

Hemispheric asymmetries depend on the phonetic feature: A dichotic study of place of articulation and voicing in French stops

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ABSTRACT

Dichotic listening experiments show a right-ear advantage (REA), reflecting a left-hemisphere (LH) dominance. However, we found a decrease in REA when the initial stop consonants of two simultaneous French CVC words differed in voicing rather than place of articulation (Experiment 1). This result suggests that the right hemisphere (RH) is more involved in voicing than in place processing. The voiceless–voiced contrast is realised as short positive vs. long negative VOT in French stop consonants, but as long vs. short positive VOT in English. We tested whether the relative involvement of the LH and RH is governed by their respective putative specialisation for short and long events. As expected, in French, the REA decreased when a voiced stop was presented to the left ear and a voiceless stop to the right ear (+V –V), whereas the REA had been shown to decrease for (–V +V) pairs in English. Additionally, voiced stops were more frequently reported among blend responses when a voiced consonant was presented to the left ear. In Experiment 2, VCV pairs were used to reduce the stimulus dominance effect for voiced consonants, which probably contributed to the low REA for (+V –V) pairs in Experiment 1. The reduction of the REA due to a voicing difference was maintained, which provides evidence for the relative independence of the mechanisms responsible for stimulus dominance and perceptual asymmetries in dichotic listening. The results are discussed in the light of the Asymmetric Sampling in Time (AST) model.

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1. Introduction

Speech is known to be processed preferentially by the left hemisphere in most right-handers. It is generally admitted that this hemispheric dominance can be accounted for by two competing hypotheses: (i) the linguistic hypothesis, whereby speech, whatever its acoustic content, triggers a specific processing mode most favourably associated with left brain areas and (ii) the auditory hypothesis, according to which some brain areas specialise in the processing of certain acoustic and temporal events, whether speech or non-speech.

The auditory hypothesis can be further split into two different sub-hypotheses. The first one holds that certain cerebral areas of the right hemisphere (RH) specialise in the decoding of spectral features while the left hemisphere (LH) normally engages in the processing of temporal events. The LH specialisation for temporal aspects has been evidenced by greater responses of the left Heschl's gyrus to the increased rate of temporal changes, while an increased number of spectral elements mainly recruited the right

anterior superior temporal gyrus in a PET study (Zatorre & Belin, 2001). Such asymmetry for temporal and spectral processes has also been reported from electrophysiological recordings associated with CV syllables and non-verbal sounds (Liégeois-Chauvel, de Graaf, Laguitton, & Chauvel, 1999; Liégeois-Chauvel, Giraud, Badier, Marquis, & Chauvel, 2001), and by neuropsychological investigation of patients presenting with focal left or right brain damage (Johnsrude, Penhune, & Zatorre, 2000; Poeppel et al., 2004; Robin, Tranel, & Damasio, 1990; Samson & Zatorre, 1994; Sidtis & Volpe, 1988; Zatorre, 1988). Temporal processing, and then LH areas, is assumed to be strongly recruited in speech listening, because the signal is characterised by the rapidity of auditory temporal changes, which may be the basis for the overall left lateralization observed in speech perception (Binder et al., 2000; Blumstein, Tartter, Nigro, & Stalender, 1984; Schwartz & Tallal, 1980; Schönwiesner, Rübsamen, & von Cramon, 2005; Shtyrov, Kujala, Palva, Ilmoniemi, & Näätänen, 2000; Tallal, Miller, & Fitch, 1993; Tervaniemi & Hugdahl, 2003).

The second sub-hypothesis states that the superior involvement of the LH or RH depends on whether short or long events (respectively) are processed. According to the Asymmetric Sampling in Time model (AST), the apparent opposition between temporal and spectral specialisation can be derived from a more fundamental

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difference in the time scale at which acoustic cues are analysed. It is assumed that both hemispheres are sensitive to the temporal structure of information but they may differ in their temporal resolution. By analogy with the local vs. global distinction in the visual domain (Navon, 1977), LH areas may preferentially extract information from short (25–40 ms) temporal integration windows, while RH areas may extract information from larger (150–250 ms) integration windows (Poeppel, 2003). As a consequence, rapid spectral changes such as formant transitions associated with place of articulation information or rapid frequency-modulated tones may be better processed by the LH. On the contrary, RH areas may use longer integration windows, which may favour spectral information, energy envelope of syllables, prosodic phenomena, frequency-modulated sounds with slow rates of change or with long duration (Poeppel et al., 2004). On the one hand, the LH specialisation for the microstructure of temporal events has been evidenced by psychophysical and clinical research (Nicholl, 1996; Samson, Ehrié, & Baulac, 2001). On the other hand, Boemio, Fromm, Braun, and Poeppel (2005) independently varied spectral and temporal dimensions of acoustic information in an fMRI study, and observed an interaction between hemisphere and segment duration, which reflected stronger activation in the dorsal bank of the *right* superior temporal sulcus for slow modulation rates (i.e. long segment duration). A RH advantage has also been reported for the detection of long (but not short) frequency transitions (200 ms), particularly when occurring at the front of the stimulus (McKibbin, Elias, Saucier, & Engebregston, 2003).

