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Abstract

It is well known that language function is based in the left-hemisphere in the vast majority of neurologically normal adults. There are a number of claims that this specialisation extends to, and is in fact based on, a specialisation for dynamic auditory nonspeech contrasts. Here we examine the extent of hemispheric asymmetry for a particular temporally-based task — gap detection — which has had conflicting reports about the extent to which it is better processed in one ear or the other in behavioural tasks. Three experiments were carried out in the same five normal hearing listeners, all involving the detection of short gaps in otherwise continuous flat-spectrum broadband noise presented via headphones. Stimulus presentation was monaural or dichotic (in which an identical noise burst without a gap was always presented contralaterally to the test ear). Various experiments used combinations of two-interval and one-interval tasks, adaptive and fixed level procedures, and blocked and random presentations. There was no effect of ear of presentation, nor dichotic vs. monaural presentation in any experiment. In short, we found no ear asymmetry in gap detection.

Introduction

It has long been known that damage to the left cerebral hemisphere is associated with aphasia, whereas damage to the right hemisphere typically leaves speech and language processing more or less intact. From such clinical observations in the last century, and studies on split-brain patients more recently, it has become clear that the two cerebral hemispheres do not perform the same tasks. In particular, speech and language centres are located primarily in the left hemisphere for the vast majority of neurologically normal adults. What is much less clear is the extent to which this cerebral specialisation is primarily linguistic, or founded on a more basic sensory specialisation. There have been many claims that auditory areas in the left hemisphere are more skilled at processing rapidly changing auditory patterns than those in the right. Accordingly, it might be supposed that speech and language centres, through evolution, thus became centred in the left hemisphere in order to exploit this pre-existing sensory specialisation.

Efron (1963a) appears to be the first person to suggest that the left hemisphere (LH) is specialised for the processing of rapidly changing sensory patterns in his claim that "… temporal discriminations of order and simultaneity are 'performed' in the hemisphere which is dominant for speech". This study compared temporal order judgements (TOJs) in people with left or right hemispheric lesions and found that listeners with aphasia (all with LH lesions) showed impaired temporal order judgement compared to listeners without aphasia (primarily RH lesions).

Most studies investigating functional asymmetries in normal adults have been concerned with the processing of speech sounds, and nearly all use the technique of dichotic listening to limit the access of each hemisphere to a single (contralateral) ear (Kimura, 1961). It is well known that afferents from each ear project bilaterally to

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auditory cortex through sub-cortical pathways, such that each cerebral hemisphere receives information from both ears. Therefore, split-brain patients, whose cerebral commissures have been sectioned, show no differences in performance between the two ears with monaural presentation of speech sounds. However, under conditions of dichotic listening, with speech in both ears, they perform much more poorly with speech presented to the left ear than to the right, often even denying that anything was heard in the left ear (Milner *et al.*, 1968). This suppression of ipsilateral auditory information from a contralateral sound supports the dominance of contralateral auditory projections (also clear in recent fMRI studies by Melcher *et al.*, 1999) and validates the use of dichotic presentations for investigations of normal function.

A number of studies have convincingly demonstrated a LH (or right ear) advantage for speech sounds presented dichotically, although it is well known that the degree of asymmetry varies according to the phonological and acoustic properties of the sounds (*e.g.*, Cutting, 1974; Darwin, 1971; Studdert-Kennedy & Shankweiler, 1969). On the other hand, given the early impressive findings of Efron, the evidence for a LH specialisation of nonspeech temporal auditory processing in normal listeners is disappointingly slim, even though such a specialisation has been argued for strongly in a recent review of behavioural evidence by Nicholls (1996).

That the LH temporal specialisation hypothesis is closely associated with the well-accepted LH language specialisation gives two clues about the kinds of auditory processes one might be expected to be lateralised. First, these processes should be involved in essential contrasts used in speech, and second, should be impaired in people with language-related disorders.

Farmer & Klein (1995) claimed that auditory gap detection satisfies both these criteria, although there is much recent evidence that gap detection abilities are uncorrelated with language-related skills (Ahissar *et al.*, 2000; Schulte-Korne *et al.*, 1998; Vance *et al.*, 1999). Moreover, the evidence for LH specialisation of gap detection is mixed. Two studies have claimed to find right ear advantages (REAs) for gap detection (Brown & Nicholls, 1997; Vroon *et al.*, 1977), whereas at least one study has failed to find ear differences (Efron *et al.*, 1985). Perhaps surprisingly, given the well-known bilateral projection of auditory afferents discussed above, all these studies used monaural presentations without competing contralateral sounds. So, even if gap detection were lateralised, we might not expect to find ear differences for monaural sounds.

