

Pausing for thought: engagement of left temporal cortex during pauses in speech

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Received 24 March 2003; revised 19 September 2003; accepted 19 September 2003

Pauses during continuous speech, particularly those that occur within clauses, are thought to reflect the planning of forthcoming verbal output. We used functional Magnetic Resonance Imaging (fMRI) to examine their neural correlates. Six volunteers were scanned while describing seven Rorschach inkblots, producing 3 min of speech per inkblot. In an event-related design, the level of blood oxygenation level dependent (BOLD) contrast during brief speech pauses (mean duration 1.3 s, SD 0.3 s) during overt speech was contrasted with that during intervening periods of articulation. We then examined activity associated with pauses that occurred within clauses and pauses that occurred between grammatical junctions. Relative to articulation during speech, pauses were associated with activation in the banks of the left superior temporal sulcus (BA 39/22), at the temporoparietal junction. Continuous speech was associated with greater activation bilaterally in the inferior frontal (BA 44/45), middle frontal (BA 8) and anterior cingulate (BA 24) gyri, the middle temporal sulcus (BA 21/22), the occipital cortex and the cerebellum. Left temporal activation was evident during pauses that occurred within clauses but not during pauses at grammatical junctions. In summary, articulation during continuous speech involved frontal, temporal and cerebellar areas, while pausing was associated with activity in the left temporal cortex, especially when this occurred within a clause. The latter finding is consistent with evidence that within-clause pauses are a correlate of speech planning and in particular lexical retrieval.

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Keywords: Gyri; Speech; Clause

Introduction

Although speech during normal conversation often sounds continuous, as much as half of the total speech time can involve silence, mainly comprising pauses of 250–2500 ms (Goldman Eisler, 1968). During these brief pauses, the speaker is often

planning what to say next and how to articulate it (Butterworth, 1980). There is a fairly direct relationship between the demands on planning during speech and the amount of pausing (O'Connell et al., 1969). For example, when subjects are required to interpret a cartoon strip (by explaining the joke), the pause time per word is three times longer than when they simply describe what the strip depicts. With practice, pause time at clause boundaries drops sharply in the description condition, but not in the interpretation condition (Goldman Eisler, 1961). This difference reflects the distinction between pauses that occur at grammatical junctions (i.e., between clauses) and pauses within clause boundaries. The latter typically occur before relatively unpredictable (and infrequent) words and have been associated with lexical retrieval (Levelt, 1983; Maclay and Osgood, 1959). Pauses between clauses in contrast have been related to a more general “long-term” planning of the following clause (word ordering, syntactic encoding), although this process may also involve lexical access to some extent.

Little is known about the brain areas that are engaged during pauses. However, patients with Wernicke's aphasia (which is associated with lesions in the left temporoparietal cortex) produce neologisms and paraphasias, which have been interpreted as reflecting an impaired mental lexicon (Caramazza and Hillis, 1990). They also have difficulties in constructing coherent, intelligible speech, which is thought to be partly related to impaired sentence planning (Huber et al., 1975). Compared to healthy control subjects, patients with Wernicke's aphasia exhibit a decrease in the total duration of pausing (Christenfeld and Creager, 1996). The few hesitations that do occur are mainly evident immediately before neologisms (Butterworth, 1979; Niemi and Koivuselka Sallinen, 1987; Panzeri et al., 1990), again suggesting that hesitations reflect abnormalities in lexical retrieval and/or storage. The production of neologisms and incoherent speech by patients with schizophrenia may also be related to impaired lexical retrieval and sentence planning (Docherty et al., 2000; Kircher et al., 2002; Spitzer et al., 1993). It is associated with both a reduction in left posterior superior temporal grey matter volume (Shenton et al., 2001) and attenuated engagement of this region during continuous speech (Kircher et al., 2001b). Moreover, incoherent speech in schizophrenia is associated with a reduced frequency of pauses (Maher et al., 1983; Spitzer et al., 1994).

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Available online on ScienceDirect (www.sciencedirect.com.)

In the present study, we used functional magnetic resonance imaging (fMRI) to examine the neural correlates of speech pauses. Neural activity was measured while healthy subjects were talking in a continuous and unconstrained way about abstract designs (Rorschach inkblots). Using an event-related design, we compared the pattern of activity during pauses to that when they were actually speaking. On the basis of the literature described above, we predicted that pauses would be associated with activation in the left superior temporal cortex. In particular, this area would be activated during pauses occurring within (as opposed to between) clauses, as they are associated with lexical retrieval.