Voicing analysis may be an interesting issue to assess the relative involvement of the LH and RH in speech processing. According to a review by Simos, Molfese, and Brenden (1997), empirical evidence does not support an unequivocal superiority of the LH in language processing. More specifically, while a tradition of studies dating back, at least, to the early 1970s (Cutting, 1974; Darwin, 1971; Haggard, 1971; Hugdahl & Andersson, 1984; Studdert-Kennedy & Schankweiler, 1970), has demonstrated that dichotic listening experiments involving stop consonants often showed a strong right-ear advantage (REA), which reflected an LH advantage, the voicing contrast has been shown to rely more heavily (than other phonemic contrasts) on the RH (Cohen, 1981). This special pattern of lateralization for the processing of voicing has been found in several studies. For instance, Cohen and Segalowitz (1990) showed that the acquisition of a non-native voicing contrast by adults was easier and quicker when the target sounds were presented to the RH rather than to the LH. Additionally, in Molfese (1978) and Segalowitz and Cohen (1989), event-related potentials were recorded while subjects listened to a series of stop consonants with varying Voice Onset Time (VOTs). The findings revealed that ERPs from the LH varied linearly (low level processing) with the VOT while those from the RH were found to vary categorically. Moreover, neuropsychological studies showed that aphasic patients, whose RH was spared, were more efficient in the processing of voicing rather than place of articulation contrasts (Blumstein, Baker, & Goodglass, 1977; Miceli, Caltagirone, Gainoti, & Payer-Rigo, 1978; Yeni-Khomshian & Lafontaine, 1983), while RH or LH unilateral brain lesions in non-aphasic patients were associated with a similar impairment in voicing processing, which suggests the role of RH areas in the categorical processing of voicing cues (Yeni-Komshian, Ludlow, Rosenberg, Fair, & Salazar, 1986).

In participants without cerebral lesions, dichotic presentation is useful to assess hemispheric lateralization for different types of phonetic features. In dichotic listening tasks, each ear is simultaneously supplied with a different speech stimulus, and the recall of information reveals a right-ear advantage (REA) in a majority of right-handers, provided that stop consonants are used. Since contralateral projections in the auditory system provide better transmission and take precedence over ipsilateral ones, the REA

has been assumed to reflect the dominance of LH areas in the task (Hugdahl & Wester, 1992; Kimura, 1967; Milner, Taylor, & Sperry, 1968; Sparks & Geschwind, 1968). In 1970, Studdert-Kennedy and Shankweiler observed a larger REA when the stimuli differed by place rather than voicing, which suggests a lesser LH lateralization for voicing than for place processing. To our knowledge, this effect has not yet been replicated, except in an experiment derived from dichotic listening (Cohen, 1981). Subjects were required to rate the difference between two successive stimuli containing a consonant, while the other ear was supplied with a white noise. An LEA was observed when the stimuli differed by voicing. This categorical behaviour of the RH may reflect a possible phonological representation of voicing associated with this hemisphere.

The goal of this article is to conduct two dichotic listening experiments based on French stops in order to examine how brain functional asymmetries differ depending on whether the competing stimuli differ in voicing, place of articulation, or both, with special attention to the hypothesis that the processing of voicing involves the RH to a greater extent than that of place of articulation. While the stimuli in most previous studies within this paradigm are English stops, we used French stops instead. The reason for this stems from the fact that the phonetic implementation of voicing contrasts varies between French and English, in its acoustic and temporal cues. While in English this contrast is realised as long vs. short positive VOT (Lisker & Abramson, 1964), in French the opposition is based on short (almost null) positive vs. long negative VOT (phonologically voiceless vs. voiced stops, respectively, for both languages). The long negative VOT is composed of a periodic low-frequency sound typically spanning some 100 ms before the release of the burst (word-initially, in isolated words). This key difference is interesting in the light of the second sub-hypothesis of the auditory hypothesis, whereby short events are preferentially processed by the LH and long ones, by the RH. In accordance with this sub-hypothesis, Rimol and colleagues (2006) observed that the lowest REA in dichotic listening occurred when a long positive VOT (English voiceless stops) was presented to the left ear, while a short positive VOT (English voiced stops) was presented to the right ear.

According to the same hypothesis, we assumed that dichotic CVC riming pairs of French words would produce a lower REA when the initial consonants differed by voicing rather than by place of articulation. More precisely, since a long acoustic event (pre-voicing) occurs in French voiced stops, we predicted that this effect would be mainly due to dichotic pairs where a voiced consonant was presented to the left ear. In other words, we assumed that the magnitude of the REA could not be directly predicted by the value of the voicing phonological feature presented to the left ear – RH (voice vs. voiceless), but rather by its phonetic implementation, i.e. the duration of the VOT.

2. Experiment 1

2.1. Methods

2.1.1. Participants

The participants were 24 native French speakers (mean age 25 years 3 months, SD = 6 years; 7 males and 17 females) who were recruited at Lyon 2 University, France. They were healthy students, with no history of neurological disease. Hearing of all subjects was tested by determining ascending and descending thresholds for each ear individually for pure tones of 250, 500, 750, 1000, 2000, 4000, 6000 and 8000 Hz. No participant had inter-ear threshold differences of more than 10 dB. Overall absolute hearing thresholds for the right ear and the left ear were found to be below 20 dB, except in very few speakers whose threshold was higher for specific frequencies (typically, 6000–8000 Hz). All

participants were right-handed (9 or 10 right-handed responses out of a total of 10 of the most reliable items of the Edinburgh Handedness Inventory, Oldfield, 1971). All of them were naïve to the experimental task. Participation was rewarded with bonus course credits and the participants gave written informed consent before the experiment.