Of the three gap detection studies mentioned above, there is some degree of confusion regarding the experimental design, and its possible influence on the results. Vroon *et al.*, (1977), whose study showed a REA, used a paradigm whereby the gap was placed randomly at one of three positions in a relatively long duration noise (3 s). Efron *et al.*, 1985) suggested that it was this ‘uncertainty’ of gap placement that led to the REA in Vroon *et al*.’s study. Darwin (1971) has shown that the introduction of uncertainty (in this case, as to speaker) can convert a vowel contrast that is normally perceived equally well in both ears, to one that enjoys a right ear advantage.

Brown & Nicholls (1997) attempted to address this issue of temporal uncertainty by measuring gap detection with both stable gap positions (centre of a 300 ms noise) or variable positions (75 ms, 150 ms or 225 ms after start of a 300 ms noise) and failed to find an effect of temporal uncertainty. However, given the short duration of the noise relative to that used in Vroon *et al.*'s study, the variability of gap position would be much less salient in Brown and Nicholl's study.

A further issue that needs addressing is the bandwidth of the noise signal used by Efron *et al.* (1985). Brown & Nicholls (1997) dismiss this study on the basis of the signal bandwidth used, suggesting that the use of "narrow-band noise bursts containing frequencies in the range of 200-400 Hz" may have resulted in spectral cues that may have overridden any right-ear advantage. However, this claim is based solely on a misprint. It is true that at one point in their paper, Efron *et al.* describe their stimulus as a "broad-band noise (200 Hz-400 Hz)", but the 'Instrumentation' and 'Discussion' sections clearly indicate a noise bandwidth of 200 Hz - 4000 Hz (confirmed by Yund, pers. comm.).

The aims of the present study were threefold. Firstly, to measure gap detection in the presence of a dichotic, non-informational, masking signal. Secondly, to attempt to repeat the study of Brown & Nicholls (1997) with stable gap positions only. And thirdly, to measure absolute gap thresholds using an adaptive procedure to avoid the response bias described by Brown & Nicholls (1997).

Methods

Five normal hearing listeners (2 male, 3 female, threshold < 15 dB HL, 125 Hz to 8 kHz in both ears) were recruited from the student and researcher population at University College London. All listeners reported having had no history of hearing problems. Their ages ranged from 21 to 45 years (mean = 28.8 years). Four listeners demonstrated a strong right-handed tendency (handedness quotient greater than or equal to +40) and one subject (SC) demonstrated a left-handed tendency (handedness quotient less than or equal to -30) as measured by the Edinburgh Handedness Inventory (Oldfield, 1971).

All tests were carried out in a sound-attenuating chamber with the stimuli presented through Sennheiser HD475 headphones. The gap detection tasks were all carried out using a computer-controlled procedure to generate the stimuli, which were then output via a Tucker-Davis Technologies (TDT) DSP Card, DD1 digital-to-analogue converter and anti-aliasing filter. This stereo signal was then passed, via two TDT PA4 programmable attenuators and custom-built headphone amplifiers, to the headphones in the listening chamber.

The stimuli all consisted of a broadband software-generated noise (10 Hz-10 kHz, 50 kHz sampling frequency), the spectrum of which was corrected in the software to give a flat spectrum over the headphones as measured on a B&K 4157 artificial ear. The spectrum level of the noise was adjusted to 35 dB to give an overall level of 75 dB SPL. At the beginning of each block or adaptive run, a 3.2768 s buffer of noise was generated for use during that test. On each trial, a 300 ms portion of the buffer was chosen at random from the first half of the buffer for each masker interval. The envelope of this was then shaped to give 20 ms raised-cosine ramps at the onset and offset. Additionally, a gap was applied to the signal as appropriate. This gap consisted of a short silent section of appropriate length with 0.5 ms raised-cosine offset and onset ramps. The gap was approximately centred in the noise, with the start of the gap placed 150 ms after the noise onset. The gap duration was measured from the midpoint of each ramp. Thus the shortest possible gap was 0.5 ms. In the dichotic conditions, an uncorrelated noise of identical spectrum was played to the other ear without the gap being present (chosen at random from the second half of the pre-computed noise buffer). The temporal pattern of this contralateral masker was identical to the target sounds, save that it never had any gaps in it.