Material and methods

Subjects

Six healthy, right-handed (Annett, 1970) male volunteers were recruited by a newspaper advertisement and from hospital staff. Their mean age was 34.0 (SD 7.9) years, while their mean IQ (measured using the NART; Nelson and Willison, 1991) was 107.6 (9.6). Exclusion criteria were past or present medical or psychiatric illness and psychiatric illness in first degree relatives. Only subjects able to complete three trials of the task to be used during scanning were included. Permission for the study was obtained from the local ethical committee. After complete description of the study to the subjects, written informed consent was obtained.

Experimental setting

During scanning, seven Rorschach inkblot plates (Rorschach, 1942) were presented on a screen viewed by the subject via a mirror for 3 min, with breaks of about 1 min between presentations. Subjects were instructed to speak about whatever came to mind, starting as soon as the stimulus appeared. Their speech was recorded on a computer in digitized form using a non-metallic microphone.

Image acquisition

Gradient-echo echoplanar MR images were acquired using a 1.5 Tesla GE Signa System (General Electric, Milwaukee, WI, USA) fitted with Advanced NMR hardware and software (ANMR, Woburn, MA, USA). In each of 14 non-contiguous planes parallel to the inter-commissural (AC-PC) plane, 60 T₂*-weighted MR images depicting BOLD contrast were acquired with TE = 40 ms, TR = 3000 ms, theta = 90°, in-plane resolution = 3.1 mm, slice thickness = 7 mm, slice skip = 0.7 mm. Head movement was limited by foam padding within the head coil and a restraining band across the forehead. For anatomical coregistration, a 43-slice inversion recovery echoplanar image of the whole brain was acquired. These data have in part been used for different analysis previously (Kircher et al., 2000, 2002).

Analysis of verbal responses

Subjects' speech was transcribed from the recordings verbatim by a typist blind to the purpose of the study. These transcripts were used in conjunction with the recordings of the speech in the data analysis. Pauses between 550 and 3000 ms duration occurring

during the 21 min of speech per subject were selected as the event of interest using commercially available software (Cool Edit 96, Syntrillium Software, Phoenix, USA). The same software was used to filter scanner noise for better understandability of the speech samples. Pauses were defined as absence of speech output and duration was the sole criterion for selection. Since pause length varied systematically across subjects, the 85 longest pauses (<3000 ms) per subject were selected for analysis. A figure of 85 was chosen as we estimated that this would provide a sufficient number of events in each 21-min speech sample for the analysis. This also resulted in an average of about 15 s between each event, allowing enough time for the HRF to almost return to baseline. A total of 85 pauses per subject allowed for subcategorisation of the events into two samples large enough for the separate analysis of pauses within and between clauses. We selected the 85 longest pauses in each subject (<3000 ms) because the longer the processing time,

Table 1

Main foci of activation ($P < 0.001$) during speech pauses (mean length 1261 ± 301 ms) and fluent speech in six subjects

Cerebral region	BA	Side	x (mm)	y (mm)	z (mm)	No. activated voxels
<i>Pauses</i>						
Superior temporal sulcus	39 22	L	−33 −46	−64 −56	15 20	27 10
<i>Speech</i>						
Lingual/fusiform gyri	18/19	L	−6 −9 −6 −9 −3	−89 −92 −89 −81 −69	−7 −2 4 −13 −2	135 109 75 73 21
		R	14 29	−86 −81	−7 −13	107 75
Inferior frontal gyrus/ Insula/middle temporal sulcus	22/45	R	55 35	−22 −3	4 −2	118 59
Cuneus	18/31	L	−6 −3 −3	−94 −89 −67	9 15 31	78 23 14
		R	9	−81	20	15
Precuneus	7	R	20 3	−75 −61	37 42	74 23
		L	−14	−69	42	12
Cerebellum		L	−9	−64	−18	44
		R	26	−81	−18	27
Middle frontal gyrus	8 46	L R	−23 29	28 44	42 15	37 20
Inferior frontal gyrus	44/45	R	49 −35 −52	3 33 14	9 4 9	34 13 12
Precentral gyrus	6	L	−46	−6	42	28
Lateral geniculate		R	20	−22	−2	26
Body		L	−20	−25	−2	18
Cingulate gyrus	24	R	3 0	−14 −3	42 37	25 12
Thalamus		R	12 14	−31 −15	9 15	21 20
Middle temporal sulcus	22	L	−58	−33	4	17

BA represent Brodmann's Areas, according to the atlas of Talairach and Tournoux (Talairach and Tournoux, 1988).

the greater the cerebral demand and thus the larger likelihood to detect activations.