2.1.2. Stimuli and procedure

The total list contained 15 pairs of rhyming CVC French words differing only in the first stop consonant (/p, b, t, d, k, g/). The vowel was always /a/. All CVC sequences produced real French words. The stimuli were recorded by a male native speaker of standard French. In the V condition, the initial consonants of the words of each pair only differed in voicing, in the P condition, they differed in place of articulation, and in the VP condition, they differed in both voicing and place. The mean token frequency of the test words starting with a voiceless or a voiced stop were 319 and 18 items per million words respectively in the V condition, and 539 and 28 items per million respectively in the VP condition. In other words, the test words starting with a voiceless stop are much more frequent than their voiced counterparts. More generally, the higher frequency of voiceless stops holds word-initially in French as Table 1 suggests (computed from the Lexique database; New, Brysbaert, Veronis, & Pallier, 2007). Each member of the six word-pairs was presented 4 times to the right ear and 4 times to the left ear in the P and VP conditions, and each member of the three word-pairs was displayed 8 times to each ear in the V condition, so as to provide an equal number of items in the three conditions. The dichotic material was presented in 4 runs of 36 trials each (total 144 trials), which were punctuated by rests.

Due to different phonetic/acoustic properties of the consonants, words starting with a voiced consonant were slightly longer, because of the low-frequency signal occurring during closure. Such 'prevoicing' is characteristic of voiced stops in French. In a dichotic experiment conducted in Finnish, a language where pre-voicing also occurs in voiced consonants, Tallus, Hugdahl, Alho, Medvedev, and Hämäläinen (2007) set temporal alignment between the left and right channels at the first period of the large amplitude vocalic portion of the syllables. We applied the same principle. As a consequence, the signal for voiced consonants started 73–131 ms earlier than for unvoiced consonants. However, the subjects reported that they could hear only one single word, like in the English Fused Dichotic Words Test (FDWT, Wexler & Halwes, 1983), which presents with the advantage of being almost not influenced by atten-

tional manipulations (Asbjordnsen & Bryden, 1996). Both syllables were matched for peak intensity. The signals were played through Beyerdynamic DT 770 Pro headphones. Testing took place in a sound-proof booth. The experiment was run with the Praat program.

The participants were informed that the signal was slightly altered but they did not know that the syllables in each dichotic pair were not alike. They were invited to focus on the centre of their head to identify the word and immediately report it aloud. At the start of the experiment, the participants heard the list of stimuli in binaural presentation in order to become familiar with the words, and they were required to recall each word aloud before the subsequent stimulus was displayed. In this practice list, the experimental stimuli were mixed with all the other words, which shared the same rime but differed in the initial consonant. This was done so that the participants could hear not only the stimuli, but also their lexical competitors.

2.1.3. Data analysis

For each participant, the number of correct CVC recalled from the right and left ears was determined in the three conditions (see Table 2, for the left and right ear scores), and the lambda value was calculated for the V, P, and VP conditions. The lambda coefficient (λ) is computed as follows:

$$\lambda = \ln \left(\frac{R + 1}{L + 1} \right)$$

where ln is the natural logarithm, R is the number of responses from the right ear, and L the number of responses from the left ear (Bryden & Sprott, 1981). It is considered to be particularly reliable and does not depend on overall accuracy (de Bode, Sininger, Healy, Mathern, & Zaidel, 2007; DiStefano, Marano, & Viti, 2004; Fernandez & Smith, 2000). A positive lambda indicates an REA, a negative lambda an LEA.

An analysis of variance with repeated measures was conducted on the lambda coefficient. Some participants consistently reported the same member of a pair regardless of ear of presentation. The pairs for which all the responses given by a participant reflected such a stimulus dominance effect are considered an obstacle to an accurate measurement of auditory asymmetries (Voyer & Techentin, 2009). They were therefore discarded from the data as recommended by Wexler and Halwes (1983; see also Zatorre, 1989). Out of the 48 stimuli presented in each condition, the average number of items removed for a subject on account of total

Table 1
Frequency of word-initial stops in French.

Initial stop consonant	Monosyllabic words		Polysyllabic words	
	Token frequency per million words	Type frequency per million words	Token frequency per million words	Type frequency per million words
/p/	35 683	902	75 940	12 254
/b/	8386	866	19 712	7 133
/t/	47 980	724	54 860	6 771
/d/	61 180	435	86 039	11 989
/k/	27 349	852	48 528	13 312
/g/	3563	501	6201	3774
Total voiceless	111 012	2478	179 328	32 337
Total voiced	73 129	1802	111 952	22 896

Table 2
Percentage of mean right ear and left ear responses for conditions V, P, and VP in Experiments 1 and 2.