Three experimental protocols were used in the study. (1) A 2-interval 2-alternative forced-choice (2I-2AFC) task was used to measure a psychometric function (percent correct with increasing gap duration). (2) A single interval forced-choice (yes/no) task was used to measure the psychometric function. (3) A 2I-2AFC adaptive task was used to determine the minimal detectable gap. During the test the listeners responded via a button box, with lights to indicate the stimulus intervals and to give feedback where appropriate.

Experiment 1

A 2I-2AFC task was used to measure psychometric functions in both ears (L & R) using both monotic and dichotic stimulation conditions (M & D; thus ML indicates monotic-left, for example). Five gap durations were used (2, 3, 4, 5 and 6 ms). Each test session was divided into 20 blocks, and each block consisted of one of the 4 condition/ear combinations (ML, MR, DL, DR) and one of the 5 gap durations. The order of the blocks was randomised between listeners, and each of the listeners completed three sessions (block order randomised for each session). Within each block the subject was given 5 practice stimuli followed by 20 test stimuli for which the percent correct were calculated. Thus there were 3 repeated measurements of percent correct for each of the condition/ear/gap-duration combinations for each of the 5 listeners (a total of 3 x 2 x 2 x 5 = 60 blocks per listener).

Figure 1 shows the mean psychometric functions for each of the 4 condition/ear combinations. As expected, performance improves with increasing gap duration. Most listeners score around chance (50% correct) with 2 ms gap durations and almost perfectly with durations of 6 ms. However, no consistent difference between conditions or ears is evident from the data.

In order to further investigate this, the mean of the three scores for each of the condition/ear/gap duration combinations was calculated and the data were analysed with a 3 factor repeated measures ANOVA. The only significant effect of the three factors is that of gap duration (*gap*). There is no significant effect of either side of presentation (*ear*) or presence of dichotic masker (*condition*). Table 1 shows the summary details of this ANOVA. Repeating this analysis with the data from the 4 right-handed listeners only produced similar results, with only the main effect due to gap duration being significant.

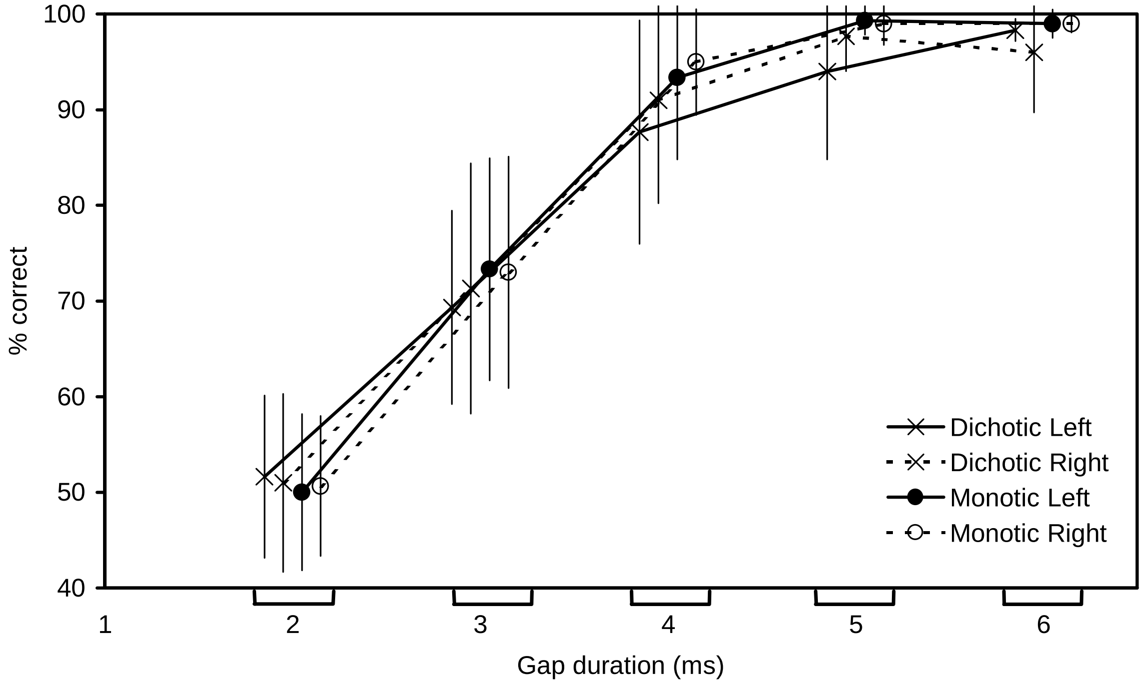

Figure 1. *Psychometric functions estimated in experiment 1. Percent correct gap identification in a 2-interval 2-alternative forced choice task. Data points represent the average results across the 5 listeners ±1 standard deviation.*

