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Research Note

On the Use of the Distortion-Sensitivity Approach in Examining the Role of Linguistic Abilities in Speech Understanding in Noise

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Purpose: Researchers have used the distortion-sensitivity approach in the psychoacoustical domain to investigate the role of auditory processing abilities in speech perception in noise (van Schijndel, Houtgast, & Festen, 2001; Goverts & Houtgast, 2010). In this study, the authors examined the potential applicability of the distortion-sensitivity approach for investigating the role of linguistic abilities in speech understanding in noise.
Method: The authors applied the distortion-sensitivity approach by measuring the processing of visually presented masked text in a condition with manipulated syntactic, lexical, and semantic cues and while using the Text Reception Threshold (George et al., 2007; Kramer, Zekveld, & Houtgast, 2009; Zekveld, George, Kramer, Goverts, & Houtgast, 2007) method. Two groups that differed in linguistic abilities were studied: 13 native and 10 non-native speakers of Dutch, all typically hearing university students.
Results: As expected, the non-native subjects showed substantially reduced performance. The results of the distortion-sensitivity approach yielded differentiated results on the use of specific linguistic cues in the 2 groups.
Conclusion: The results show the potential value of the distortion-sensitivity approach in studying the role of linguistic abilities in speech understanding in noise of individuals with hearing impairment.

Key Words: linguistic abilities, speech in noise, distortion sensitivity

Reduced speech understanding in noise is a major complaint of individuals with hearing loss (e.g., Kramer, Kapteyn, & Festen, 1998). The main reason for this disability is reduced hearing capacity and auditory processing (e.g., Humes & Roberts, 1990). However, there is growing insight that auditory factors are only partly responsible for these problems (e.g., Stenfelt & Rönnberg, 2009). It has been shown that the ability to comprehend speech in challenging listening situations is influenced by both bottom-up auditory and top-down cognitive capacities (e.g., Pichora-Fuller, Schneider, & Daneman, 1995). The most relevant cognitive functions affecting speech comprehension are the speed of information processing, working memory, and the ability to use linguistic context (e.g., Akeroyd, 2008; Kramer, Zekveld, & Houtgast, 2009).

Various studies have demonstrated the importance of linguistic skills in speech understanding in noise (e.g., van Wijngaarden, Steeneken, & Houtgast, 2002; Cutler, Weber, Smits, & Cooper, 2004; Garcia Lecumberri & Cooke, 2006; Zekveld et al., 2007). For instance, van Wijngaarden and colleagues (2002) showed a reduced Speech Reception Threshold (SRT; Plomp & Mimpen, 1979) for non-native young listeners with typical hearing (up to 7 dB decrement) as compared with native listeners. Current literature (e.g., Cutler et al., 2004; Bradlow & Alexander, 2007; Cooke, Garcia Lecumberri, & Barker, 2008; Cutler, Garcia Lecumberri, & Cooke, 2008) discusses two explanations for this reduced non-native speech perception in adverse conditions: reduced processing of bottom-up signal cues or reduced exploitation of knowledge-driven information. Bradlow and Alexander (2007) found that non-native listeners require more

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signal clarity than do native listeners to exploit semantic–contextual information. They conclude that higher level support for bottom-up derived information is available to non-native listeners but in a less effective way than to native listeners. Their suggestion is that experience-dependent mistuning to linguistic structures ranging from subsegmental levels to the more abstract semantic, syntactic, and pragmatic levels might be a cause of this relative inefficiency.