Condition	V		P		VP	
	Left ear	Right ear	Left ear	Right ear	Left ear	Right ear
Experiment 1	39.32	52.26	31.25	71.01	21.18	55.47
Experiment 2	30.82	30.47	31.16	42.97	30.40	35.02

stimulus dominance was 8, 15, and 3 in the P, V, and VP conditions respectively (rounded to the nearest integer). Then, each subject's laterality index was computed as a lambda coefficient. Partial η^2 were calculated to estimate the size of the effects. The analysis of variance was only conducted on the P and V conditions, since a specific phenomenon was observed in the VP condition. Many inaccurate responses occurred in the VP condition: an average of 14% blend errors (combining the voicing value of one word with the place of articulation of the other word) were made; in the sub-condition where a voiced consonant was addressed to the left ear and a voiceless one was addressed to the right ear in the VL condition, 38% blend errors were made. Consequently, the REA was computed on fewer accurate responses in the VP condition, and it could not be directly compared with the REA observed in the P and V conditions. A subsequent qualitative analysis of blend errors will be conducted to appreciate the involvement of each cerebral hemisphere in the VP condition.

Inaccurate responses occurred mainly in the VP condition. Most of them were blend responses: voicing was extracted from one of the words and place of articulation from the other. We evaluated whether the voicing value of the response was taken from the stimulus displayed to the right or to the left ear. The corresponding percentages were compared with a Wilcoxon test.

2.2. Results

The repeated measures analysis of variance conducted on the lambda values, with the condition (V, P) as within-subject factor, showed a main-effect of this factor, ($F(1, 23) = 42.46$; $p = .0001$, $\eta^2 = .65$), as illustrated in Fig. 1. The stimulus dominance in each pair, computed as the difference between the percentages of recall of the two words, explained 70% of the variation of the REA ($R^2 = .70$, $F(1, 14) = 30.39$, $p = .0001$).

A complementary analysis of variance was performed to compare the REAs in items providing the left vs. the right ear with a word beginning with a voiced consonant (+V) in the V condition (+V –V and –V +V items, respectively). In this condition, in which the REA was low, we recorded an REA only for –V + V items (mean REA (λ) = 2.06, $SE = .22$), while an LEA was recorded for +V –V items

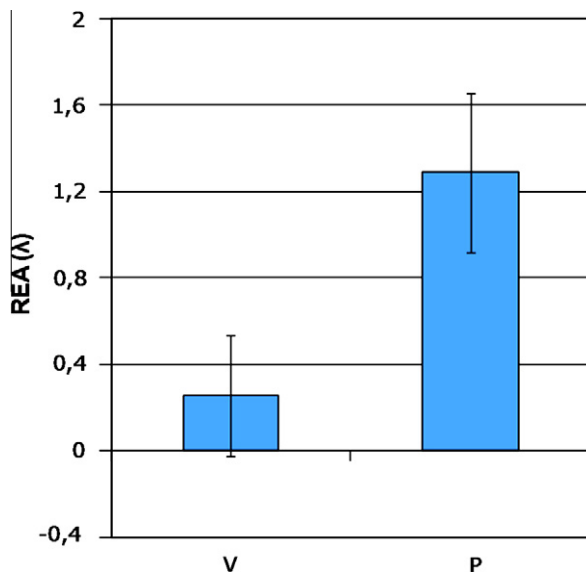


Fig. 1. Mean Right-Ear Advantage (REA) in Experiment 1, calculated as the lambda value for the two conditions: the initial consonant of the two words differed in voicing (V), or in place of articulation (P). Vertical bars indicate 95% confidence intervals.

($\lambda = -1.60$, $SE = .26$), and the difference between the λ values was significant, ($F(1, 23) = 102.08$, $p = .0001$, $\eta^2 = .82$).

Very few errors occurred in the V and P conditions, and most errors in Experiment 1 were recorded in the VP condition. As illustrated in Fig. 2, the voicing value reported in these erroneous responses was more frequently the voiced feature than the voiceless feature, $T = -4.13$, $p < .0001$. However, the voiced feature was more frequently retained from the left ear (right hemisphere) than from the right ear (left hemisphere), $T = -4.00$, $p < .001$, while the voiceless feature was not differently retained from the right and the left ear, $T = -0.91$, $p = .37$.

2.3. Discussion (Experiment 1)

An REA was observed for all conditions, which is in line with previous findings. However, the magnitude of the REA was significantly reduced in the V condition (i.e. when the parameter was voicing). In accordance with our hypothesis, the results reflected the increased role of the RH in the processing of voicing, as well as a reduction of the role of the LH (Table 2). A close examination of the data showed that the decrease in REA for the V condition was mainly due to stimuli pairs in which the left ear was presented with the voiced consonant (+V –V). This result was also in accordance with our prediction. With English speech stimuli, Rimol and colleagues (2006) reported an atypical LEA when the left ear was associated with a voiceless stop, which is characterised by a long VOT in this language. With French words, we reported an LEA when the left ear was presented with a voiced stop, which is also characterised by a long acoustic event (i.e. the voice bar). Therefore, it appears that the magnitude and direction of the ear advantage in dichotic listening cannot be directly predicted by the voicing phonologic feature pairings, but rather by acoustic characteristics of voiced vs. voiceless consonants in the language under study. Consequently, the magnitude of the REA seems to be due to cerebral asymmetries in processing short and long acoustic cues.