Effect	Df	F - ratio	P value
Gap	4, 16	91.641	< 0.001**
Condition	1, 4	1.062	0.361
Gap x Condition	4, 16	0.750	0.572
Ear	1, 4	3.739	0.125
Gap x Ear	4, 16	0.456	0.767
Condition x Ear	1, 4	0.032	0.866
Gap x Condition x Ear	4, 16	0.143	0.964

Table 1. *Summary statistics from an ANOVA of the results of experiment 1.*

Experiment 2

In an attempt to repeat the experiment of Brown & Nicholls, (1997), a 1-interval 2-alternative forced-choice task (yes/no) was used to measure psychometric functions in both ears, but this time with no dichotic conditions (*i.e.*, ML and MR only). As in experiment 1, five gap durations were used (2, 3, 4, 5 and 6 ms). The presentations were blocked with gap duration being fixed within a block. Each block consisted of 60 trials (30 presentations to each ear in random order) with a 50% probability of the gap being present in each presentation (*i.e.*, approximately half of the trials contained a gap). The listeners were instructed to indicate whether a gap was present. Each session consisted of five blocks (5 gap durations in random order) and each subject completed 4 sessions. Instead of percent correct, the percent error was calculated for comparison with the data of Brown & Nicholls (1997).

Figure 2 shows psychometric functions for each of the five listeners. Again there is an obvious effect of gap duration, but no clear indication of any difference in performance between the two ears.

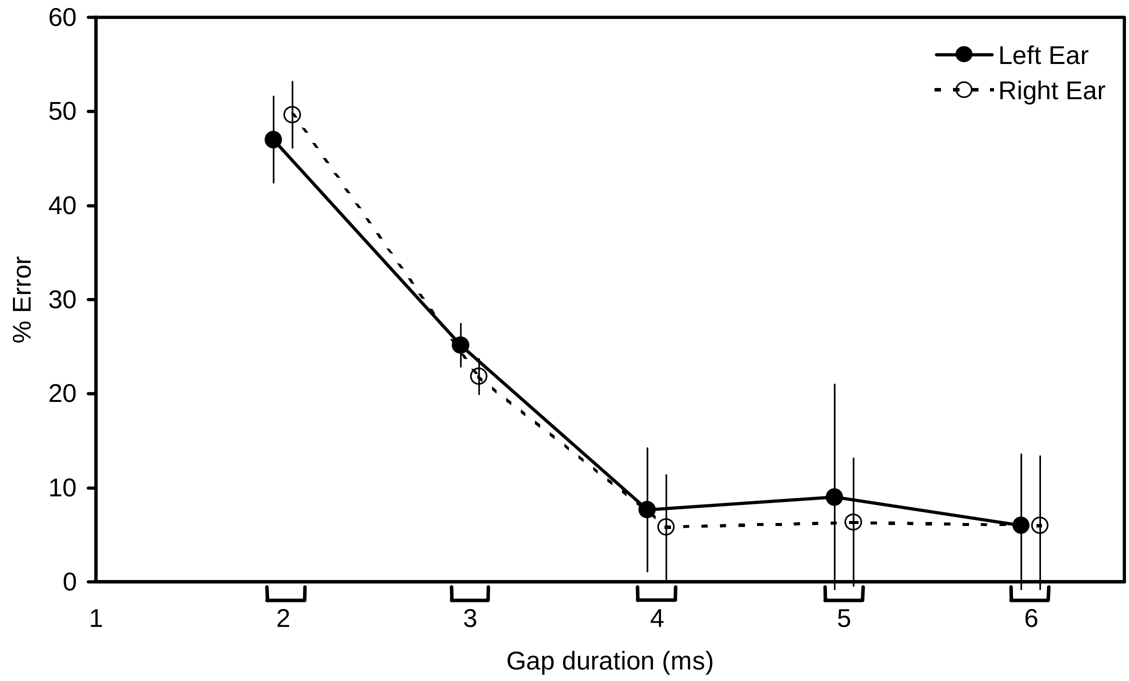

Figure 2. *Psychometric functions estimated in experiment 2. Percent error in gap identification in a single-interval 2-alternative forced choice task. Data represent the average results across the 5 listeners ± 1 standard deviation*