Image analysis

The 7×3 min series of images acquired from each individual were combined (providing a 21-min data set per subject) and used for further analysis. The effects of subject motion during data acquisition were corrected by a two-stage process involving realignment and regression (Brammer et al., 1997). The BOLD response associated with pauses (the events of interest) was contrasted with that during continuous speech (baseline). Pauses shorter than the 85 longest were treated as “continuous speech”, that is, baseline. The pattern of events was convolved with two Poisson functions parameterising haemodynamic delays of 4 and 8 s (Friston et al., 1998). The weighted sum of the two convolutions that gave the best fit (least-squares) to the time series was then computed. The sums of squares due to this fitted model and the residual errors were then computed and the ratio of the two was used to form a goodness of fit statistic (GFS). After computing the GFS from the observed data, this was repeated 10 times after random permutation of the time series at each voxel (Bullmore et

al., 1996). This process resulted in 10 permuted maps of GFS in each plane for each subject. Observed and permuted GFS maps were transformed into standard space (Talairach and Tournoux, 1988) and smoothed by a 2D Gaussian filter with full width at half maximum (FWHM) is 7 mm. The median observed GFS, at each intracerebral voxel, over all individuals in the group was then tested against the null distribution of median GFSs obtained from the permuted data. For a one-tailed test of size $P < 0.001$, the critical value is the $100 \times (1 - P)$ th percentile of the permutation distribution. Activated voxels were color coded and superimposed on an inversion recovery EPI data set (Brammer et al., 1997).

The same approach was used in a post hoc analysis to examine activation during pauses occurring within and between clauses. Pauses were subdivided according to these types and in two additional separate analyses, the BOLD response associated with each type of pause was the event of interest. They were contrasted with articulation during speech (baseline).

Regarding the cluster size of activated voxels by chance, we previously determined their size using the same methodology as described by Calvert et al. (2000). In brief, the matrix size of the image, after transformation of the data into stereotactic space, was $64 \times 64 \times 25$, a total of 102,400 voxels. However, only