However, an alternative explanation may involve a stimulus dominance effect. As suggested by Voyer and Techentin (2009), the LEA reported for English dichotic pairs presenting the left ear with a voiceless consonant could be due to the “dominant response” elicited by voiceless consonants over voiced ones in English. The same reasoning can apply to our experiment in French, where voiced consonants dominated over voiceless ones. Consequently, it is difficult to disentangle the role of the stimulus dominance effect and the assumed impact of RH specialisation in the

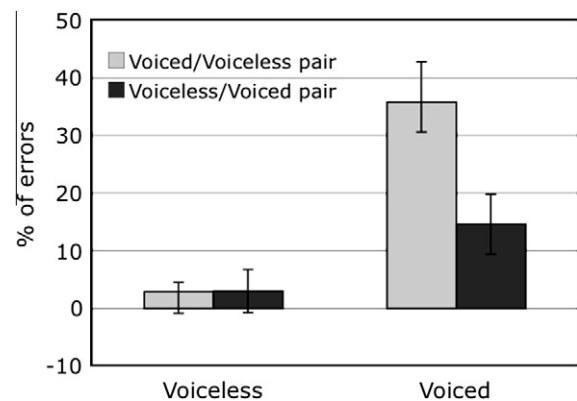


Fig. 2. Percentage of erroneous responses starting with a voiceless or a voiced consonant and given from a pair of stimuli where a voiced consonant and a voiceless consonant were respectively presented to the left and to the right ear (voiced/voiceless), or the reverse (voiceless/voiced), in the VP condition in Experiment 1.

processing of acoustic characteristics of voiced stops, to account for the dramatic reduction of REA in the V condition.

What causes stimulus dominance is not fully elucidated. It may not be due to lexical frequency effects, because French words are more frequently initiated by voiceless consonants than by voiced consonants, and the token frequency of the test words initiated by voiced consonants in Experiment 1 was higher than that of the test words initiated by voiceless ones. The stimulus dominance has been suggested to be a bottom-up factor, because non-sensory variables have minimal effect on it (Niccum, Speaks, Katsuki-Nakamura, & Leather, 1989). The stimulus dominance effect observed for words initiated by a voiced stop in our experiment could be due to the earlier auditory signal that it provided, compared with the stimulation provided to the other ear by the concurrent voiceless stop. In Experiment 1, the signal for voiced consonants started earlier than for voiceless consonants. The (pre-)voice bar at the start of the initial voiced consonant in a CVC French word could indeed be considered as an informative event. On the contrary, the silence during the same period of time in a CVC starting with a voiceless consonant could not be considered as an event, because it was not preceded by anything else. This difference may have produced a dominance effect in favour of voiced consonants to the detriment of voiceless ones. This experimental bias may partly explain the low REA observed in the V condition. Experiment 2 was designed to reduce the influence of stimulus dominance effect, and we hypothesised that the difference in REA for the V and the P conditions would still be found.

This hypothesis was motivated by the observation of another result, which suggested that the REA exists above the influence of the stimulus dominance. In blend responses produced for VP items, voicing was extracted from one stimulus, while place of articulation was taken from the other. Regarding the voicing feature, blend responses confirmed the saliency of the voiced feature (+V), which was more frequently recalled than the voiceless one (–V). However, beyond this replication of the voiced consonants dominance effect, we showed that +V was more frequently reported when it was presented to the left ear than to the right ear (Fig. 2). This difference was statistically significant and its interpretation was not as ambiguous as the comparison between the LEA observed for +V –V pairs and the REA recorded for –V +V pairs. Since the latter effects were opposite in direction but did not differ in magnitude, they could indeed be accounted for by the pure dominance of voiced stop. On the contrary, +V in the voiced consonants produced as blend responses was clearly more frequently reported from the left ear than from the right ear.

Therefore, Experiment 2 was designed to replicate the pattern of results observed in Experiment 1, with stimuli which did not introduce a temporal advantage for voiced consonants. In order to avoid this experimental bias, we tested dichotic listening with stop consonants presented in a VCV context. When preceded by a vowel, the silence before the burst in voiceless consonants could be considered as an informative event, since it has a ‘beginning’ (i.e. the end of the preceding vowel). We assumed that the correlation of the REAs with the stimulus dominance scores would reduce in Experiment 2. However, we hypothesised that the REA would remain lower in the V condition than in the P condition.

3. Experiment 2

3.1. Methods

3.1.1. Participants

The participants were 24 native French speakers (mean age 24 years 6 months, SD = 6 years; 4 males and 20 females) who were recruited at Lyon 2 University, according to the same criteria as in Experiment 1.

3.1.2. Stimuli and procedure

The total list contained 15 pairs of VCV pseudo-words differing only in the central stop consonant (/p, b, t, d, k, g/). The vowels were always /a/. Three of the VCV combinations yielded real words: /apa/, /aba/, and /aka/; their token frequency is however relatively low: 5.97, 2.28, and 0.01 occurrences per million words respectively. The stimuli were recorded by the same speaker as in Experiment 1. In the V condition, the stimuli of each pair only differed in voicing, in the P condition, they differed in place of articulation, and in the VP condition, they differed in both voicing and place. An equal number of items was provided in the three conditions. The dichotic material was presented in 4 runs of 36 trials each (total 144 trials), which were punctuated by rests.