Averaging the data across the four sessions and using a 2-factor repeated measures ANOVA revealed a significant effect of gap duration, as expected, but no effect of side of presentation (Table 2). Removal of the left-handed subject (SC) from the analysis did not change these conclusions — again only gap duration had a significant effect.

Effect	df	F – ratio	P value
Gap	4, 16	66.561	< 0.001**
Ear	1, 4	2.382	0.198
Gap x Ear	4, 16	2.305	0.103

Table 2*. Summary statistics from an ANOVA of the results of experiment 2.*

Experiment 3

The final experiment used an adaptive procedure to measure the minimal detectable gap in each ear, with and without a dichotic masker. A 2I-2AFC maximum-likelihood estimation (MLE) procedure was used to measure the gap duration which the subject could identify 80% of the time. The initial gap duration was set to 10 ms. Three practice trials were presented at this duration before the adaptive track was started. A minimum of 15 and maximum of 50 trials were allowed in each adaptive run. The procedure was halted if the standard deviation of the last 10 presentations was less than 0.3 ms. In the MLE procedure the shape of the psychometric function was estimated using logistic regression on the data from experiment 1. The same shape (equation 1) and slope (*s* = 2.0) was used for all listeners. The midpoint (*m*) of the fitted psychometric functions in the MLE procedure was constrained to be between 0 and 20 ms with a ‘resolution’ of 0.1 ms. The false-alarm rate (*FA*) in this 2-alternative forced choice task is 0.5.

$$probability(correct\,response) = FA + \frac{(1 - FA)}{[1 + e^{s(m-x)}]}$$ **equation 1**

As in experiment 1, 4 combinations of ear and presence or absence of dichotic masker were used (MR, ML, DR and DL). In each session 20 thresholds were measured (5 of each of the condition/ear combinations, in random order). Each subject completed 2 sessions, giving 10 estimates of each threshold.

Figure 3 shows boxplots of the thresholds for each of the 5 listeners. It is clear that the median threshold for all the listeners is around 3 ms (for 80% correct) although listener RB appears to have a slightly higher threshold than the other 4 listeners.

Outlying thresholds (*i.e.*, greater than 6 ms and less than about 1 ms — see fig. 3 caption for how outliers are defined) appear to be due to the operation of the MLE procedure. If the listener responded incorrectly when the gap was clearly audible, the procedure occasionally failed to recover and reduce the gap duration to near the true threshold. On the other hand, listeners occasionally guessed correctly on several consecutive trials when the gap was clearly inaudible, thus resulting in abnormally small gap thresholds.

Visual inspection of figure 3 again reveals no consistent difference between either side of presentation, or presence of a dichotic masker. Table 3 shows the mean gap duration at threshold for each of the 4 ear/condition combinations (averaged across the five listeners).

