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Temporal processing and context dependency of phoneme discrimination in patients with aphasia

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Abstract

Standard diagnostic procedures for assessing temporal-processing abilities of adult patients with aphasia have so far not been developed. In our study, temporal-order measurements were conducted using two different experimental procedures to identify a suitable measure for clinical studies. Additionally, phoneme-discrimination abilities were tested on the word, as well as on the sentence level, as a relationship between temporal processing and phoneme-discrimination abilities is assumed. Patients with aphasia displayed significantly higher temporal-order thresholds than control subjects. The detection of an association between temporal processing and speech processing, however, depended on the stimuli and the phoneme-discrimination tasks used. Our results also suggest top–down feedback on phonemic processing.

Keywords: Auditory processing; Temporal-order threshold; Phoneme discrimination; Language comprehension; Aphasia

1. Introduction

The processing of temporal information in the speech signal has been investigated explicitly over the last few decades. As speech evolves over time, it contains information on different time scales (Rosen, 1992). In the time domain of about 20–40 ms information about the place of articulation in stop consonants is contained. Formant transitions, characterized as short sound waveforms that change frequency across a time interval of ca. 40 ms vary according to the place of articulation. These spectral changes at the release of the closure depend on the articulatory structure that is used to form the constriction (labial /b/, /p/; alveolar /d/, /t/; velar /g/, /k/) (Stevens, 1998). Moreover, a difference in duration of about 20 ms in the time between the burst and the onset of laryngeal pulsing, defined as the voice-onset time (VOT), distinguishes voiced (/b/, /d/, /g/) from voiceless stop consonants (/p/, /t/, /k/) (Stevens, 1998). In contrast, the time scale of 150–250 ms is assumed to be connected to syllabic and prosodic information (Rosen, 1992). As has been shown, syllable durations are usually around 200 ms long (Greenberg, 1999). This time constant is a characteristic feature across languages and has been assumed to be relevant for perceptual unit formation, i.e., encoding syllables (Poeppel, 2003).

The two temporal windows are embedded in the asymmetric sampling in time (AST) model proposed by Poeppel (2003) which suggests a functional asymmetry in the processing of auditory and speech signals in the time domain. AST suggests that the short temporal window is associated with γ-band activity over the left cerebral hemisphere, whereas the longer temporal window is correlated with θ-band activity over the right hemisphere. Based on psychophysical and physiological research, rhythmic brain activity is thought to provide fundamental temporal-building blocks in sensory and cognitive processing. Magnetoencephalographic recordings (MEG) in humans suggest that 40-Hz activity is involved in the perceptual separation of

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acoustic events over time. These MEG recordings are believed to result from a coherent 40-Hz resonance between thalamocortical loops responsible for binding neural processes involved in perception (Joliot, Ribary, & Llinás, 1994; Llinas & Ribary, 1993; Pöppel, 1997). In addition, a longer temporal integration window in audition of around 150–250 ms has been proposed based on EEG and MEG studies (Näätänen, 1992; Yabe, Tervaniemi, Reinikainen, & Näätänen, 1997).

In the present study, the association between temporal processing in the time range of 20–40 ms and phonemic processing is addressed. Findings indicate that deficits in the processing of rapidly changing signals, i.e. increased thresholds for the detection of temporal order of acoustic stimuli, are often correlated with phoneme-identification and phoneme-discrimination impairments in patients with left-hemispheric lesions to the brain and aphasia, children with specific language impairment and children and adults with dyslexia (e.g., Farmer & Klein, 1995; von Steinbüchel, Wittmann, Strasburger, & Szelag, 1999; Swisher & Hirsh, 1972; Tallal & Piercy, 1973; Wittmann, Burtscher, Fries, & von Steinbüchel, 2004). Based on these associations some authors have suggested that the processing of rapid temporal changes in the speech signal is required for correct phonemic processing (Efron, 1963; Pöppel, 1997; Tallal, 1980; Tallal, 1984; Wittmann, 1999).

Over the last years several diagnostic methods have been developed to assess temporal-processing mechanisms in children (Tallal et al., 1996). Nonetheless, no standard diagnostic tool has been established to assess auditory temporal-order detection in adult patients with aphasia in a clinical setting (Wittmann & Fink, 2004). Temporal-order measurements are usually conducted by presenting two consecutive stimuli and varying the inter-stimulus intervals (ISI). Subjects repeatedly have to indicate the order of the presented stimuli until a perceptual threshold is determined. In different studies stimuli vary concerning their physical properties, duration, and stimulation modes. In the alternating monaural condition, two sounds (e.g., clicks) are presented to the participants, one to the left and the other to the right ear. Subjects have to indicate the sequence of sounds: left-right or right-left. These sounds usually have identical physical properties and are equal in duration (e.g., 1 ms; Berwanger, Wittmann, von Steinbüchel, & von Suchodoletz, 2004; Lotze, Wittmann, von Steinbüchel, Pöppel, & Rönneberg, 1999; Mills & Rollman, 1980). In a binaural stimulation mode, a sound is presented to both ears followed by a second different sound with a certain ISI in between, and the subjects have to indicate the order of the two stimuli. Studies employing binaural tasks commonly use pairs of tones with different frequencies but the presented tones vary in *frequency* and *duration* over different studies (e.g., Hirsh & Sherrick, 1961; Kanabus, Szelag, Rojek, & Pöppel, 2002).