The temporal alignment between the left and right channels was set at burst release. Both stimuli were matched for peak intensity. The duration from the end of the first vowel to the release of the stop burst ranged from 80 to 91 ms for voiced consonants (it can be equated with pre-voicing duration), and from 114 to 134 ms for voiceless consonants. The stimuli were played through the same headphones as in Experiment 1, and the participants received the same instructions, but were informed that stimuli were not familiar words. The experiment began after a practice block.

3.2. Results

As in Experiment 1, the items exhibiting a total dominance by one member of the pair were removed. Out of the 48 stimuli presented in each condition, the average number of items removed for a subject on account of total stimulus dominance was 18, 21, and 15 in the P, V, and VP conditions respectively (rounded to the nearest integer). The same repeated measures analysis of variance as in Experiment 1 was conducted on the lambda values. It showed a main-effect of the condition, ($F(1, 23) = 10.06; p = .004, \eta^2 = .30$), which can be considered as a large effect, according to Cohen (1988). As illustrated in Fig. 3, the V condition resulted in an LEA, whereas an REA was recorded in the P condition. The stimulus dominance explained only 12% of the REA variation and this relationship was not significant ($R^2 = .12, F(1, 14) = 1.82, p = .20$). However, as in Experiment 1, the difference between the λ values for +V –V items (mean $\lambda = -.84$,

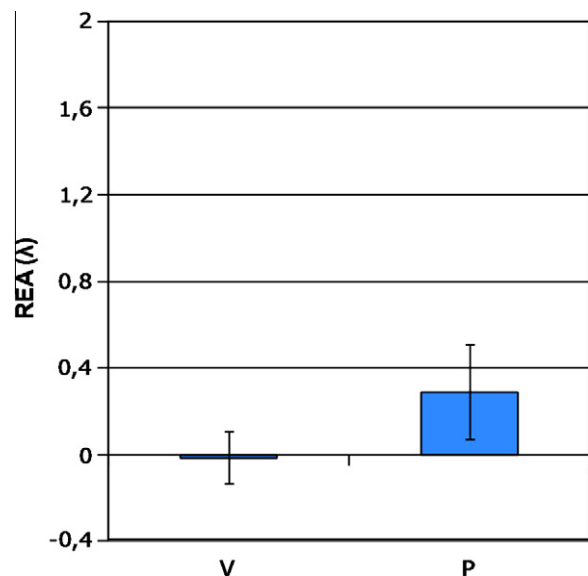


Fig. 3. Mean Right-Ear Advantage (REA) in Experiment 2, calculated as the lambda value for the two conditions: the initial consonant of the two words differed in voicing (V), or in place of articulation (P). Vertical bars indicate 95% confidence intervals.

$SE = .11$) and $-V +V$ items (mean $\lambda = .85$, $SE = .12$) was significant ($F(1, 23) = 60.21$, $p = .0001$, $\eta^2 = .72$).

A complementary analysis of variance conducted on the combined data of Experiments 1–2 showed that the λ values were significantly lower in Experiment 2 than in Experiment 1 ($F(1, 46) = 14.59$, $p = .0004$). Additionally, the Condition \times Experiment interaction was significant ($F(1, 46) = 15.48$, $p = .0003$), which reflected the lower effect of the type of phonetic difference between the stimuli in Experiment 2 than in Experiment 1.

Very few errors were made in Experiment 2, and since only 2.31% of errors occurred in the VP condition, no statistical analysis was conducted on these data (Fig. 4).

3.3. Discussion

In Experiment 2, an REA was recorded, but its size was smaller than in Experiment 1. This overall reduction of the REA is not surprising since the largest REAs have been produced by presenting word-initial stops (Bryden, 1988), while we used intervocalic consonants stimuli in Experiment 2. Additionally, most stimuli in Experiment 2 are pseudo-words rather than meaningful words as in Experiment 1. The lexical status of speech stimuli has been shown to engage left temporal and extra-temporal areas (the frontal operculum and fusiform gyrus) more strongly, which suggests lexical semantic computations (Zahn et al., 2000). According to ERP studies, there is greater activity in the LH for words than for pseudo-words (Pulvermüller, Shtyrov, Kujala, & Näätänen, 2004), and an REA has been observed for words compared with pseudo-words (Yasin, 2007). According to magnetic brain responses to the same brief acoustic stimulus presented either as a noise, or within a pseudo-word, or within a word, it appeared that neither the physical properties nor the phonemic status of a sound were sufficient for LH dominance to be recorded. The sound had to be placed in the context of familiar language elements, such as frequently produced syllables or words, for hemispheric laterality to be observed (Shtyrov, Pihko, & Pulvermüller, 2005). Thus the intervocalic presentation of a consonant within pseudo-words in Experiment 2 did not provide the best conditions for a large REA to occur.

However, the intervocalic location of the stop consonants precluded an experimental bias, which strongly contributed to the stimulus dominance of voiced consonants over voiceless ones in Experiment 1. With VCV stimuli, the negative VOT in $+V$ stimuli, but also the silence before the burst in $-V$ stimuli, could be considered as events, because they followed a vowel. Thus, the temporal advantage for $+V$ consonants in Experiment 1 was avoided. How-

ever, an REA was recorded in Experiment 2, and only a small part of this effect can be explained by the dominance effect (only 12% rather than 70% in Experiment 1). This result confirmed Voyer and Techentin's notion (2009) that the mechanisms responsible for stimulus dominance and perceptual asymmetries in dichotic listening are separate. Therefore, VCV stimuli yielded better controlled conditions to observe an REA, which does not just reflect a confounding factor. Thus, the REA observed in Experiment 2 provided new evidence for the relative independence of the mechanisms responsible for stimulus dominance and perceptual asymmetries in dichotic listening.