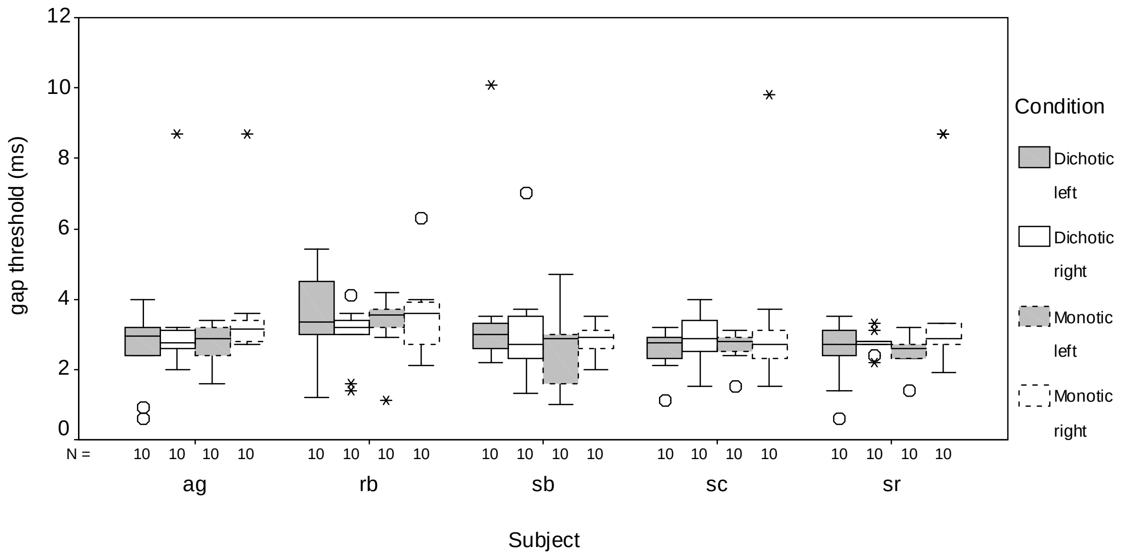

Figure 3. *Box plots of gap detection thresholds estimated using a 2-interval 2-alternative forced choice adaptive procedure. Lines through the boxes indicate the median thresholds, boxes indicate inter-quartile range, whiskers indicate range without outliers (o, between 1.5 and 3 times inter-quartile range from median) and extremes (*, greater than 3 times inter-quartile range from median).*

	All measurements		**With outliers removed**		
Condition/Ear	**Mean**	**Standard deviation**	**Mean**	**Standard deviation**	**N**
DL	3.0	1.40	3.0	0.76	45
DR	3.0	1.18	2.9	0.54	41
ML	2.8	0.75	2.9	0.68	47
MR	3.5	1.80	2.9	0.56	45

Table 3. *Mean minimum detectable gap for 5 listeners as a function of condition. Fifty observations make up each mean when all measurements are included.*

For statistical analysis, the averages of the 10 threshold measurements were calculated for each listener and subjected to a 2-factorial repeated measures ANOVA. A summary of this analysis is shown in table 4. Note that while there is no significant effect of condition or ear, there is a significant interaction between the two factors. This interaction can be seen in table 3 where for the dichotic condition the mean thresholds are virtually the same for the two ears, whereas in the monotic condition the means differ by 0.7 ms. This analysis was again repeated for the right-handed listeners only, and the outcome was similar, with the interaction term becoming slightly less significant (p = 0.032).

Source	df	F-ratio	P-value
Condition	1, 4	0.294	0.616
Ear	1, 4	2.759	0.172
Condition x Ear	1, 4	15.839	0.016*

Table 4. *Results of an ANOVA for the results of experiment 3, including all the data.*

Given that the outliers and extremes in figure 3 are most likely to be due to the MLE procedure rather than a true representation of variability in gap threshold, the above analysis was repeated with these points removed. The mean thresholds are also shown in table 3.

Again, averaging the measurements within each subject, a 2-factor repeated measures ANOVA was performed on the data (summarised in table 5). Removal of the outliers and extremes removes the interaction term. However, there is now a significant effect of condition on the thresholds (i.e. presence or absence of dichotic masker). Looking back at table 3, the mean thresholds with a dichotic masker present are slightly higher than those without. Again, this analysis was repeated for the right-handed listeners alone and the effect of condition became just insignificant (p = 0.071).

Source	Df	F-ratio	P-value
Condition	1, 4	10.143	0.033*
Ear	1, 4	0.871	0.404
Condition x Ear	1, 4	1.422	0.299

Table 5. *Results of an ANOVA for the results of experiment 3, excluding outliers.*

Discussion

This study has attempted to address the issue of whether the left hemisphere of the brain is better able to detect sounds with short gaps than the right. Three previous studies provided conflicting evidence about this issue.

Of the previous studies, two with conflicting results are very similar in nature if we consider only the conditions in which the gap was centrally placed in the noise burst (Efron *et al*., 1985; Brown and Nicholls, 1997). One significant difference between the two that may account for the discrepancy is that Brown & Nicholls (1997) randomly varied the side of presentation trial by trial, thus giving the listener a large degree of uncertainty as to which ear to listen to. Efron *et al.*, on the other hand, interleaved trials so that presentations alternated strictly between the two ears. This gives a much greater degree of predictability as to which ear the listener should attend to. It is possible that the extra degree of uncertainty required by Brown and Nicholls' task lends itself to more efficient processing by one hemisphere than by the other, in a similar way that uncertainty of speaker can convert a vowel contrast that is normally perceived equally well in both ears, to one that enjoys a right ear advantage (Darwin, 1971). It may also be the case that only relatively naïve listeners are affected by such a manipulation. This may explain why experiment 2 here still failed to show an ear effect, even in the presence of uncertainty.