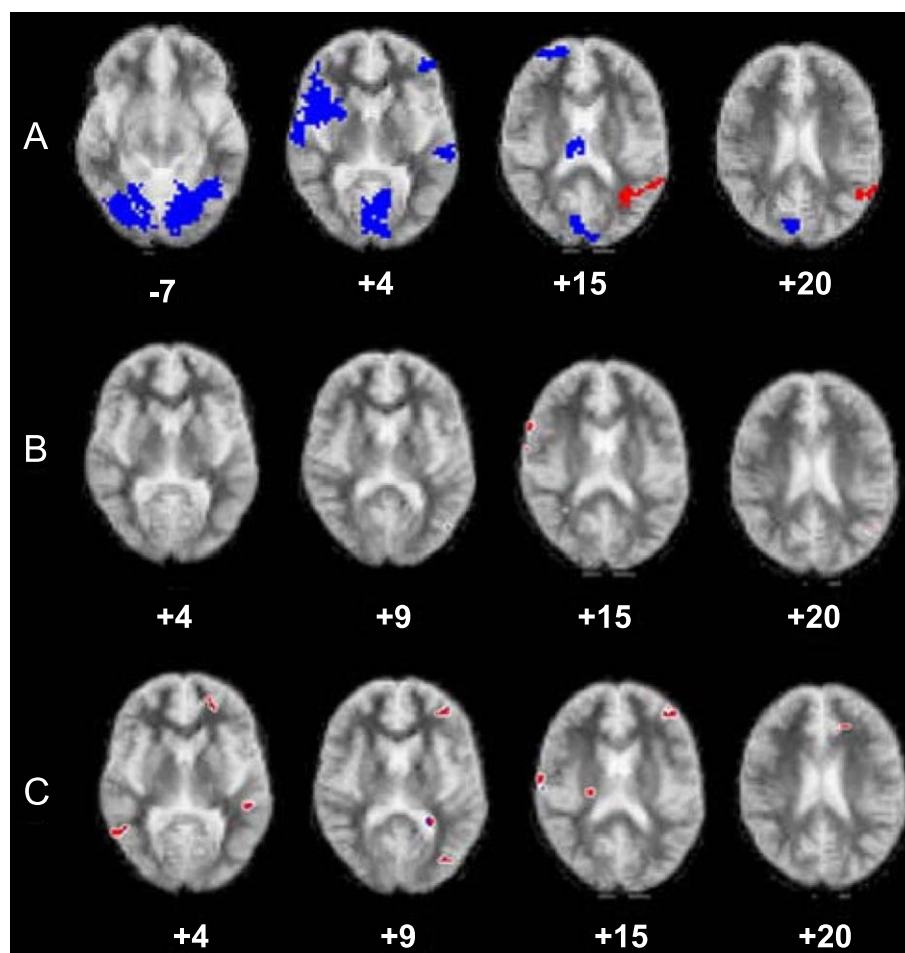


Fig. 1. (A) Short speech pauses during fluent speech correlate with activation in the superior temporal sulcus (red), between superior/middle temporal gyrus and parietal lobe ($P < 0.001$). Activated voxels during overt speech are shown in blue. (B) Pauses during grammatical junctions (red) vs. overt continuous speech. (C) Pauses within clauses (red) vs. overt continuous speech. Talairach z coordinates (Talairach and Tournoux, 1988) are shown below each slice. The left side of the map represents the right side of the brain.

approximately 22,000 voxels in this matrix lie within the brain and computations are only performed on this subset. To assess the probability of clusters of different sizes appearing in this search space by chance, we have conducted a bootstrapping experiment using six data sets acquired in the scanner without experimental paradigm. One hundred synthetic data sets were constructed by bootstrapping from these six “null” data sets and each synthetic data set was subjected to the image processing procedures described in the current study. At a voxel-wise type I error rate of 0.001, the probability of a single cluster >4 voxels occurring anywhere in the search space in a single experiment was 0.05. To minimise the chance of interpreting random clusters, we thus only accepted clusters of >5 voxels as genuine activations.

Results

Behavioral data

The mean total number of words spoken per subject during the 21-min period was 2921.5 (SD 632.6), while the mean number of pauses (as defined above) was 85.5 (SD 11.7), with a mean duration of 1261 (SD 301; range 550–2940) ms. Pauses occurred randomly across the 21-min sample. We did not have to exclude any pauses because of the 550 ms cut off point, as none of the pauses were shorter than 550 ms.

In a post hoc analysis, we subdivided events of interest into two classes: pauses at grammatical junctions or within clauses, defined according to the criteria of Goldman Eisler (1968). Fifty-five percent of the pauses was between grammatical junctions and 45% were within clauses. We calculated the median log frequency of words for each subject, for each word, using the CELEX (Baayen et al., 1995), separately for the words following pauses within and between clauses as well as the words following no pauses (continuous speech, “baseline” in the fMRI analysis). This gives a factor “count” with three levels. The frequency was weighted by the number of times that the word was used in a given subject. The CELEX gives wordform frequencies derived from an 18 million token corpus. The median frequency of words following pauses at grammatical junctions was 11.0 (range: 3.1; min: 1.0, max: 263.0). The mean duration of pauses at grammatical junctions was 1277 ms (SD, 351). The median frequency of words that followed pauses within clauses was 7.5 (range: 2.6; min: 1.0, max: 40.4), and the median pause duration was 1037 ms (SD, 186; $P = 0.05$, $T = 2.5$). The median frequency of words following no pause, that is, the words during continuous speech was 7.8 (range: 1.1; min: 0.0, max: 2628.0). A multilevel analysis of variance modeling median frequency as a function of “count” revealed a main effect of $P < 0.0001$, with no interaction of subject $\times$ count. This main effect was due to the difference between words following pauses between clauses vs. words during continuous speech ($P < 0.001$). There was no difference between the log frequency of words following pauses within clauses vs. words during continuous speech ($P = 0.1$). Thus, pauses between clauses were longer and were followed by higher frequency words than pauses within clauses.