More importantly, despite the overall lower REA, the LH dominance effect still appeared to be less important in the V condition than in the P condition. Moreover, as in Experiment 1, it was mainly due to $+V -V$ pairs. This effect reflected the reduction of the involvement of LH areas in the processing of French voiced stops. More precisely, it is probably the (long) duration of the voice bar (approx. 100 ms) that caused the decreased involvement of the LH. The persistence of this pattern of results, despite that the stimulus dominance effect was less determinant in the REA magnitude, was in line with our prediction.

4. Discussion

The purpose of the present research was to provide new evidence for the involvement of RH areas in the processing of voicing, and to show that it is partly due to the ability of this hemisphere to process long acoustic events. We tested these assumptions with stimuli pairs which differed in voicing, place of articulation, or both, in two dichotic listening tasks.

We obtained an overall REA, which reflected the classic LH dominance for speech processing, in the two experiments. But, in accordance with our hypothesis, the REA was lower in the condition which required the processing of voicing (V condition). This reduction of LH dominance in the analysis of voicing can be surprising, given the purported LH superiority in language processing. However, bilateral activation of dorsal temporal areas is associated with pre-phonemic analysis of complex sounds (Blumstein, Myers, & Rissman, 2005; Liebenthal, Binder, Spitzer, & Medler, 2005), particularly when the acoustic-phonetic processing is difficult, for instance for the less-prototypical exemplars of a phonetic category (Myers, 2007). Similarly, the competition in dichotic experiments may provide difficult conditions for the acoustic-phonetic analysis. In addition, decreased hemispheric lateralisation for voicing analysis has already been reported by behavioural (Cohen, 1981; Cohen & Segalowitz, 1990; Studdert-Kennedy & Schankweiler, 1970), neuropsychological (Blumstein et al., 1977; Miceli et al., 1978; Yeni-Khomshian & Lafontaine, 1983; Yeni-Komshian et al., 1986) and electrophysiological studies (Molfese, 1978; Segalowitz & Cohen, 1989, for a review, see Simos et al. (1997)). The modulation of the REA in our experiments does not necessarily reflect any inability of the LH to process voicing, but voicing processing entails an increased involvement of the RH. This is not in line with the strong version of the linguistic hypothesis, and it is better accounted for by the auditory hypothesis, which suggests that some cerebral areas of the RH may be proficient in the processing of the acoustic cues of voicing.

According to one version of the auditory hypothesis, the temporal resolution of the analysis conducted by cerebral structures may differ between the hemispheres. The relative importance of LH and RH in speech processing may be governed by the presence of short vs. long acoustic events (respectively). It is likely that the RH preferably extracts information from a longer temporal integration window (Poeppel, 2003). The speech signal is characterised by quick changes, which probably entail the classic overall LH domi-

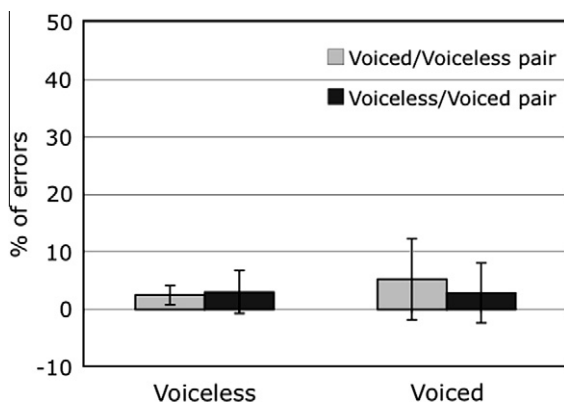


Fig. 4. Percentage of erroneous responses starting with a voiceless or a voiced consonant and given from a pair of stimuli where a voiced consonant and a voiceless consonant were respectively presented to the left and to the right ear (voiced/voiceless), or the reverse (voiceless/voiced), in the VP condition in Experiment 2.

nance in language processing. However, with dichotic listening in English, Rimol and colleagues (2006) reported the association of an LEA (i.e. RH dominance) with stimuli pairs requiring the processing of a long VOT by the left ear-RH and a short VOT by the right-ear-LH. On the one hand, this effect could be interpreted as a major involvement of the RH in the phonological ability to process voiceless stops. On the other hand, it may be due to a more general skill of the RH to process long acoustic events. These contradictory hypotheses have been pitted against each other, with the voiced–voiceless phonological contrast, which is opposite in English and in French in terms of the length of the corresponding acoustic events. A long acoustic event is indeed associated with voiced stops in French (i.e. the voice bar), whereas it is associated with voiceless stop consonants in English (i.e. long positive VOT).

Two major results favoured the second interpretation. Firstly, we showed that the RH was involved in the processing of French voiced stop consonants. We recorded an REA for $-V +V$ pairs, but an LEA for $+V -V$ pairs, not only in Experiment 1, but also in Experiment 2. Secondly, voiced consonants were more frequently reported in blend responses, when a voiced stimulus was presented to the left ear-RH rather than to the right ear-LH. Therefore, the RH appears to be efficient in $+V$ extraction from the long voice bar of French voiced stops. However, voiceless consonants were equally reported from both ears in blend responses. This pattern of results is consistent with increased RH activity for long-duration auditory stimuli, without any concomitant increase in LH activity for shorter-duration stimuli (Boemio et al., 2005; Britton, Blumstein, Myers, & Grindrod, 2009). This pattern of results is consistent with the Asymmetric Sampling in Time (AST) model (Poeppel, 2003), but it cannot be predicted by the strong version of AST. Boemio et al. (2005) described a slightly different model, which accounted for the rightward lateralization for long-duration stimuli by attributing lateralization to differential routing of information from the superior temporal gyrus (STG) to the superior temporal sulcus (STS). They assume the existence of two timescales in the STG, and the neuronal populations corresponding to each timescale are supposed to differently target the STS, with the right STS essentially receiving afferents carrying information processed on the long timescale, whereas the left hemisphere shows sensitivity to both long and short integration windows (Britton et al., 2009; see also Belin et al. (1998), for additional results showing the bilateral sensitivity of the auditory cortex to long stimuli, but a reduced response of the right auditory cortex to rapid acoustic transitions).

Taken together, these results are consistent with the decrease in REA due to the reduction of the rate of acoustic changes found in previous researches (Schwartz & Tallal, 1980; Studdert-Kennedy & Schankweiler, 1970). They also agree with the left ear-RH advantage observed for the processing of long frequency transitions (200 ms) (McKibbin et al., 2003). Therefore, like the LH, the RH is involved in the processing of temporal information, but it specialises in temporal events requiring a low time resolution.

The Asymmetric Sampling in Time model (AST) provides a framework for our pattern of results. Language processing beyond the interface of speech perception is highly left-lateralised. However, the primary auditory cortex initially processes the auditory signal in a symmetric manner to build 'high-fidelity' representations of the signal, which are then sampled by bilateral non-primary areas on different time scales, before making contact with the mental lexicon (Poeppel et al., 2004). The auditory analysis of speech is associated with bilateral activation at the level of core and surrounding supra-temporal gyri, and each hemisphere differs in the manner in which acoustic signals are quantized in the time domain (Binder et al. 2000). The stream of sounds is supposed to be divided into temporal windows, whose length differs according to each hemisphere (Hesling, Dilharreguy, Clément, Bordessoules, & Allard, 2005), which amounts to a difference in sampling rate.

The right non-primary auditory cortex may be remarkably sensitive to temporal structure of long, steady acoustic parameters, whereas left cortical areas may handle the analysis of input signal through a smaller integration window. Therefore, the well-documented dissociation of global and local visual processing is assumed to illustrate a more general organisational principle of the brain (Sanders & Poeppel, 2007).

Regarding the difference in duration of the small and long temporal windows, a body of psychophysical and physiological evidence supports the notion that they have duration of approximately 25–50 ms vs. 150–300 ms (Boemio et al., 2005; Poeppel, Idsardi, & van Wassenhove, 2008). However, it has been shown that stimuli with segment duration greater than 85 ms produced robust activation in the dorsal bank of the right superior temporal sulcus (STS). Thus, a bias in RH mechanisms could be observed for long segment duration as early as 85 ms, which is consistent with the mean duration of the voice bar in the French voiced stops used in our experiments.

According to Poeppel et al. (2004), the opposition between the two timescales is not incompatible with the hypothesis which associates the rightward and leftward lateralisation with spectral vs. temporal information, respectively (Zatorre & Belin, 2001). Left areas may favour temporal information in speech processing because speech contains many fast changing events (e.g. formant transitions), while spectral information (e.g. pitch change) needs longer integration windows, which preferentially drives the RH (Poeppel, 2003). In the present research, we suggested that the presence of short and long acoustic cues for voicing could directly account for the difference in RH and LH involvement in French voiced and voiceless stops.

However, in addition to the consensual importance of VOT as a relevant cue for voicing in stops, other parameters may come into play. The duration of the first formant transition (F1) varies with the VOT (Stevens & Klatt, 1974), and in English F1 onset frequency is higher for voiceless than for voiced consonants (Lisker, 1975; Soli, 1983). Moreover, intensity variations of the second harmonic are associated with voiced consonants, and variations in the burst intensity are also related to voicing. Additionally, in another language with pre-voicing in stops (Dutch), the presence vs. absence of pre-voicing has been shown to be more informative than its exact duration (van Alphen & McQueen, 2006), and this acoustical event contains more spectral information than the gap between burst and vowel in voiceless stops. Since these spectral parameters are known to modulate the perception of voicing (Lisker, 1978; Miller & Eimas, 1983; Summerfield & Haggard, 1977), the assumed specialisation of RH areas in spectral parameters analysis (Zatorre & Belin, 2001) could also explain part of the substantial involvement of the RH in analysing voicing distinctions. The lower REA for $+V -V$ stimuli than for $-V +V$ stimuli, while closure duration is equivalent in voiceless and voiced stops (Experiment 2), suggests that the LH and RH involvement is not determined by the length of those cues only. The higher spectral complexity of the voice bar may also play a role. Future studies should attempt to investigate the relative contribution of such acoustic characteristics on the observed asymmetries.

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