In addition to the specific issue of whether a REA exists for temporal processing in a gap-detection task, there is the important issue of what such an advantage really means in the monaural tasks used in the three studies mentioned above. If the ascending auditory pathways were purely to the contralateral hemisphere, then association of a REA in gap detection with better temporal resolution in the left-hemisphere would be entirely justified. However, since the ascending projections are clearly bilateral, then these experiments do not rule out involvement of the ipsi-lateral hemisphere. Clearly then, to rule out any bilateral judgements of temporal resolution, a non-informative contralateral signal is needed. Such dichotic stimulation has been used widely to investigate hemispheric asymmetry in processing of speech (*e.g.*, Kimura, 1961), but not (as far as we are aware) in such a basic temporal processing task as gap-detection.

Our first experiment was designed to address the issue of whether a contralateral “masker” did indeed have any effect on gap-detection and on any ear advantage. However, for the listeners used in this study no significant ear advantage was measured in either a monotic or dichotic condition.

The second experiment attempted to repeat that of Brown & Nicholls (1997), albeit only with the “stable” gap location. Brown and Nicholls showed a clear REA, with the just-detectable gap smaller by about 0.8 ms in the right ear than the left (logistic regression on the original data indicates that gaps of 4.5 ms and 5.3 ms in the right and left ears respectively are detectable 75% of the time). The present study failed to find any difference between the two sides of presentation. Interestingly, the listeners in Brown and Nicholls’ study also showed a clear response bias in that, for a given gap duration, a higher proportion of “gap” responses were made when the presentation was to the right ear than when it was to the left. A similar response bias was also found in a study of temporal processing abilities in the visual modality (Nicholls, 1994). Analysis of the response bias in the present study failed to find such an effect.

The third experiment in the present study was aimed primarily at eliminating response bias by using an adaptive procedure to measure the smallest possible gap that could be detected in each ear, both with and without a contralateral masker. Again, there was no evidence of an effect of side of presentation on gap threshold either in a monotic or dichotic condition.

Another interesting point regarding previous studies of possible ear advantages in gap detection is that the just-detectable gap (jdg) tends to be large compared to values found in typical gap detection experiments. Both Efron *et al.* and Brown and Nicholls report jdg’s on the order of 4 ms or greater, very long compared to the mean of 2.4 ms measured by Shailer & Moore (1983) using a 2I-2AFC task and broadband noise. Vroon *et al.* report somewhat better performance, but still with jdg’s greater than 3 ms. Both experiments 1 and 2 of the present study give equivalent jdg’s of less than 3 ms. Also, assuming that the psychometric function used in the maximum-likelihood procedure is an accurate reflection of the true psychometric function, then the mean jdg of approximately 3 ms for 80% correct measured in experiment 3 corresponds to 2.6 ms for 71% correct (the proportion tracked by Shailer and Moore). Part of the reason we found more sensitive performance almost certainly lies in the greater degree of testing undergone by the listeners in the experiments here (insofar as we expect performance in almost any psychoacoustic task to show improvements over time). Also, two listeners (the two senior authors) have been part of various psychoacoustic studies over many years.

It might be thought that this overall difference in sensitivity is irrelevant to the question about the extent to which a REA occurs. On the other hand, it can be argued that as the essence of the LH specialisation hypothesis concerns the limits of sensory acuity, we can only consider the existence of asymmetries when that limit has been reached. From this point of view, it seems much more likely that the REAs reported from studies with poor sensory acuity arise from differences in some post-sensory response/decision mechanism than from differences in sensory capabilities of the two hemispheres

In summary, we have failed to provide any support for the suggestion that the left hemisphere of the brain is better able to detect short gaps in a burst of noise. The reasons for the discrepancies in outcome among the four relevant studies is far from clear. In our view, it seems likely that ear differences will only be found when using relatively naïve listeners in conditions of high uncertainty, and that the ear differences so displayed do not reflect differences in sensory acuity. Note that this hypothesis also explicitly allows ear advantages to be found with monaural stimulation. However, the demonstration of true hemispheric differences in the acuity of auditory sensory processing requires performances at the limits of sensory acuity under dichotic conditions.

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