Head movement

Analysis of the estimated time series of rotations and translations in three dimensions revealed evidence of only a small

Table 2

Main foci of activation during ($P < 0.001$) speech pauses at grammatical junctions and within clauses in six subjects

Cerebral region	BA	Side	x (mm)	y (mm)	z (mm)	No. activated voxels
<i>Pauses at grammatical junctions</i>						
Inferior frontal gyrus	44/45	R	−52	18	15	7
<i>Pauses within clauses</i>						
Middle temporal gyrus	21	R	55	−56	4	10
		L	−40	−31	−2	8
Middle frontal gyrus	10	L	−14	58	9	9
	46	R	46	39	15	7
Superior parietal lobe	7	L	−52	−31	48	9
			−32	−53	48	6
Superior frontal gyrus	10	L	−25	50	4	8
Superior temporal gyrus	22	L	−46	−33	4	6
			−40	−39	15	5
Postcentral gyrus	40	L	64	−14	15	6
Middle occipital gyrus	19	L	−32	−72	9	5

BA represent Brodmann's Areas, according to the atlas of Talairach and Tournoux (Talairach and Tournoux, 1988).

amount of motion in each individual. The maximum amount of head movement in all subjects during the 21-min acquisition time series was: 2.4 mm (SD 1.5) in the x dimension, 2.4 (1.5) mm in the y dimension, and 4.9 (2.6) mm in the z dimension.

Activation associated with pauses

The occurrence of pauses during speech (relative to articulation during speech) was correlated with the BOLD response in a single region that spanned the banks of the posterior part of the left superior temporal sulcus (Brodmann Areas [BA] 22 and 39), at the junction between the temporal and parietal lobes. Conversely, articulation during continuous speech was associated with greater left-sided activity in the insula and precentral gyrus, and in the inferior frontal (Brodmann Area 44/45), middle frontal (BA 8) and anterior cingulate (BA 24) gyri, the banks of the middle temporal sulcus (BA 21/22) and the cerebellum, bilaterally. Speaking was also associated with a greater BOLD response in the lingual and fusiform gyri, (BA 18/19), the cuneus, (BA 18) and the precuneus (BA 7) bilaterally (Table 1; Fig. 1).

Activation associated with pauses within and between clauses

Relative to articulation during speech, pauses within clauses were associated with activation in the left superior temporal (BA 22), superior frontal (BA 10) and in the middle temporal (BA 21) and middle frontal (BA 10 and 46) gyri bilaterally (Table 2; Fig. 1). Pauses at grammatical junctions were associated with activation in the right inferior frontal gyrus (BA 44/45).

Discussion

In our study, subjects spoke continuously while fMRI data and overt speech were recorded. The occurrence of pauses during speech (events of interest), relative to articulation during speech (baseline), was correlated with signal changes in a single region

that spanned the banks of the posterior part of the left superior temporal sulcus (STS), a region approximately corresponding to Wernicke's area. As pauses of the duration we examined are generally associated with lexical retrieval and sentence planning (Goldman Eisler, 1961, 1972; Sabin et al., 1979), the engagement of the left temporoparietal cortex may reflect its involvement in these processes.

Our results are in line with data from brain-damaged patients. Patients with lesions in the left superior temporal region (and who have Wernicke's aphasia) frequently produce paraphasias, jargon and neologisms (Kreisler et al., 2000). It has been hypothesised that these symptoms arise from impaired access and/or storage processes in the mental lexicon (Caramazza and Hillis, 1990; Levelt, 1992). The association we observed in the post hoc analysis between left temporal activation and pauses within clauses but not at grammatical junctions is also consistent with such a role. Furthermore, Patients with Wernicke's aphasia show impaired planning on a sentence level, with erroneous reduplications of clauses and clause inversions, termed paragrammatism (Kleist, 1934; Kreisler et al., 2000). In line with these lesion studies are data from more recent functional imaging work on the processing of complex sentences. They indicate that reading (for review, see (Kaan and Swaab, 2002) and the production (Haller et al., submitted for publication; Kircher et al., submitted for publication) of syntactically complex sentences are associated with activation in the left posterior superior temporal gyrus. Again, our findings of left STG activation during pauses are consistent with these data.

Patients with schizophrenia produce speech which is similar in some aspects to that of Wernicke patients, although they do not have an aphasic syndrome. In particular, these two groups of patients commonly produce neologisms, paraphasias, perseverations and incoherence (Faber et al., 1983). These abnormalities, termed formal thought disorder in schizophrenia, have been related to a dysfunctional semantic network (Kircher, 2003; Kircher et al., 2002; Spitzer et al., 1993). Intriguingly, we have found that the expression of thought-disordered speech is associated with reduced engagement of the left superior temporal cortex (Kircher et al., 2001b). In addition, structural imaging studies in schizophrenia show that the grey matter volume of the same region is reduced in patients who exhibit thought disorder (Shenton et al., 2001).