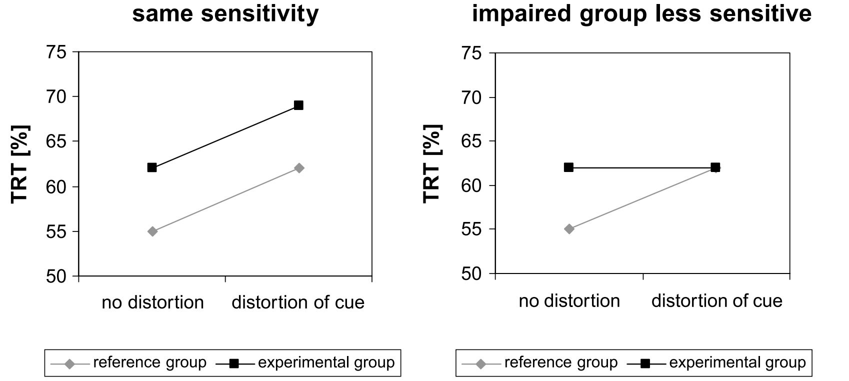
Quantifying the role of linguistic skills in speech understanding in noise is especially important in clinical audiological practice. Hearing impairment in early childhood can cause reduced morphosyntactic, phonological, and lexical knowledge and skills because of quantitatively and qualitatively reduced auditory input as well as reduced incidental learning (e.g., Delage & Tuller, 2007; McGuckian & Henry, 2007). Poor linguistic skills and knowledge—whether it is due to hearing loss or for some other reason—allow listeners with hearing impairment fewer resources for compensation of lack of auditory information (Rönnberg, 2003; Stenfelt & Rönnberg, 2009). Researchers in two studies (Dirks, Takayanagi, Moshfegh, Noffsinger, & Fausti, 2001; Tagayanaki, Dirks, & Moshfegh, 2002) investigated the effect of lexical factors on spoken word recognition in listeners with typical hearing and listeners with hearing impairment. The authors showed that speech recognition scores of the subjects with acquired hearing loss were determined not only by audibility but also by lexical difficulty.

In addition to lexical processing, other linguistic skills such as semantic and syntactic processing might be important in speech recognition of individuals with typical hearing and individuals with hearing impairment. Therefore, there is a need for a method that can identify the contribution of specific linguistic skills to speech understanding in noise. The purpose of the present study was to investigate whether it is possible to apply the distortion-sensitivity approach in this field.

The Distortion-Sensitivity Approach

The *distortion-sensitivity approach* has been used in the psychoacoustical domain to investigate the relative influence of coding of spectral, phase/temporal, and intensity information in speech reception in noise (Goverts & Houtgast, 2010; Houtgast & Festen, 2008; van Schijndel, Houtgast, & Festen, 2001). In the distortion-sensitivity approach, the subjects perform a task while perturbations of specific signal cues in the stimulus material are introduced. This can be illustrated in the results of van Schijndel et al. (2001), who studied speech intelligibility in listeners with hearing impairment and listeners with typical hearing. Acoustic signal cues in the domains of frequency, time, and intensity were distorted. To examine whether the reduced performance of the group with hearing impairment on the speech intelligibility test was related to a specific problem—for example, in the spectral domain—they measured performance as a function of the amount of spectral distortion. The basic assumption of the distortion-sensitivity approach in this example is that if the auditory system of the group with hearing loss does not make full use of spectral information, this group will be less sensitive to this distortion than will the reference group. This should lead to "convergence" in the distortion-sensitivity approach (basically, in accordance with Figure 1, right panel). Such a pattern of convergence was indeed observed by van Schijndel et al. The implication of convergence is that the reduced performance of the group with hearing loss on the original task is indeed related to a deficit in the processing of spectral information. If,

Figure 1. Illustration of the distortion-sensitivity approach, using artificial data. Performance of a group of subjects with hearing impairment as a function of distortion (experimental group; black) is compared with that of the reference group (gray). Two possible outcomes of such an experiment are indicated by "no convergence" (left panel) or "convergence" (right panel). TRT = Text Reception Threshold.



on the other hand, the effect of distorting the cue information in listeners with hearing impairment is found to be similar to that in the reference group (which, in fact, was the case for temporal information), this would suggest that such cues are processed as accurately in listeners with hearing impairment as in listeners with typical hearing. This would lead to "no convergence" in the distortion-sensitivity approach (see Figure 1, left panel).

In the distortion-sensitivity approach, performance on a specific task (e.g., a task that examines speech intelligibility) is investigated as a function of the amount of perturbation of a particular signal cue (e.g., the temporal information in the stimulus). Thus, this experimental method indicates whether this specific signal cue is actually processed during task performance. This concerns an advantage over the use of a correlation paradigm, which uses separate tests to measure the processing of this signal cue on the one hand and performance on this specific task on the other hand. Finding a correlation between signal-cue processing and task performance does not necessarily imply that the stimulus information in question is typically exploited while performing the task.