As these behavioural tasks require attention by the subject, they are difficult to conduct in patients with attention deficits. To study auditory discrimination abilities in subjects with attention problems the mismatch negativity (MMN), a component registered in measures of event-related potentials, can be used. It is elicited by discriminable changes in auditory stimulation and its occurrence is not dependent on attention. Studies showed that MMN to non-speech and speech sound discrimination is attenuated or even diminished after left hemispheric lesions (Aaltonen, Tuomainen, Laine, & Niemi, 1993; Ilvonen et al., 2003). These results indicate that MMN can be used to test auditory discrimination abilities in individuals with attention deficits and that it can be employed as an additional measurement to behavioural data in all tested subjects to rule out the influence of cognitive factors.

To compare different measurement procedures, we conducted an earlier study employing different auditory temporal-order threshold measurements in healthy younger and older adults (Fink, 2004; Fink, Churan, & Wittmann, 2005). Results showed that temporal-order thresholds clearly depend on the physical properties of the stimulus. Re-test reliabilities indicate that an increase in the number of temporal-order measurements improves the validity of the measurements, especially with click stimuli, differentiating subjects with and without disturbances in temporal processing. Furthermore, the results indicate that temporal-order measurements with tones are more suitable for clinical intervention studies than measurements with clicks for at least two reasons. First, the re-test reliability for tones is higher than for clicks. This is important in clinical settings, where multiple measurements are difficult to conduct due to time constraints. Second, a significant positive correlation between temporal-order measurements and phoneme-discrimination abilities could only be confirmed for measurements with pairs of tones, pointing to the validity of the procedure for clinical diagnostic purposes. One important objective of the present study was to determine whether the stronger association between temporal-order thresholds obtained with tones and phoneme-discrimination abilities also exists in patients with aphasia.

Not only diagnostic procedures to test for temporal-processing abilities have recently been developed, but also training procedures have been designed to improve the ability to detect the temporal order of acoustic features in the speech signal in subjects with language impairments. Results show that feedback-training in temporal processing abilities can improve phoneme identification in children with language-learning impairments (Merzenich et al., 1996) and in patients with aphasia (von Steinbüchel, Wittmann, & Pöppel, 1996). Moreover, it has been shown, that purely non-linguistic training can improve reading skills in dyslexic children (Kujala et al., 2001). Although the audio–visual stimuli used in this training contained no rapid transitions, enhanced MMN occurred to infrequent order reversals of tone pairs with 40 ms tones after the training. Most of the training procedures, however, use also modified language stimuli with enhanced and extended formant transitions (Rey, De Martino, Espesser, & Habib, 2002; Tallal et al., 1996). In light of the temporal-processing hypothesis, however, training procedures using modified language seem questionable. Since training with modified verbal stimuli includes additional linguistic cues it is difficult to isolate supposed training effects in temporal processing from those improvements due to the training in phoneme discrimination. To carefully control for the size of training effects on temporal-order perception one has to use non-verbal stimuli in the training procedure and then assess the effects the training had on phoneme discrimination (for a thorough discussion of this argument, see Wittmann & Fink, 2004).

Furthermore, theoretical criticism of the temporal-processing hypothesis has been voiced by Studdert-Kennedy and Mody (1995). They argued that the difficulty in differentiating stop consonant vowel syllables may be caused by an inability to identify similar short stimuli and not by problems in detecting the temporal order of spectral features. Accordingly, language-impaired subjects confuse stop consonants because of their spectral similarity and not because of an underlying general auditory deficit in perceiving rapidly changing acoustic events. Brevity of similar speech stimuli, but not the transitional character of acoustic features in consonants, is seen as the critical variable causing problems for language-impaired individuals.

Another critical aspect in the diagnosis of possible temporal-processing deficits causing phoneme-discrimination disabilities is the presentation of stop consonant vowel syllables without a language context and the generalization of the results to complex language comprehension. In habitual language use we do not have to discriminate isolated syllables, as they are embedded in words and sentences. Language understanding is more than bottom–up processing of the stream of speech. Listeners have to integrate the environmental context with their general knowledge to select the appropriate meaning from a variety of possibilities.

Over the past years, several studies have investigated the influence of *lexical and contextual information* on phoneme categorization. This research has demonstrated that the identification of a phoneme is affected by the lexical status of the spoken word in which the phoneme occurs—called the "lexical effect" (Ganong, 1980). Studies examining the lexical effect use voice-onset time series in which, for example, the voiced end of the continuum is a word, but the voiceless end is a non-word, such as /duke/ – /tuke/ (Burton, Baum, & Blumstein, 1989). Listeners are asked to label the initial phoneme as being either a /d/ or a /t/. Results show that there is a shift in the category boundary towards the endpoint of the voice-onset time series that represents the non-word (/tuke/), indicating that the subjects more often understood the real word.

Another factor that seems to influence phoneme identification is *word frequency*. Connine, Titone, and Wang (1993) used a voice-onset time continuum in which both endpoints represented words that differed in their frequency of usage in spoken language. Results demonstrated that the initial phoneme representing the word used with greater frequency was identified more often than the phoneme representing the word less frequently. Not only the frequency of the target word influences phoneme identification, but also *lexical neighborhood* effects affect the classification of phonemes (Newman, Sawusch, & Luce, 1997).

Phoneme categorization is also affected by the *sentence context*. Borsky, Tuller, and Shapiro (1998) used a voice-onset time series embedded in target sentences that biased the phoneme categorization to the voiced or voiceless endpoint. In this experiment the identification functions showed a shift reflecting more responses consistent with the semantic bias, thereby confirming the hypothesis that the sentence context influences phoneme categorization. The linguistic context can also be used for identification when the acoustic information is replaced by noise, for example (Warren, 1970). In such a situation a listener can automatically add the missing element to identify the speech signal. Nittrouer and Boothroyd (1990) demonstrated that lexical, semantic, and syntactic context also affect speech perception in a noisy environment.

The above-mentioned studies clearly show that lexical and contextual information affect phoneme categorization in healthy subjects. This raises the question whether patients with aphasia who have a phoneme-discrimination disability can compensate for their deficit by using lexical or contextual information. One investigation examined the effect of contextual information on phoneme identification in patients with aphasia (Baum, 2001). Results showed that patients with aphasia used the contextual influence to categorize the phonemes. It seems that patients with aphasia suffering from impaired phonetic perception can compensate for this deficit by using the semantic context (Baum, 2001; Blumstein, Burton, Baum, Waldstein, & Katz, 1994; see also: Caplan & Aydelott-Utman, 1994).

Based on the hypothesis of a temporal-processing deficit in the range of 20–40 ms as an underlying cause for deficient phonemic perception, this study investigated the association between temporal processing and phoneme discrimination in patients with aphasia. Temporal-order thresholds were assessed using two different measurement procedures to identify a feasible, reliable, and efficient procedure for use in clinical-intervention studies. A new measurement procedure was also developed to test phoneme-discrimination ability on the sentence level to investigate the influence of lexical and contextual information.

2. Materials and methods

2.1. Participants

Nineteen patients with aphasia and 19 age- and gender-matched controls took part in the study. All subjects were native German speakers and had no hearing deficits. Hearing function for both ears was assessed using pure-tone audiometry (Audiometer MA 15, Maico Diagnostic GmbH). The adaptive procedure used frequencies ranging from 500 to 4000 Hz (500, 750, 1000, 1500, 2000, 3000, and 4000 Hz) and a dB range from −10 to 100 dB in steps of 5 dB. A hearing level of 10 dB, for example, means that the subject requires 10 dB more than the average for tone detection. The exclusion criteria were a hearing level above 30 dB for all frequencies tested and differences in the hearing level between the two ears above 20 dB. Patients with aphasia were included if they had no deficits in single-word reading, no additional clinically diagnosed neuropsychological deficits, as well as the ability to analyze gender-specific definite articles (for an explanation see language stimuli below). See Table 1 for description of the patient sample.

Three test sessions were conducted with all participants on three different days. Temporal-order threshold measurements were repeated every session. All subjects were tested individually; a single auditory temporal-order measurement lasted for approximately 10 min; a test session on one day lasted approximately 1 h. Subjects were paid for their participation in the study.

2.2. Cognitive functions

To control for additional cognitive deficits that might interfere with the assessed timing functions, attention and working memory were tested in all subjects. The testing procedures included an alertness test from a test battery for measuring attention functions (TAP—Testbatterie zur Aufmerksamkeitsprüfung; Zimmermann & Fimm, 1993). Memory span was assessed using the CORSI block test (Corsi, 1972).

2.3. Experimental design

In the present investigation, auditory temporal-order thresholds were assessed using a computer-aided system (Pentium 3 processor; soundblaster audigy soundcard). All stimuli (non-verbal and verbal) were presented with 82.3 dB SPL via headphones (SONY MDR-CD 480).

2.4. Temporal-order threshold

The auditory temporal-order threshold is defined as the minimum temporal interval between two auditory stimuli that must exist before a person is able to identify the correct order of two successive events. In the present investigation, the threshold corresponds to 75% correct order discrimination. Two measurements were taken under different stimulation and stimulus presentation conditions.

All stimuli used for the temporal-order measurements were pairs of acoustic events. The stimuli were generated with the program Cool Edit 2000 (sampling rate 44.100 Hz, 16-bit). In one condition, clicks were used, and in the other, sinusoidal tones. Clicks were rectangular pulses of 1 ms duration presented in an alternating monaural stimulation mode (one click to each ear). Tone stimuli consisted of a low tone (800 Hz) and a high tone (1200 Hz). The duration was 10 ms with 1 ms rise-and-fall time (linear shape of rise and fall), and the tones were presented in a binaural stimulation mode (a tone is presented to both ears followed by a second tone to both ears). Thresholds were obtained using YAAP (Treutwein, 1997), an adaptive maximum-likelihood based algorithm, for the presentation of the ISI (time from the offset of the first stimulus and the onset of the second stimulus) according to the subject's responses. Stimuli in each trial are set at the current best estimate of the threshold. This tracking procedure estimates a threshold corresponding to 75% correct order discrimination based on a logistic psychometric function. The stimulus presentation is terminated when the location of the threshold parameter is with a probability of 95% inside a ±5 ms interval around the currently estimated threshold. ISIs ranged from 10 to 700 ms.

At the beginning of each test session, practice trials were carried out to demonstrate the task and to make sure the

Table 1
Description of the patient sample

Subject	Medical diagnosis	Aphasic diagnosis	MPO[a]	Age[b]	Gender
1	Traumatic brain injury, bilateral parieto-temporal lesion	Anomic aphasia	46	27	Male
2	Cerebral hemorrhage, left parietal	Anomic aphasia	15	43	Female
3	Cerebral infarct, left posterior	Wernicke‘s aphasia	7	80	Male
4	Cerebral infarct, left anterior	Broca‘s aphasia	2	45	Male
5	Cerebral hemorrhage, central portion of the left insula, lateral basal ganglia	Wernicke‘s aphasia	11	48	Male
6	Cerebral infarct, left temporo-parietal	Broca‘s aphasia	2	25	Female
7	Cerebral hemorrhage, left	Non-classifiable aphasia	5	41	Male
8	Cerebral hemorrhage, left parieto-occipital	Non-classifiable aphasia	4	49	Female
9	Cerebral hemorrhage, left gyrus temporalis superior	Anomic aphasia	2	24	Male
10	Cerebral hemorrhage, left	Non-classifiable aphasia	6	50	Male
11	Cerebral infarct, left temporo-parietal	Anomic aphasia	6	52	Female
12	Cerebral infarct, left	Anomic aphasia	1.5	74	Female
13	Cerebral infarct, left	Anomic aphasia	2	35	Female
14	Cerebral hemorrhage, left; cerebral infarct, left	Broca‘s aphasia	5	47	Male
15	Cerebral infarct, left	Anomic aphasia	1	60	Female
16	Cerebral hemorrhage, left temporal	Non-classifiable aphasia		42	Male
17	Cerebral hemorrhage, left temporal	Broca‘s aphasia	86	33	Female
18	Cerebral hemorrhage, left temporal	Anomic aphasia	4	59	Female
19	Cerebral hemorrhage, left; thalamus infarct, right	Non-classifiable aphasia	2	55	Male

[a] Months post onset, time between neurological incident and study.
[b] In years.

subjects understood the instructions. In this practice phase, trials with an ISI of 500 ms were repeated several times to ensure that subjects could discriminate between the two stimuli. If patients with aphasia were not able to reliably identify the correct order at this level, the ISI was increased and the training phase repeated. For all measurements, each trial included three warning signals prior to the stimulation to focus the subjects‘ attention on the task. The time between the warning signal and the stimulus was 1500 ms. The order of stimulus presentation was randomized.

2.5. Phoneme discrimination on the word level

In the phoneme-discrimination task on the word level, subjects had to discriminate between the words /*danken*/ (to thank) and /*tanken*/ (to fuel) (Kiss, 2002). The task included 10 stimuli varying in the voice-onset time of the initial stop consonant. Stimuli were created by manipulating the voicing duration of the stop consonant in a naturally spoken /*tanken*/. This resulted in phonemes with voice-onset times ranging between 0 and 90 ms in 10-ms steps. During a test session, every stimulus was presented 10 times in randomized order using the method of constant stimuli. Participants responded by pointing to a response card, and the responses were documented by the experimenter. Fig. 1 displays the two response cards used in the phoneme-discrimination test.

2.6. Phoneme discrimination on the sentence level

In this study a new measurement procedure to assess the phoneme discrimination ability on the sentence level—called *T-M-D-S* (Tölzer Minimalpaardifferenzierungen im Satzkontext)—was used (Fink, 2004). In this test, pairs of phonemes (b–p; d–t; and g–k) are embedded in sentences and presented to the subject. Three types of sentences are applied.

(1) Category I: sentences including morphologic or syntactic cues.
(2) Category II: meaningful sentences without cues.
(3) Category III: senseless sentences.

In the first category 14 sentences were created to provide the possibility to compensate for a phoneme-discrimination deficit by using the morphologic or syntactic cues. Patients with aphasia were selected who were able to recognize the provided cues. The two sentences, for example [Die *B*ar ist alt/ Das *P*aar ist alt (The bar is old/ The couple is old], contain not only different phonemes [*B*ar/ *P*aar], but also different definite articles [*die* Bar/ *das* Paar]. Therefore, the sentences were morphologically biased to one phoneme. Response cards were created to avoid biased results due to linguistic deficits. Fig. 2 displays the two response cards belonging to the sentences cited above.

In the second category, four meaningful sentences without cues, such as [Die *G*asse ist dunkel/ Die *K*asse ist dunkel (The lane is dark/ The cash register is dark)], were presented. In these sentences, no cues were presented to compensate for a possible phoneme-discrimination deficit. Again, response cards were drawn to avoid biased results due to deficits in verbal expression.

In a third category, 20 senseless sentences were presented, such as [Grüne *G*assen schlafen wütend/Grüne *K*assen schlafen wütend (Green lanes sleep furiously/Green cash registers sleep furiously)]. These sentences contain no cues that help to analyze the meaning of the relevant word (e.g., Gassen, Kassen). Subjects have to analyze the acoustic–phonetic structure of the speech signal to understand the words. In this sentence category, the response cards contained the target words, as no pictures could be drawn illustrating the senseless sentences.

All sentences were naturally spoken by a native German-speaking female to ensure simulation of everyday language. They were balanced according to the positions of the target phoneme, the number of syllables of the target words, and the number of words within the sentences. The same pairs of words were used in all categories to control for word frequency effects over the three categories. A training phase was conducted at the beginning of this test to ensure the patients with aphasia understood the task.

2.7. Data processing

Psychometric functions were fitted using psignifit version 2.5.41 (see http://bootstrap-software.org/psignifit/), a software package which implements the maximum-likelihood method described by Wichmann and Hill (2001). We used a logistic psychometric function model and estimated three parameters of the psychometric function: the threshold, corresponding to 75% correct order discrimination, the

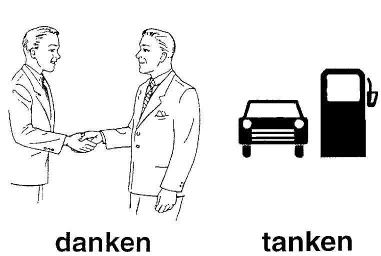

Fig. 1. Response cards of the phoneme discrimination test on the word level; left: to thank, right: to fuel.

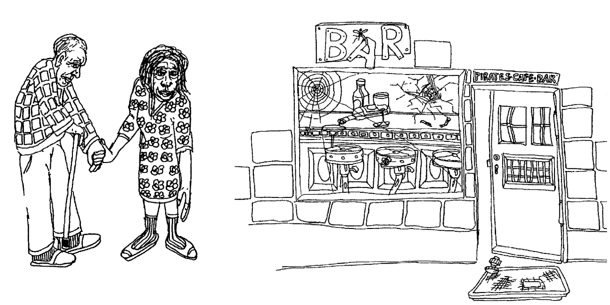

Fig. 2. Response cards of the *T-M-D-S*, left, the couple is old; right, the bar is old.

slope, and the lapsing rate (Strasburger, 2001). As the obtained temporal-order thresholds indicate the ISI corresponding to 75% correct order discrimination, stimulus-onset asynchronies (SOA) were assigned by adding the stimulus duration to the thresholds (clicks: 1 ms; tones: 10 ms). The mean value of the three temporal-order measurements was taken for further analysis.

The fitting procedure was also used to analyze phoneme-discrimination abilities on the word level. Thresholds corresponding to 50% identification of the word /*tanken*/ were defined as the category boundary. The lapsing rate (rate at which the subjects respond /danken/ even at clearly supra-threshold voice-onset times) was used to further describe the general uncertainty of the subjects in the phoneme-discrimination task.

Phoneme-discrimination abilities assessed on the sentence level were analyzed using the percentage of incorrect responses. Error rates were calculated separately for the three different categories.

2.8. Statistical analysis

The Kolmogorov–Smirnov test was applied to the data to test for normal distribution. Results showed that ca. 50% of the data were not normally distributed. Therefore, non-parametric methods were used to analyze the data. Wilcoxon tests were applied to compare the different stimuli. Mann–Whitney U tests were implemented to analyze group differences. Spearman rank correlations were used to test associations among different measurements. The statistical significance level for one-sided tests was set at 5%.

3. Results

3.1. Cognitive functions

Results from the alertness test showed no significant differences between the patients with aphasia and the control group (alertness: $z = -1.420$; $p = .158$), whereas significant differences were found in the working-memory test (CORSI: $z = -2.053$; $p = .049$). Although the comparison between the two groups reached the significance level in the CORSI block test, we do not expect this cognitive variable to influence our timing and phoneme-discrimination tasks, as patients with aphasia show values within the normal range of healthy subjects (Kessels, von Zandvoort, Postma, Kappelle, & Haan de, 2000). Further, no significant correlations were found between the timing measurements and the memory span in the group of aphasic patients.

3.2. Temporal processing

Patients with aphasia had significantly higher temporal-order thresholds for both measurement procedures (clicks: $z = -2.89$, $p = .003$; tones: $z = -2.45$, $p = .014$). As displayed in Fig. 3, temporal-order thresholds obtained with tones were much higher than those obtained with clicks in

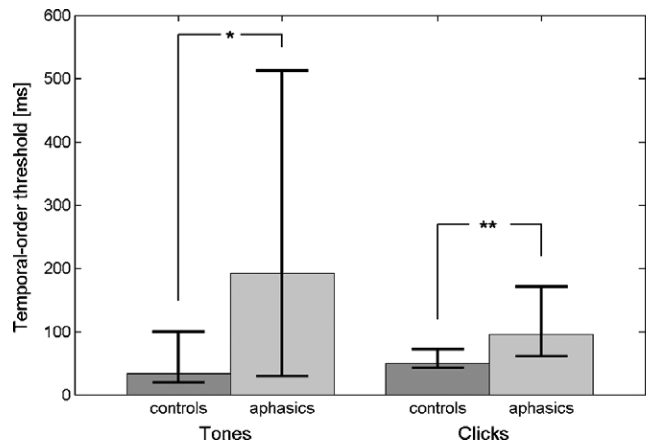

Fig. 3. Median, 25th percentile and 75th percentile of temporal-order thresholds in ms for the two groups obtained with two different measurement procedures.

patients with aphasia. They also show greater inter-individual variance.

3.3. Phoneme discrimination

3.3.1. Word level

As has been shown previously, the response patterns of patients with aphasia in phoneme-discrimination tasks are more variable than that of healthy control subjects (von Steinbüchel et al., 1996). In addition to the thresholds we used the lapsing rate as a second variable to describe the phoneme-discrimination ability of the subjects. Figs. 4A and B show two examples of identification functions for a voice-onset time continuum ranging from /d/ to /t/. Voice-onset times from 0 to 90 ms are displayed on the x axis, and responses are plotted on the y axis. Fig. 4A shows an unimpaired phoneme-discrimination performance in this task. Stimuli with short voice-onset times are identified as /d/, whereas stimuli with longer voice-onset times are identified as /t/. Fig. 4B shows an impaired phoneme-discrimination performance. As can be seen in this figure, stimuli with longer voice-onset times are often misclassified as /d/, resulting in a higher lapsing rate.

Group comparisons of phoneme-discrimination ability were conducted using two variables—category boundary (corresponding with 50% of /tanken/ responses) and lapsing rate of the psychometric function. Results show that there is no significant difference in the category boundary between patients with aphasia and control subjects ($z = -0.46$, $p = .663$). In contrast, a significant difference for the lapsing rate was found ($z = -2.22$, $p = .031$). In stimuli with higher voice-onset times—representing a /t/ -, patients with aphasia often classified the phoneme as /d/ (approximately 30%), whereas healthy control subjects almost always classified these phonemes as /t/. The lapsing rate will be used for further analysis. Fig. 5 displays the category boundary and the lapsing rate for the two groups.

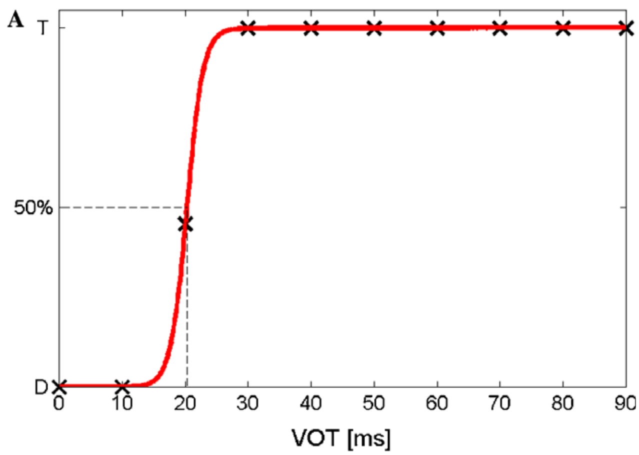

Fig. 4. (A and B) Phoneme identification functions for a voice-onset time continuum from /d/ to /t/; top, unimpaired performance; bottom, impaired performance.

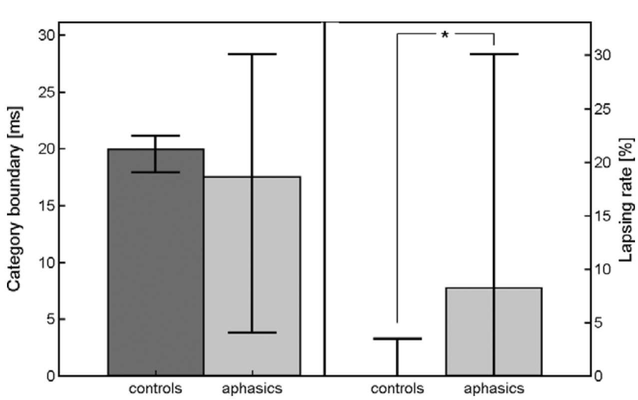

Fig. 5. Left, median; 25th percentile and 75th percentile of the category boundary for the two groups; right, median; 25th percentile and 75th percentile of the lapsing rate for the two groups.

3.3.2. Sentence level

Phoneme discrimination on the sentence level was compared using the percentage of incorrect responses. Comparisons between healthy subjects and patients showed no significant differences for the percentage of incorrectly iden-

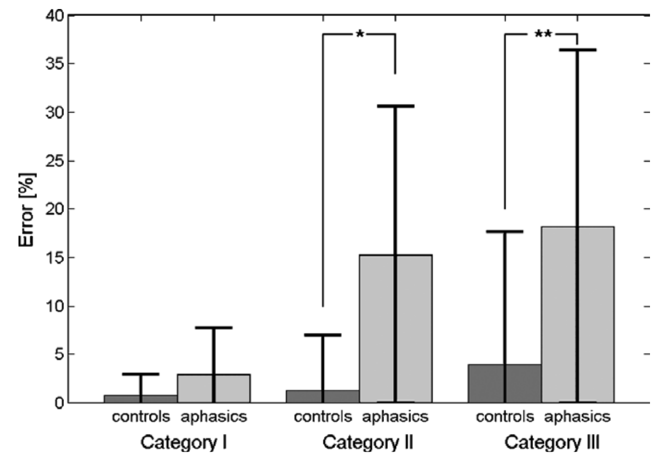

Fig. 6. Mean and standard deviation of error rates of the phoneme-discrimination test on the sentence level [for a better illustration mean and standard deviation were chosen here].

tified phonemes in the category of meaningful sentences including morphologic or syntactic cues ($z = -1.64$, $p = .246$). In contrast, results showed significant differences in the error rates in the category of meaningful sentences without cues ($z = -2.65$, $p = .050$). Patients with aphasia displayed higher error rates than the control subjects. The same result was found for senseless sentences. Again, patients with aphasia showed more errors than the healthy subjects, resulting in significant group differences ($z = -3.72$, $p < .001$). Fig. 6 shows the error rates for the two groups for all three categories of sentences.

Correlation coefficients were calculated between phoneme-discrimination abilities on the word level and on the sentence level in the group of patients with aphasia. Results showed no significant correlation coefficient between phoneme-discrimination abilities on the word level and meaningful sentences including morphologic or syntactic cues ($r = .395$, $p = .094$). No significant correlation coefficient with the phoneme-discrimination on the word level was found for the category of meaningful sentences without cues, either ($r = .049$, $p = .843$). In contrast, a significant correlation between phoneme-discrimination abilities on the word level and senseless sentences was found in the analysis ($r = .732$, $p < .01$).

3.4. Association between temporal processing and phoneme discrimination

According to the hypothesis of a causal relationship between temporal-processing and phoneme-discrimination, aphasic patients with phoneme-discrimination disabilities should display higher temporal-order thresholds than aphasic patients with unimpaired phoneme-discrimination abilities. Correlations between temporal-order thresholds and phoneme discrimination on the word and sentence level were, therefore, carried out to test for this association. Results are shown in Table 2. Marked coefficients (*) have a significance level of $p < .05$.

Table 2
Correlation coefficients between temporal-order thresholds and phoneme discrimination

	Tones	Clicks
Phoneme discrimination word level	**.517***	.266
Sentences including morphologic or syntactic cues	.123	.064
Meaningful sentences without cues	.182	.101
Senseless sentences	**.518***	.234

* $P<.05$.

As can be seen in Table 2, significant correlation coefficients were only found between two measurements of phoneme-discrimination abilities (phoneme discrimination on the word level and senseless sentences) and temporal-order measurements obtained with tones. Temporal-order thresholds obtained with clicks showed no significant correlations with phoneme-discrimination measures.

4. Discussion

4.1. Temporal processing

This study was designed to investigate temporal-processing mechanisms and phoneme-discrimination abilities in patients with aphasia. Temporal-order thresholds were obtained using two procedures with different stimuli (clicks and tones). A group comparison between healthy subjects and aphasic patients revealed significant differences for both measurement procedures. Patients with aphasia displayed higher temporal-order thresholds than the control subjects for measurements with clicks and with tones. This result confirms the findings of previous studies showing higher temporal-order thresholds in patients with aphasia (Carmon & Nachshon, 1971; Efron, 1963; Swisher & Hirsh, 1972; Wittmann et al., 2004).

Interestingly, results varied with the different measurement methods. Temporal-order thresholds obtained with pairs of tones were significantly ($z = -2.017$, $p = .044$) higher than those obtained using clicks among the aphasic patients. The different characteristics of temporal-processing abilities appear to depend on the type of stimuli offered, as pairs of clicks are processed very differently than pairs of tones with different frequencies. Results from single-neuron-activity recording in animals provide interesting indications for processing frequency-modulated sounds. Results indicate that there exist neurons in the posterior auditory cortex which are selective for the direction of frequency-modulated sounds (McKenna, Weinberger, & Diamond, 1989; Rauschecker, 1998; Tian & Rauschecker, 1998; Tian & Rauschecker, 2004). Assuming neurons selective for the direction of frequency modulations provides a possible explanation for the dissociation of temporal-order thresholds obtained with different kinds of stimuli in the present investigation. The two tones are integrated into one percept with different spectral patterns (high-to-low; low-to-high). Therefore, the temporal order of the two stimuli can be reconstructed from the direction of the frequency-modulated sounds. As the two clicks are not integrated into one percept when the ISI is larger than 3–5 ms, it is hypothesized that different kinds of temporal-processing mechanisms are activated by the two types of stimuli (Fink, 2004; Fink et al., 2005). For the click stimuli a temporal-processing mechanism is assumed, that is involved in the detection of temporal order independent of modality and stimulus type (Pöppel, 1997). The temporal order of the two tones, in contrast, can be reconstructed from the direction of the frequency-modulated sounds without involvement of a central timing mechanism and, therefore, also without its temporal limitations.

4.2. Phoneme discrimination

4.2.1. Word level

All subjects were tested for their ability to discriminate between the words /danken/ and /tanken/. Psychometric functions describing the discrimination performance depending on the VOT were calculated for each subject and compared between the two groups. The results show that there is no significant difference between the groups in the category boundary. However, patients with aphasia displayed a more variable response pattern resulting in higher lapsing rates. This means that they often misclassified unambiguous stimuli. This result replicates findings of phoneme-discrimination deficits in patients with aphasia (Blumstein, Baker, & Goodglass, 1977).

4.2.2. Sentence level

Phoneme-discrimination abilities on the sentence level were assessed using a newly developed measurement procedure (*T-M-D-S*) employing three different categories of sentences:

Category I: sentences including morphologic or syntactic cues.
Category II: meaningful sentences without cues.
Category III: senseless sentences.

Group comparisons between patients with aphasia and controls in this test showed no significant differences in the first category. In contrast, significant differences were found between the two groups in the second and third category. According to the temporal-processing hypothesis, a general temporal-processing deficit is assumed to be the underlying cause of phonemic deficits in individuals with language disorders (von Steinbüchel & Pöppel, 1993). This hypothesis is based on the theory of bottom–up processing of the speech signal. Therefore, phoneme discrimination was tested with isolated words, and two categories of sentences (categories II and III) that require primarily bottom–up processing. In habitual language use, however, bottom–up processing is complemented by top–down processes. As described earlier, studies have demonstrated the influence of lexical and contextual information on phoneme categorization in both healthy subjects and patients with aphasia (e.g., Baum, 2001; Ganong, 1980). The category of sentences including morphologic or syntactic cues was therefore created to facilitate top–down feedback during phonemic processing.

To investigate the influence of top–down feedback on phonemic processing, the phoneme-discrimination abilities on the word level were correlated with performance on the sentence level. The patients with aphasia revealed no significant correlations between phonemic processing on the word level and in the category of sentences including morphologic or syntactic cues. This result is in favor of the theory that phonemic processing is influenced by feedback from higher levels of processing, as in interactive theories of recognition (e.g., Samuel, 1981). It further supports the assumption that patients with aphasia tested in this study could compensate for their deficit, as those patients with phoneme-discrimination deficits on the word level showed unimpaired performance on the sentence level.

In the second category of sentences we assumed that phoneme-discrimination deficits in patients with aphasia may lead to more errors because an analysis of the acoustic–phonetic structure of the speech signal is required to decode the target phonemes. However, no significant correlation between phoneme-discrimination abilities on the word level and this sentence category was detected. The reason for this unexpected finding could be the naturalness of the sentences. In natural speech, the signal contains multiple and redundant cues for feature distinctions. Stop consonants in natural speech, for example, not only differ in their voice-onset time, but also in the presence or absence of an aspiration, the length of the preceding vowel, and the frequency of the noise component (Bishop, 1997). As the stimuli in the phoneme-discrimination test on the word level were artificially constructed, they only differed in voice-onset time. Thus, it is possible that the dissociation between phoneme-discrimination on the word and sentence level was influenced by the number of cues available to classify the phonemes. Additionally, it has to be mentioned, that the provided semantic context can be used to narrow down the number of adequate phonemes. For the phoneme-discrimination process itself, however, the semantic context of our sentence category provided no additional cue.

For the category of senseless sentences, significant correlations with phoneme-discrimination abilities on the word level were found in the analysis. Neither morphologic nor syntactic cues that facilitate decoding of the target phoneme were provided in this third category. Moreover, no contextual information was presented, as the words within the sentences were semantically incoherent. Therefore, to be able to correctly classify the target phoneme, a purely bottom–up analysis of the speech signal was required. Although the sentences contained more acoustic–phonetic features than the isolated words, the results in this third category of sentences indicate that the additional information does not help aphasic patients to correctly identify the target phonemes within senseless sentences. In this category, the other words in the sentence just function as distracting features with no reference to the target word. Therefore, the identification of the target word in this third category is aggravated as compared to the second category of sentences.

To sum up, the results indicate that patients with aphasia tested in this study could compensate for possible phoneme-discrimination deficits by using the morphologic and syntactic cues presented. Moreover, phoneme-discrimination disabilities of patients with aphasia vary depending on the context. Our results emphasize the importance of top–down mechanisms when testing for language-processing deficits.

4.3. Association between temporal processing and phoneme discrimination

Correlations between phoneme discrimination on the word level and temporal-order thresholds only showed a moderate correlation coefficient for the tones condition. Temporal-order thresholds obtained with clicks showed no significant association with phoneme-discrimination abilities. Therefore, our results indicate that measurements with pairs of tones are more suitable to test the association with phoneme discrimination than measurements with pairs of clicks. This result could be due to the different physical properties of the stimuli. The pairs of tones presented in rapid succession generated frequency transitions and were, therefore, more similar to the physical properties of speech sounds.

Correlations between phoneme discrimination on the sentence level and temporal-order thresholds showed no significant coefficients for sentences including morphologic or syntactic cues. This result confirms the finding that phonemic processing is influenced by top–down feedback (Bowers & Davis, 2004; Ganong, 1980). Listeners can use the environmental context and their general knowledge to select the appropriate meaning.

No significant correlations with temporal-order thresholds were found for the second category of sentences, either. As discussed earlier, the results could have been influenced by the naturalness of the sentences. In the third category of senseless sentences, significant correlations were found only for temporal-order measurements with tones. We had found this individual correlation already for phoneme-discrimination abilities on the word level.

Addressing the question of identifying a feasible, reliable, and efficient measurement procedure to test for auditory temporal-order thresholds in patients with aphasia, the results of the present investigation confirm the assumption of stimulus-dependent processing of the temporal-order threshold, as has been shown for healthy subjects (Fink, 2004; Fink et al., 2005). Additionally, the stronger relationship between temporal-order thresholds obtained with tones and phoneme-discrimination abilities also exist in patients with aphasia, indicating that temporal-order measurement procedures with tones are more suitable to test for this association. Furthermore, the association between temporal processing and phoneme discrimination depends on the language test used. Our findings indicate that it is difficult to generalize results assessed with isolated syllables or words to complex language comprehension, as top–down processing mechanisms play an important role in habitual language use.

These results have further implications for training procedures. First, the finding of stimulus-dependent processing of temporal order implies that different training procedures have to be developed and tested for efficiency. Second, results of the phoneme-discrimination test on the sentence level showed that patients with aphasia can compensate for their phoneme-discrimination deficits under certain conditions. In contrast to conventional synthetic consonant–vowel syllables, natural language contains cues that facilitate the use of top–down processing strategies, as well as more acoustic–phonetic features for a bottom–up analysis of the auditory speech signal. However, impairments in patients with aphasia can be additive, which means that temporal-processing deficits can aggravate the disturbances on different linguistic levels (Divenyi & Robinson, 1989). Based on this assumption, temporal processing improved by training could also provide processing capacities that can be used for other linguistic analyses. However, it remains to be seen whether purely non-linguistic training can improve temporal-processing abilities in patients with aphasia and whether an improvement in language processing can be observed as well, as has been shown for dyslexic children by Kujala et al. (2001).

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