To further elucidate speech planning at the sentence level in our post hoc analysis, we investigated cerebral activation during pauses at grammatical junctions, which are associated mainly with this process. Pauses of this type (as opposed to those occurring within clauses) were associated with activation in the right inferior frontal gyrus. This might reflect memory retrieval and search processes, when subjects think about what to say next between clauses (conceptual organisation). Interestingly, this region was activated in subjects who listened to grammatically incorrect sentences and had to repair them (Meyer et al., 2000). Given the limited frequency of the subtypes of pauses, we cannot exclude the possibility that we did not detect all the activation associated with pauses within and between clauses due to lack of statistical power.

It has been suggested that pauses at grammatical junctions reflect mainly sentence planning, whereas pauses within clauses correspond to lexical retrieval (Levelt, 1989). Consistent with this, we found that pauses within clauses preceded less frequent words and were of shorter duration than pauses at grammatical junctions. In addition, they were associated with activation in the superior and middle temporal gyri bilaterally, areas previously implicated in lexical retrieval (Indefrey and Levelt, 2000; Kircher et al., 2000,

2001a) and error correction (McGuire et al., 1996), whereas pauses occurring at grammatical junctions were not.

A supplementary hypothesis implies that verbal self-monitoring processes occur during pauses (Levelt, 1983). These processes constantly monitor our own speech plans and check for errors that can be corrected before articulation. Activation in the left STS would be consistent with this explanation, as listening to one's own and other voices has been associated with bilateral STS activation, as has the performance of tasks that engage verbal self-monitoring (Belin et al., 2000; Binder et al., 1997; Fu et al., 2003; Kircher and David, 2003; McGuire et al., 1996; Wise et al., 1999). In our study, the signal changes in the STS occurred during silence, which could reflect an association between internal speech error monitoring and detection processes and the left, but not the right STS (Levelt, 1989).

The internal validity of our method was indicated by the topographic distribution of signal changes during articulation, which involved areas normally activated during speech production: the left insula and precentral gyrus, and the inferior frontal, dorsolateral prefrontal, anterior cingulate and superior/middle temporal and cerebellar cortices bilaterally (Blank et al., 2002; Just et al., 1996; Kircher et al., 2000, 2001a; McGuire et al., 1996; Wise et al., 1999). Additional activation in the occipital cortex and precuneus may have reflected relatively a greater degree of visual attention when subjects (who were viewing abstract pictures) were speaking rather than pausing (Kosslyn et al., 1999; Mellet et al., 1996). Overt speech responses during fMRI may be associated with head movement and susceptibility artefacts can also be introduced by changes in the sinus cavities and the pharynx during phonation (Amaro et al., 2002). However, at 1.5 T, when overt responses are continuous, these effects on grouped data are likely to be small except in areas bordering sinus cavities, where macro-susceptibility-induced signal loss is maximal (Barch et al., 1999). Barch et al. compared activation during an fMRI study of a task involving overt and covert verbal responses. They concluded that overt articulation was not associated with marked artefacts, particularly if this was occurring in both experimental and control conditions, and in group analyses. A number of other recent fMRI studies have shown that analysis of overt speech production data is possible without specific acquisition sequences (Bullmore et al., 1999; Leger et al., 2002; Riecker et al., 2000). Analysis of head movement data in our sample indicated that there was surprisingly little movement during scanning. This may be related to the fact that subjects were speaking continuously, rather than articulating single words in response to stimuli at intervals. In addition, as they had no real interlocutor, their speech sounded less expressive than in conversation. Head movement occurs mainly during conversational situations (Altorf et al., 2000) and in particular during a peak in loudness or a major phonetic stress (Hadar et al., 1984).

Overall, our data suggest that pauses during continuous speech, particularly those occurring within clauses, are associated with even greater engagement of the left temporal cortex than is evident during articulation of continuous speech. The left STS lies between the parietal lobe, implicated in supramodal association processes and the language areas of the lateral temporal lobe. These observations suggest that pausing during speech might be an important step in the translation of abstract preverbal thoughts into intelligible speech. However, as our sample size was small, the results should be interpreted with some caution and their replication in a larger sample is desirable.

Acknowledgments

T.K. was supported by the Deutsche Forschungsgemeinschaft (DFG; German Research Foundation). We thank Harald Baayen, Nijmegen for the word frequency analysis.

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