The Present Study

Although the distortion-sensitivity approach has been proven successful in the signal-driven domain, in this study we aimed to examine whether it can also be used in the psycholinguistic, knowledge-driven domain. More specifically, we investigated the use of the distortion-sensitivity approach to evaluate the relative influence of specific linguistic factors in speech understanding in adverse conditions. Introducing linguistic distortions in speech stimuli would require new recordings of the speech material—for example, for reasons of coarticulation—whereas these distortions can be applied in a straightforward manner to written text. Hence, we decided to use a visual text processing task instead of a speech perception task.

Speech understanding in noise is often quantified by the signal-to-noise ratio needed to reach 50% speech intelligibility, measured with the SRT method (Plomp & Mimpen, 1979). This method uses short everyday sentences as stimuli and speech-shaped noise as a masker. Recently, we developed a visual equivalent of this SRT method, the Text Reception Threshold (TRT) test (George et al., 2007; Kramer et al., 2009; Zekveld et al., 2007). In this TRT test, the same sentence material is used as in the SRT test, but the sentences are presented visually on a computer screen, adaptively masked by a bar pattern. The TRT score is the percentage of open space in the bar pattern needed to reproduce 50% of the sentences correctly. The aim of this method is to identify at least some of the relevant nonauditory factors in processing linguistic material while the auditory channel is bypassed.

In the present study, we looked for particular groups of subjects such that a large variance in linguistic skills was to be expected while keeping auditory factors and nonauditory, nonlinguistic factors globally constant. Therefore, we studied native and non-native typically hearing speakers of Dutch—all university students. Note that the results for listeners with various skill levels in Dutch serve merely as an illustration of how the distortion-sensitivity approach can be used in populations such as individuals with hearing loss.

In summary, the main question addressed in this research note is whether we can use the distortion-sensitivity approach to measure the role of specific nonauditory linguistic abilities in speech understanding in noise. Because we used the TRT method, a preliminary question to address is whether differences in linguistic competence lead to different performance on the TRT test, as they do on the SRT test. In other words, the question to be answered here is whether non-nativeness that is known to influence speech perception abilities (as reported by van Wijngaarden et al., 2002) also affects performance in the TRT test.

Method and Materials

Subjects

Participants were 13 university students with Dutch as their native language (M = 22 years of age; range = 20–25 years) and 10 university students (M = 29 years of age; range = 19–45 years) who learned Dutch as a second language in a university program for non-native speakers. All subjects had typical hearing (hearing thresholds not exceeding 15 dB HL at 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz). Native languages of the non-native speakers were Polish (2), Spanish (2), Russian (2), Servo Croatic (2), Hungarian (1), and Bengal (1). The non-native speakers were selected to have reached the highest finishing levels (3 or 4) in the university course. Finishing Level 4 is needed to enter the state examination for Dutch as a second language.

Measurements and Stimuli

The SRT was measured in free field in a sound-insulated room according to the procedures described by Plomp and Mimpen (1979). The task for the subjects was to correctly repeat the acoustically presented sentences. The stationary noise level was kept constant, and the sentence level was varied adaptively using a step size of 2 dB. The SRT is defined as the signal-to-noise ratio at which 50% of the sentences are repeated correctly. The TRT was measured following the procedures described by Zekveld et al. (2007). The task for the subjects was to correctly repeat the visually presented sentences. The width of the bars masking the text was varied adaptively using a step size of 6%. The TRT is defined as the percentage of unmasked text required for correct reproduction of 50% of the sentences.

In both tests, lists consisting of 13 Dutch everyday short sentences were used as stimuli (Versfeld, Daalder, Festen, & Houtgast, 2000). Distortions of the linguistic cues were only introduced in the TRT test by manipulating the sentence material used in the TRT test in three domains: lexicon, semantics, and syntax (see Table 1). Distortions in the lexical domain were introduced by replacing one word in the sentence by a pseudoword (i.e., a nonsense word that is phonologically and morphologically correct in Dutch). Distortions in the semantic domain were introduced by replacing one word in the sentence with a word that was syntactically and morphologically correct but semantically incorrect. Distortions in the syntactic domain were introduced by randomizing word order of an existing sentence and distorting the congruence between subject and verb. It should be noted that an interaction between syntactic and semantic distortion could not be avoided in the syntactic distortion condition.

Procedure

Tests and conditions were presented in a fixed order because we were primarily interested in differences between the two groups. The order of the conditions was as follows: (a) undistorted TRT, (b) TRT with semantic distortion, (c) TRT with syntactic distortion, (d) TRT with lexical distortion, and (e) undistorted SRT in stationary noise. All TRT tests were administered four times; the SRT test was administered two times. Thus, all participants performed 18 tests in total. For each test, a new list of sentences was used.

Results

Table 2 shows the median, first, and third quartile of the SRT and the undistorted TRT as well as the TRT in the three distorted conditions. The sensitivity to the applied distortions was quantified by the *distortion-sensitivity (DS) value,* calculated as the difference between distorted TRT in a certain domain and the undistorted TRT in percentage points (pp). Table 2 gives these DS values for the three domains of distortion. Undistorted and distorted TRT values are graphically presented in Figure 2.

The data show a difference of about 8 dB in SRT between native (n1) and non-native (n2) listeners. Table 2 also reveals a difference of about 9% in the undistorted TRT values between these two listener groups. The significance of both differences was confirmed by a Mann–Whitney U test: SRT, U = 0, n1 = 13, n2 = 10 ($p < .001$); TRT, U = 0, n1 = 13, n2 = 10 ($p < .001$). These data show that evident differences in linguistic competence lead to differences in performance on both the SRT test and the TRT test.

The data in Table 2 and Figure 2 suggest that, as expected, the TRT of the reference group (native users of Dutch) was sensitive to the applied distortion in all three domains. For example, the median TRT score for lexical distortion (65.65) was higher than the median TRT score in the undistorted condition (56.20), yielding a positive median DS value (9.18). This means that in the condition with lexical distortion, compared with the undistorted condition, more open space between the masking bars was required for correct written text reproduction. This also held true for semantic and syntactic distortion (median DS value of 2.65 and 7.28, respectively). The trend in the data was confirmed by *t* tests of the DS values for each type of distortion where significant differences from zero ($p < .001$) were observed. The TRT of the non-native listeners was also significantly sensitive to the applied distortion in the three domains (*t* test, $p < .01$).

Table 1. Examples in English of the procedure to introduce linguistic distortions in the Text Reception Threshold (TRT) material.

Domain	Procedure	Example
Lexical	Replace one word by a pseudoword.	The blockade lasted for more than a week. **The blockade lasted for more than a greep.**
Semantic	Replace one word by an alternative with the same morphosyntactic properties.	They are drinking beer on the terrace. **They are drinking pony on the terrace.**
Syntactic	Randomize words and remove congruence between subject and verb.	There is nobody in the street almost. **Nobody there almost street in the are.**

Note. The experiments were done with Dutch text material. For each domain, the original sentence is given, as well as the manipulated sentence (which appears in boldfaced text).

Table 2. Data on the Speech Reception Threshold (SRT) and Text Reception Threshold (TRT) in the undistorted condition, the distorted TRT in three linguistic domains, and the distortion-sensitivity (DS) values for these domains.

		Undistorted condition		Distorted TRT			DS value		
Group	Statistic	SRT (dB)	TRT (%)	Lexical (%)	Semantic (%)	Syntactic (%)	Lexical (pp)	Semantic (pp)	Syntactic (pp)
Native	Median	−4.40	56.20	65.65	58.28	63.45	9.18	2.65	7.28
	1st quartile	−4.80	55.30	63.45	57.73	62.10	7.95	1.25	5.88
	3rd quartile	−4.20	56.50	66.48	59.65	64.80	10.48	3.45	9.08
Non-native	Median	4.10	65.20	68.11	67.01	66.73	3.74	1.94	2.76
	1st quartile	1.70	62.35	66.48	63.25	65.78	2.49	1.36	0.29
	3rd quartile	5.65	67.53	72.18	69.93	69.14	6.30	2.39	4.57

Note. The *SRT* is defined as the signal-to noise ratio at which 50% of the sentences are repeated correctly. The *TRT* is defined as the percentage of open space between the masking bar pattern required for correct reproduction of 50% of the sentences. The *DS value* is the difference (in percentage points [pp]) between the TRT in the distorted and undistorted condition.

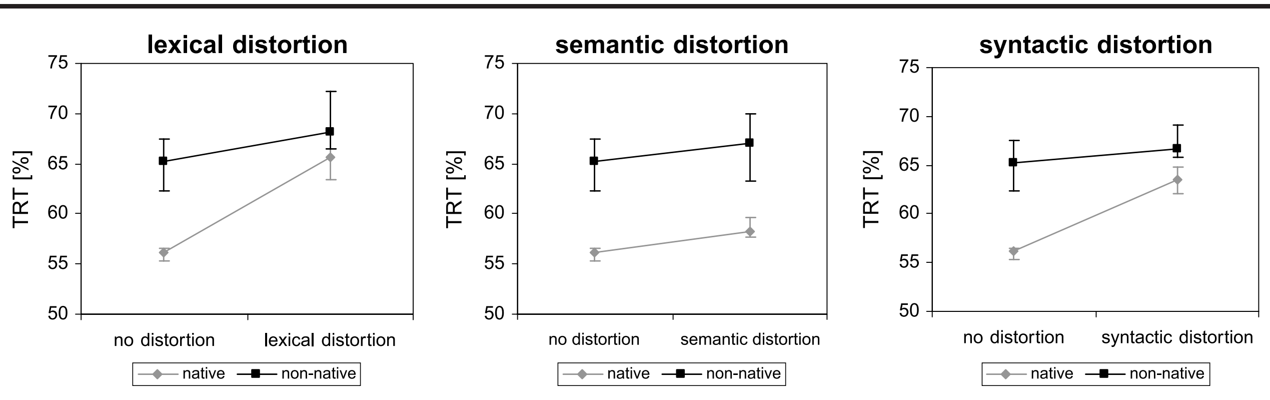
The normal distribution of the DS values for both groups was confirmed by a Kolmogorov–Smirnov test.

Figure 2 shows that the TRT results of the non-native group tended to converge with the reference results for distortion of syntax and lexicon but not for distortion of semantics. These trends in the data were confirmed by Mann–Whitney U tests on the calculated DS values: lexicon, U = 22, n1 = 13, n2 = 10 ($p < .01$); syntax, U = 16, n1 = 13, n2 = 10 ($p < .01$); semantics, U = 48, n1 = 13, n2 = 10 ($p = .313$).

Discussion and Conclusion

The main aim of this study was to examine whether we can use the distortion-sensitivity approach for measuring the role of specific nonauditory linguistic aspects in speech understanding in noise. Because of our choice to use the TRT test as a visual proxy of a speech processing task, we first examined whether differences in linguistic competence lead to differential performance on the TRT test as they do on the SRT test. We studied the processing of distorted sentences in auditory and visual presentation mode by native and non-native speakers of Dutch who had normal hearing and studied at a university. As noted before, by defining these two study groups, we introduced variance in the skills in the linguistic domain while keeping auditory factors and nonauditory, nonlinguistic factors—such as speed of information processing—essentially constant. The results showed a reduced performance on the SRT test and the TRT test in the non-native group. This means that in both presentation modes (auditory and visual), the non-native speaking students were affected more by masking in repeating the sentences correctly. Hence, it can be concluded that variance in linguistic competence leads to differential performance on the TRT test, as it does on the SRT test. The present SRT results are in line with

Figure 2. Median TRT data for the native (see gray diamonds) and non-native (see black squares) subjects. The *TRT* is defined as the percentage of open space between the bars in the masking pattern required for correct reproduction of 50% of the sentences. Error bars represent the interquartile ranges. Left panel: Distortion of lexical information. Middle panel: Distortion of semantic information. Right panel: distortion of syntactic information.



previous findings of van Wijngaarden et al. (2002). Comparing the current results with those of Zekveld et al. (2007) and George et al.(2007), it is clear that familiarity of the language of the test items has a much larger effect on both TRT and SRT than do the factors of hearing impairment and age.

Having established that differences in linguistic skills indeed lead to differential performance on the TRT test, we can now address our main question of whether the distortion-sensitivity approach can be used to examine the role of specific linguistic skills in the TRT. The following results show that this is, indeed, the case.

- