponderance of tasks are given that involve lyrics or names of familiar melodies, patients with left-hemisphere damage are impaired.

An alternative explanation is provided by Peretz (1990). She asked left- and right-temporal lobectomy patients to discriminate unfamiliar melodies, which had been altered either by preserving the overall contour of the piece or by disrupting the contour. In the latter case, where originally the melody had been rising or falling, it now did the opposite. Both patient groups were impaired. The greater impairment of the right hemisphere patients was accounted for by their failure to discern either those differences that preserved the contour of the melody or those differences that violated the contour of the melody. Left-hemisphere patients were able to detect the latter changes but not the former. Peretz interprets this as evidence that processing of local features takes place in the left hemisphere, whereas processing of global pitch parameters takes place in the right hemisphere.

Peretz (1990) also found that patients with left-temporal-lobe damage were unable to discriminate rhythms, whereas they could still discriminate some melodic differences that the right-temporal-lobe patients were unable to detect. To construct the rhythm-discrimination task, the melodies used in the melodic-discrimination task were played at a constant pitch with some alteration in the timing and length of the notes, but no change in the number of the notes. This was done to avoid subjects merely counting notes. Left-temporal lobe patients were impaired on this rhythm-discrimination task. In addition, some left-hemisphere patients were impaired on a task where they were asked to assign each rhythm to either march time or waltz time, and these two rhythm-discrimination abilities (smaller rhythmic differences and overall meter) were found to be dissociable.

The above experiments have compared patients' and control subjects' abilities to perceive musical stimuli. The present study differs in that it also tests the ability to *produce* musical sounds after damage either to the RH or to the LH, causing a nonfluent dysphasia. Only one study to date has attempted this. Kinsella et al. (1988) asked LH- or RH-damaged patients to sing a well-known song (''Happy Birthday'') and the results were assessed for correctness of pitch and rhythm. No hemispheric differences were found but the patients were worse than the controls overall. Others have claimed that the left-hemisphere is specialized for the production of movements in the temporal domain that is in a certain order or rhythm (Hammond, 1982; Blumstein, 1990; Peretz, 1990).

The present study therefore examines the production, as well as the perception, of pitch and timing. It also examines the case where the information concerning pitch is closely tied to semantic or linguistic information. The tests given to the LH and RH patients were the same tasks as those used for the affected members of the KE family and their controls (Alcock et al., submitted -a, -b). Thus, it was possible to formally compare the pattern of deficits in the KE family with those caused by acquired lesions of the left or right hemisphere.

METHODS

Subjects

In total 50 subjects took part, including 13 patients with left-hemisphere damage and subsequent dysphasia (LH dysphasic patients), with a mean age of 60.23 years (SD = 14.83), and 14 patients with right-hemisphere damage (RH patients), with a mean age of 60.31 (SD = 11.32). In addition 24 control subjects were tested, with a mean age 64.00 (SD = 9.10).

All the patients had suffered a unilateral cerebrovascular accident, except for one case whose damage resulted from a gunshot wound. The patients were selected on the basis of left or right hemiplegia and, for the left hemisphere patients, on the basis of dysphasia. All were right-handed. All patients were tested 2 months or more after onset, and all were 80 years of age or less. All the left-hemisphere patients had suffered primarily from nonfluency and had some expressive speech difficulties at time of testing. All these patients had in addition some verbal dyspraxic difficulties at time of testing, manifested as either ‘‘literal paraphasia’’ (phoneme substitutions) (Goodglass & Kaplan, 1982) or as dyspraxic errors made on the rapid oral movements subtest of the Boston Diagnostic Examination of Aphasia (BDEA). The mean Mean Length of Utterance (MLU), as calculated from description of the Cookie Theft picture from the BDEA, was 4.45.

Typical lesions for the adult patients are shown in Fig. 1. Alcock (1995) presents the lesion diagrams and descriptions for all the patients. The diagrams in Fig. 1 are based on drawings of the lesions on standard sections taken from Damasio and Damasio (1989).

The control subjects for the patients were members of the Department of Experimental Psychology’s Subject Panel, members of the support staff of the Department, spouses of patients in the unilateral brain lesion group, and subjects recruited by a local employment agency.

Data on screening tests for all patients together with summary data for control patients are shown in Table 1.

Procedures

Detailed descriptions of the experimental tasks and their scoring methods are available in Alcock et al. (submitted-a) and in Alcock (1995).

Perception Tasks

For the music-perception tasks, tapes were prepared using a music-processing package to ensure that the stimuli were as consistent as possible. Full details and musical scores of the tests used are shown in Alcock (1995). The three tests used were all discrimination tasks. The first was a pitch-discrimination task, using notes played on a digital piano, with 22 items. The second was a familiar-melody-discrimination task, with the original melody being presented first in each case, followed by either an identical rendering or an alteration. The third was a rhythm-discrimination task, with the length of notes altered without changing the number of notes present or the overall time (Peretz, 1990). Full instructions were given, and subjects indicated their choice by pointing to cards representing SAME or DIFFERENT.

Production Tasks

There were four tests of production of music and related abilities. Full details of tests, songs used, and instructions for these are given in Alcock (1995). Subjects were tested in a soundproof room in the Department of Experimental Psychology, Oxford.

Singing Single Notes

The first task was a test of pitch production. In this the tester asked the subject to sing individual notes at an appropriate octave, each one after the tester had sung it. The tester

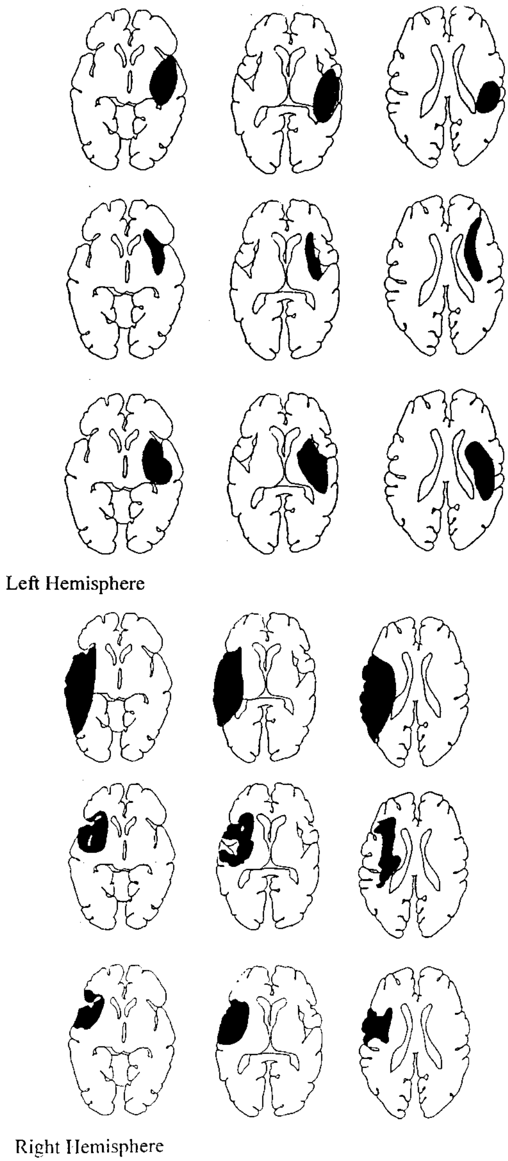

FIG. 1. Typical lesions for left- and right-hemisphere patients.

TABLE 1
Screening Data for All Patients

Subject	Sex	Age	Time since onset months	Years of education	PIQ estimate	Musical experience score	FAST score C + E	MLU on cookie jar story	Score on animal naming task
LH1	M	53	18	11		4		2.75	0
LH3	M	60	486	12		1		7.86	13
LH4	F	79	7	9		3		4.67	10
LH7	M	60	15–26	10		2		1.50	6
LH9	M	72	8–10	9		2			6
LH10	F	30	98	11		2		5.60	7
LH11	M	82	64–65	13		3		6.35	6
LH12	F	53	4–6			4		7.25	14
LH13	M	58	7–9					0.00	1
LH15	M	54	4					2.00	0
LH16	M	43	4	11		3		7.70	12
LH17	F	61	6–9	10		1		3.20	0
LH20	M	78	4	9		2		4.50	10
Mean		60.23	56.46	10.50		2.45		4.45	6.54
SD		14.83	132.13	1.35		1.04		2.59	5.09
RH3	F	75	14–23	10	85	3	17		
RH4	M	62	16–27	13	104	3	20		
RH5	M	50	12–24	10	95	2	18		
RH8	F	75	10	11	95		19		
RH9	F	64	5	10	105	3	18		
RH10	M	59	10	11	117	2	19		
RH11	F	60	3	10	91	1	16		
RH13	M	67	3	16	120	2	20		
RH14	M	42	4	10	117	2	20		
RH15	M	51	7–9	11	99	3	18		
RH16	F	79	9	11	105	2	17		
RH17	F	44	28	12	118	2	19		
RH18	M	60	24	10	84	3	19		
RH19	M	71	5–6	9	105	2	18		
Mean		61.36	11.79	11.00	102.86	2.31	18.43		
SD		11.56	8.29	1.75	12.06	0.63	1.22		
Controls mean		63.04		12.28	112.0	2.56			
Controls *SD*		9.34		2.53	10.89	1.08			

started on a note in comfortable range and sang 10–15 notes within the major scale which has the initial note as its tonic, but choosing higher or lower notes as seemed most appropriate for the subject's vocal range. The tester encouraged the subject to repeat each one, giving a cue as appropriate if the subject anticipated, or failed to sing at all, but giving no feedback as to accuracy of pitch. Items were scored as correct if the note was a correct reproduction of the model provided by the tester, to within less than one semitone. For incorrect items the size of the error in semitones was noted.

Singing Melodies

The second test was of melody production. A set of 10 songs with words and five melodies without words, or without well-known words, were chosen. The full list of songs used can be found in Alcock (1995). Subjects were asked to sing as much as they knew of each of the songs with words, given the title and/or first line. It was emphasized that the most important part of the song was the tune, rather than the words, so that the subject should sing the tune without words rather than stop if they knew no more words.

After the whole list of songs with words was tested once, any songs that subjects could not even start to sing were cued by the tester singing the first line or sometimes two lines to assist rapport. Subjects were again encouraged to sing the tune alone if the words were not known.

The melodies without well-known words were tested next, with the tester singing the first line again or more if necessary. Subjects who knew words were encouraged to sing them to assist with recall.

Scoring. Scoring was as follows: For each item, the subject was rated according to whether they had attempted the song spontaneously (apart from the melodies without words, where this was not possible), with assistance in the form of a cue, or had failed to start singing the item. Second, the number of notes needed to cue the subject was recorded. Each item was also scored for the total number of notes which corresponded to the generally accepted idea of that particular song. More detailed records were also taken for the first 10 notes of each song. The pitch transition between each pair of notes was scored. The modal pitch transition (direction and number of semitones) for all subjects for each pair of notes in each song was taken as the most common rendering of that phrase. Each pitch transition was then scored as either correct—matching the modal pitch transition—or incorrect. The differences between the actual pitch transitions and the modal pitch transitions were also calculated, giving a measure of error in semitones.

Rhythm Production

The third test, of rhythm production, contained 14 rhythms of four to nine notes in duration which were taken from the rhythms used for the discrimination task, but were shorter. The rhythms used are shown in Alcock (1995). The first part of the task consisted of the tester tapping out each rhythm on the table and then asking the subject to copy each one immediately after presentation (manual task). The second part of the test consisted of the tester vocalizing the same rhythms to the phoneme /p/and again asking the subject to repeat each one (oral task).

Scoring. The rhythms were scored first according to whether the reproduced rhythm was an exact copy of the model given. This was a stricter scoring method, with only completely correct rhythms given credit. Second, rhythms were scored according to how many notes were reproduced correctly. For this score, subjects were not excessively penalized for missing notes or extra notes. Hence, this was a more lenient scoring method. For example, where the second note was missing and the first, third, fourth, and fifth notes were present, the subject was scored as producing four notes correctly of the five rather than producing only the first note correctly in the correct position. An independent rater scored all data from 10% of the subjects in each subject group, and mean agreement rate was 84.2%.

Digitization

The recordings of the singing of single notes and the copying of both manual and oral rhythms were digitized using the Waves+ program, part of the ESPS system running on a Sun Workstation in the Oxford University Phonetics Laboratory. All single notes and rhythms were digitized. The digitized speech was then processed using one of two other ESPS programs, formant or get_f0, which both extract fundamental frequency. Pitch trace files were converted into ASCII datafiles and various parameters were calculated for each sample.

Single Notes

The following parameters were calculated: mean, maximum and minimum F_0 in Hz, and the number of semitones by which the note reproduced differed from the note given as a model.

Rhythms

The length of the interval between one note and the next was calculated, and these were then expressed as a proportion of the shortest interval produced. The intervals were then recalculated so that the unitary interval was the mean of all those intervals which rounded down to a proportion of 1 rather than the shortest interval overall. Following this the pattern of intervals produced on each item was compared with the pattern given as a model, and scores of numbers of notes and numbers of rhythms correct were given.

RESULTS

Music Perception Tasks

Pitch-Discrimination Tasks

The scores on the pitch-discrimination task are shown in Fig. 2. The t tests revealed that the RH subjects performed significantly worse on this task ($t = 2.50$, $df = 18.54$, $p = .022$). The difference between the LH-dysphasic subjects and the controls was not significant ($t = 1.592$, $df = 48$, $p > .10$). Hence the RH subjects were worse at discriminating one musical note from another.

Melody and Rhythm-Discrimination Tasks

The scores on these two tasks are shown in Fig. 3. For the melody-discrimination task it was found that both the LH-dysphasic and the RH subjects performed significantly worse than controls ($t = 3.04$, $df = 14.43$, $p < .01$ for LH and $t = 3.62$, $df = 15.31$, $p < .01$ for RH), but these two groups did not differ from each other. On the rhythm-discrimination tasks all comparisons carried out between groups were found to be significant (LH vs RH, $t = 3.384$, $df = 46$, $p < .01$; LH vs controls $t = 5.769$, $df = 46$, $p < .01$; RH vs controls $t = 2.134$, $df = 46$, $p < .05$). Hence, both patient groups

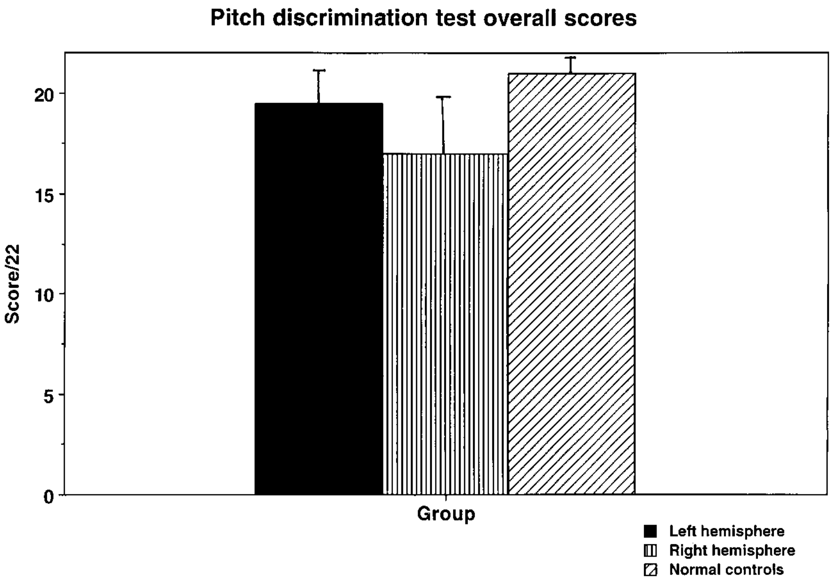

FIG. 2. Scores on pitch-discrimination tasks.

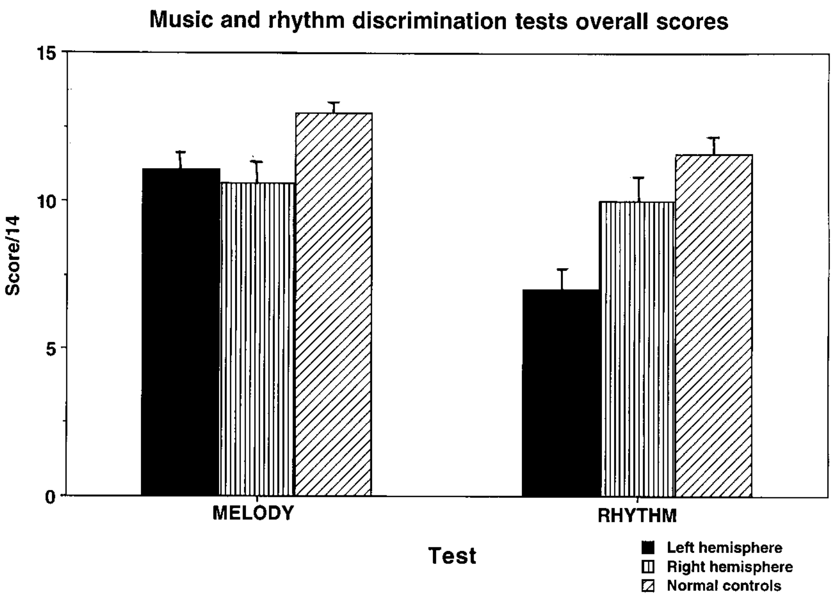

FIG. 3. Scores on melody- and rhythm-discrimination tasks.

were worse than controls at discriminating melodies and rhythms, but the LH-dysphasic subjects had greater difficulty with discriminating rhythms.

Music Production Tasks

Singing Single Notes

The proportion of notes sung correctly is shown in Fig. 4. The *t* tests revealed that the RH subjects performed significantly worse than controls on this measures ($t = 3.85$, $df = 30.18$, $p < .01$) and also on a measure of number of semitones error ($t = 3.341$, $df = 43$, $p < .01$). Hence, the RH subjects were worse at copying single notes sung to them, both in terms of number of notes correct and in terms of size of error.

Singing Songs with Words

Success rates. The songs were scored according to whether the subject sang them spontaneously, sang them with the assistance of a cue, or failed to sing them entirely. The number of songs in each of these categories is shown in Fig. 5. These three possible levels of success were entered into a MANOVA as the factor ‘‘success.’’ This revealed a significant main effect of success (whether the song could be sung spontaneously vs sung with assistance vs not sung at all) ($F = 1443.215$, $df = 2$, $p < .001$) and a significant interaction between success and group ($F = 5.942$, $df = 4$, $p < .001$). Hence all groups were more likely to sing a song spontaneously than to need assis-

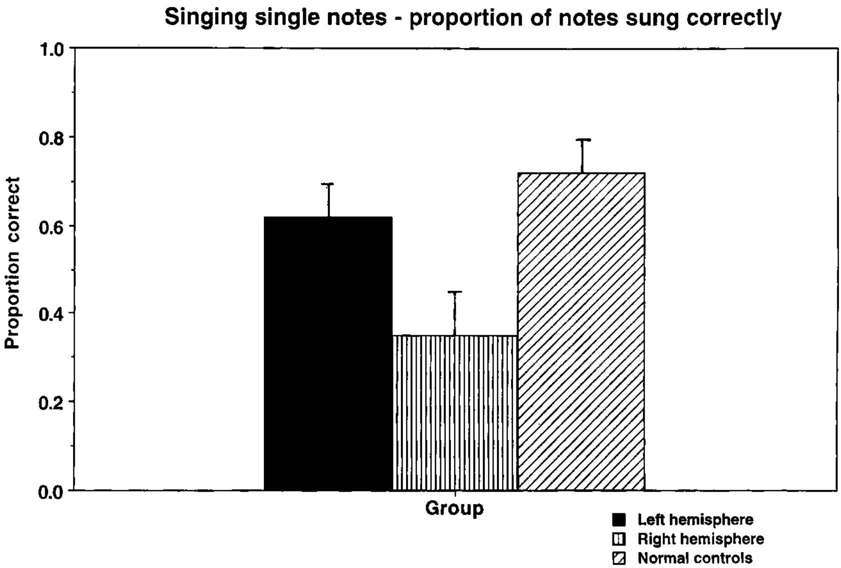

FIG. 4. Proportion of single notes sung correctly.

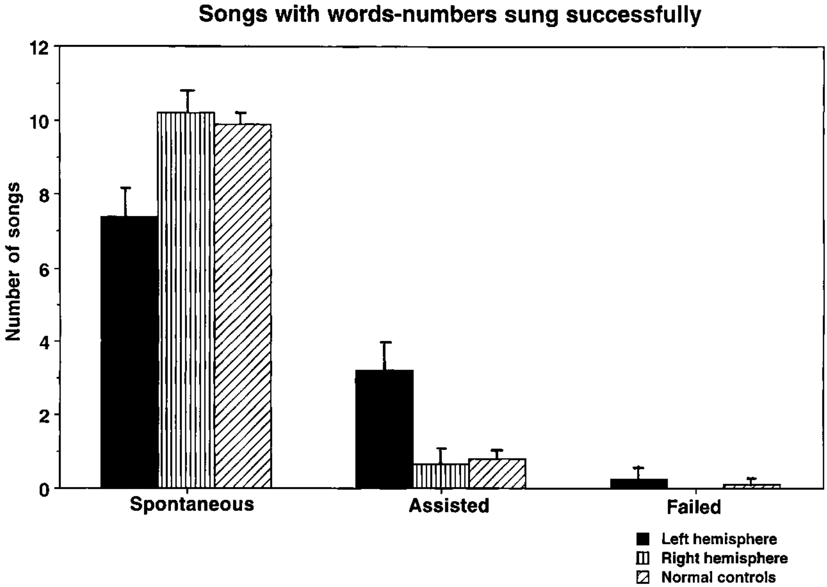

FIG. 5. Performance on songs with words.

tance or not sing it at all. The LH-dysphasic subjects were less likely than other groups to sing a song spontaneously and more likely to need a cue. They were, however, no more likely to fail to sing a song.

Number of notes cue needed. The number of notes needed to cue the subjects per song was analyzed, and a one-way ANOVA revealed a significant difference between the groups ($F = 6.3099$, $df = 43$, $p = .040$). Hence, the LH-dysphasic subjects needed more notes to cue them per song.

The number of notes known and number of syllables known per melody was also analyzed. A MANOVA revealed a significant main effect of group ($F = 7.51$, $df = 2$, $p = .002$) and a significant interaction between group and modality (notes or syllables) ($F = 16.69$, $df = 2$, $p < .001$). Hence, overall the controls remember more notes and syllables but the LH-dysphasic subjects remember fewer syllables than controls, but just as many notes, whereas the RH subjects remember fewer notes than controls, but just as many syllables.

Singing Melodies without Words

The melodies were scored according to whether the subject sang them with the assistance of a cue or failed to sing them. The two levels of success were entered into a MANOVA, which revealed a significant main effect of success (assisted vs failed) ($F = 29.66$, $df = 1$, $p < .001$) but no other effects. Hence all groups can sing more melodies than they fail to sing, and

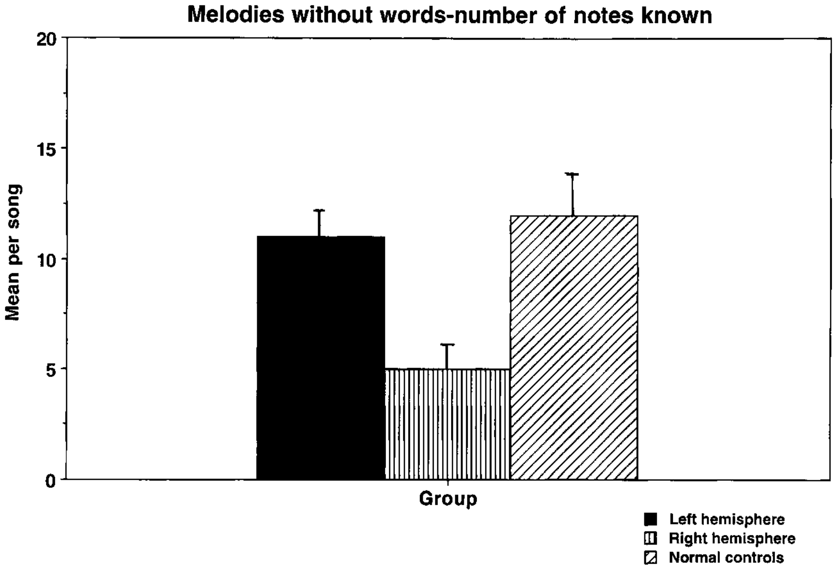

FIG. 6. Performance on melodies without words.

there were no group differences. Neither were there any group differences on the number of notes needed to cue subjects on each melody. However a one-way ANOVA looking at the number of notes known per melody revealed a significant group effect ($F = 4.9254$, $df = 43$, $p = .0119$) and a post hoc t test clarified that it was the RH subjects who differed significantly from the normal controls ($t = 3.25$, $df = 31.73$, $p = .003$). Hence the RH subjects knew fewer notes per song. This is shown in Fig. 6.

Rhythms

The proportion of rhythms copied correctly by each group is shown in Fig. 7. MANOVAs were carried out and significant main effects of group were found in the case of the proportion of rhythms copied correctly ($F = 27.35$, $df = 2$, $p < .001$) and the proportion of notes copied correctly ($F = 32.49$, $df = 2$, $p < .001$) as well as a significant main effect of modality (oral vs manual) in the case of notes correct ($F = 4.81$, $df = 1$, $p = .034$). Hence, the LH-dysphasic subjects were significantly worse than both other groups at copying rhythms, and although all subjects produced more notes correctly on oral rhythms than manual rhythms, this did not differ between groups.

Singing Single Notes

Numbers correct or nearly correct. The proportion of notes which were sung at the same pitch as the model, to within one semitone or to within one tone, was analyzed and a MANOVA revealed a main effect of group

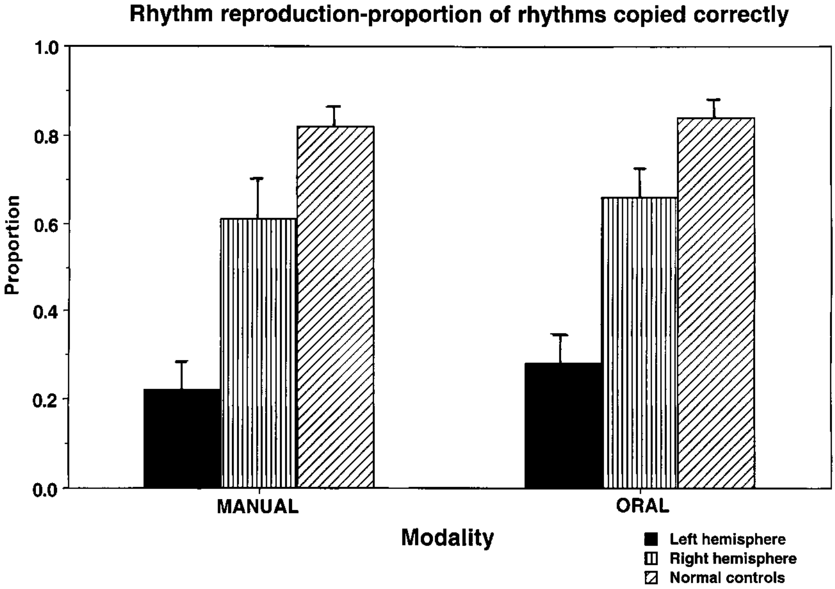

FIG. 7. Proportion of rhythms performed correctly.

($F = 5.22$, $df = 2$, $p = .011$) and of measure (0, ≤1 or ≤2 semitones) ($F = 64.093$, $df = 2$, $p < .001$). Hence, there were many items on which subjects sang close to, but not exactly at, the model, and some subject groups performed better than others. In order to examine the group effect more closely, post hoc *t* tests were carried out. Significant differences between the RH subjects and the normal controls were revealed on the number of notes which were exactly correct ($t = 3.06$, $df = 12.50$, $p < .05$) and the number which were within one semitone ($t = 3.39$, $df = 32$, $p < .05$), but the LH dysphasic subjects did not differ from controls, and there were no group differences on the number of notes which were within a whole tone. Hence, the RH subjects were less likely to come within less than a tone of the correct note.

Reproducing Rhythms

Number of Rhythms Correct. The proportion of rhythms reproduced correctly is shown in Fig. 8. A MANOVA revealed a significant main effect of group ($F = 5.93$, $df = 2$, $p = .007$) and of modality (manual vs oral) ($F = 44.05$ $df = 1$, $p < .001$) as well as a significant interaction between group and modality ($F = 13.54$, $df = 2$, $p < .001$). Hence, for all groups oral rhythms were harder than manual, and there was a smaller difference between the groups on oral rhythms.

In order to examine the group effect more closely, further MANOVAs were carried out comparing LH dysphasic subjects with controls and RH subjects with controls. The LH/controls comparison revealed a significant

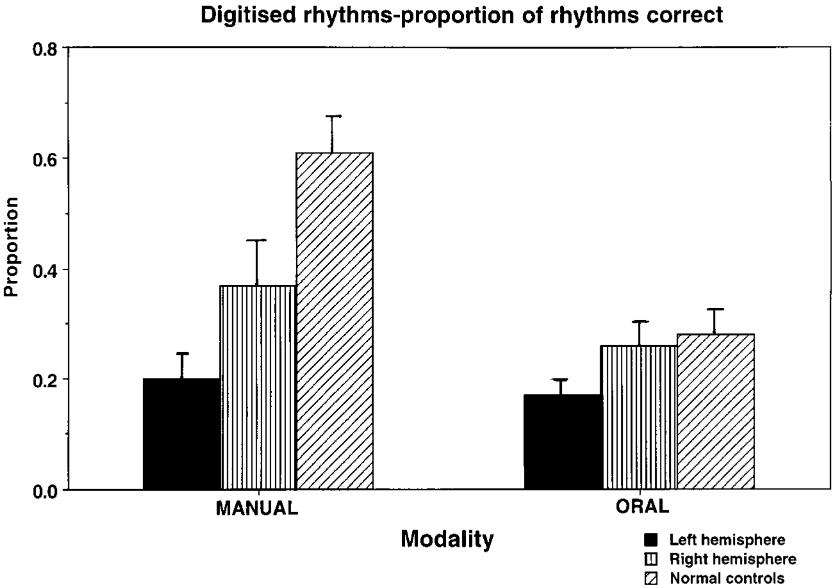

FIG. 8. Digitized rhythms—proportion performed correctly.

main effect of group ($F = 15.74$, $df = 1$, $p = .001$) as well as an effect of modality ($F = 37.92$, $df = 1$, $p < .001$) and an interaction between group and modality ($F = 25.10$, $df = 1$, $p < .001$). The RH/controls comparison revealed no group effect but a significant effect of modality ($F = 42.37$, $df = 1$, $p < .001$) and an interaction between group and modality ($F = 9.87$, $df = 1$, $p < .006$). Hence, the LH dysphasics were worse overall and all groups found oral rhythms harder than manual. The RH subjects also tended to perform worse on the manual rhythms.

Number of notes correct. The proportion of notes correct per rhythm was also analyzed. A MANOVA revealed a main effect of group ($F = 6.64$, $df = 2$, $p = .004$) and of modality ($F = 40.60$, $df = 1$, $p < .001$) as well as an interaction between group and modality ($F = 4.26$, $df = 2$, $p = .024$). Again, for all groups oral rhythms were harder than manual, and there was a smaller difference between the groups on oral rhythms.

Again, further MANOVAs were carried out to examine the group differences more closely. For the LH/control comparison a significant main effect of group was found ($F = 16.64$ $df = 1$, $p = .001$) as well as a main effect of modality ($F = 30.66$, $df = 1$, $p < .001$) and an interaction between group and modality ($F = 7.39$, $df = 1$, $p = .013$). For the RH/control comparison the only significant effect was one of modality ($F = 32.05$, $df = 1$, $p < .001$). Hence, the LH dysphasic subjects were worse overall and even worse on the manual rhythms, while all subjects found the oral rhythms harder.

DISCUSSION

A clear picture emerges from the results. The LH dysphasics had no difficulty with tasks involving pitch processing. They performed normally on the discrimination of two single notes, the singing of single notes, and the singing of notes in the context of songs with or without words. They sang just as many notes correctly as normal controls, and their errors, when they made them, were no larger than those of normal controls. On the other hand, the LH-dysphasic subjects were impaired in discriminating, and in reproducing rhythms, whether orally or manually. They produced fewer correct rhythms overall and fewer correct notes within those rhythms.

The RH subjects, in contrast, had great difficulty with intonation tasks. They were poorer than controls at discriminating two single notes and at discriminating familiar melodies from altered versions of those melodies. They were also impaired at singing single notes and songs with or without words. The RH subjects sang fewer single notes accurately at pitch or (on the digitized analysis) within one semitone of the model presented, and the notes they sang were themselves more variable in pitch, having a higher standard deviation per note. The mean difference from the model in semitones was greater, whether the notes were analyzed acoustically or scored by musically trained raters. Hence, the RH subjects found difficulty with all tasks and measures involving control and processing of intonation.

There were two results, not summarized above, which require further comment. First, the RH subjects were impaired compared with the controls in discriminating rhythms. However, the LH subjects were significantly more impaired. The RH subjects also tended to produce fewer manual rhythms correctly than the normal controls, but the difference in the number of notes produced correctly was not significant. This means that the RH patients tended to be incorrect on a small number of notes in each rhythm, whereas normal controls would reproduce most rhythms correctly and then make several errors on a few items.

Second, the LH patients were impaired, compared with controls, at discriminating familiar melodies from altered versions of these melodies. Peretz (1990) found that left temporal lobectomy patients had no difficulty in discriminating unfamiliar melodies where the alterations were of the type used in this experiment—with the contour of the melody altered. However, Zatorre (1984) suggests that tasks involving familiar songs may be harder for dysphasic subjects because of linguistic content. In the discrimination task used in this study, subjects were not specifically asked to carry out any linguistic processing, either by reproducing lyrics or by naming melodies. A labeling strategy could aid performance, though, and this may not be available to the LH dysphasic subjects.

It should be noted that all subject groups obtained scores of fewer correct notes when the notes were analyzed digitally than when they were scored by raters. This indicates a limitation of the acoustic analysis process, not of the rating methods. Although the RH subjects had greater variability of pitch within notes than the other subjects, all groups had some within-note variability. Even skilled performers do not sing a note at a constant pitch; indeed, it would sound unnatural were they to do so. Perceptually this will be resolved by the listener into an approach to the intended note in the form of an overshoot or undershoot followed by a steady state or, alternatively, a steady state followed by a tail-off. However, it is very difficult to program this perception and hence the limitations of computerized analysis have the consequence that the mean pitch will be taken as the intended pitch. This means that some notes a listener would rate as accurate in pitch, though possibly slightly variable, but acoustic analysis calculates to be one semitone away from accuracy.

The digitization of rhythms will also not necessarily analyze production as accurately as scoring by a musically trained observer. Scores are likely to be lower if digitization is used. Spoken rhythms can be particularly inaccurate, owing to the presence of both a stop consonant and voicing, either of which may be taken as the start of the note by an analysis program. This explains the lower scores on oral rhythms compared to manual rhythms, which were not found with observer scoring. These lower scores, as discussed earlier, may lead to smaller group differences on this measure.

Our findings strongly support the claim that the right hemisphere plays a specialized role in the analysis and production of pitch and intonation. Furthermore, the use of subjects with no musical training and who can be assumed to be broadly normal, premorbidly, ensures that the results can be taken as representative of the general population. Several other studies have taken as their patient population subjects who have undergone unilateral temporal lobectomies for epilepsy (e.g., Zatorre & Halpern, 1993).

Even in very simple tasks, such as discriminating or singing single notes, the RH subjects performed poorly. In singing both single notes and melodies, the RH subjects were not just failing to sing the notes but coming close to the intended pitch: their pitch was not even near the correct pitch. Peretz (1990) has claimed that RH subjects are impaired in the processing of the overall contour of a melody, but it is clear that they are also impaired with single notes. Previous studies with groups of individuals who have no musical training have not produced such clear findings. This could be partly due to the failure to include production tasks in the battery of tests.

These results are supported by recent studies using functional brain imaging. Zatorre et al. (1992) used PET to study pitch processing and reported that pitch discrimination was represented rather more anteriorly in the RH, in Brodmann area 45 and the dorsal prefrontal cortex (Brodmann areas 46 and 9). Wildgruber et al. (1996) used fMRI and reported that the right motor strip was activated when subjects sang syllables, when a comparison was made with tongue movements that did not involve vocalization.

The LH-dysphasic subjects were impaired both in discriminating and in reproducing rhythms. Peretz (1990) has previously reported that the discrimination of rhythm can be disrupted by either LH or RH lesions, but she also reported a double dissociation: two RH patients were impaired at pitch but not rhythm discrimination, and two LH patients at rhythm but not at pitch discrimination.

The present study extends the finding by including tests of rhythm production. In line with the analysis of size of error in semitones for intonation, it would have been ideal to analyze size of error for the rhythms as well. However, this did not prove possible, particularly for the LH-dysphasic subjects. These subjects performed far too inaccurately to attempt to categorize the errors and decide which notes of a reproduction were intended to correspond to which notes of the model.

The reproduction of rhythms was impaired for the LH patients irrespective of whether they produced the rhythms orally or manually. Halsband et al. (1993) have previously reported that left-sided lesions in the premotor cortex impaired the manual reproduction of rhythms, irrespective of the hand that was used. Hammond (1982) has reviewed other data that suggests that the left hemisphere may be specialized for fine acuity in temporal processing. Fiez et al. (1995) used PET to compare the activation in Broca's area when subjects discriminate a rapid series of vowel sounds or tone triplets. There was activation in the left opercular region when there were rapid stimulus changes but not when single vowels were processed.

The production of speech requires rapid movements of the articulators. Blumstein (1990) has observed particular difficulty in nonfluent dysphasic subjects in coinciding articulators. Miller (1989) argues that the evidence points toward a basic difficulty in relative timing among patients who have speech-production deficits.

Tallal et al. (1991) review evidence from a series of studies that there may be a ''temporal processing disorder'' in some subjects with specific language impairment. The tests used in the present study were also given to members of the KE family. In a companion paper Alcock et al. (submitted-a) report that the affected members of this family were not globally impaired on the perception or production of pitch and intonation, but that they were impaired on the perception and production of rhythms. In a related paper Alcock et al. (submitted-b) have also reported that there are other similarities between the developmental and acquired dysphasics. In particular there are impairments in both groups in the imitation of oral movements that are performed either sequentially or simultaneously (Vargha-Khadem et al., 1995, Alcock et al., submitted-b).

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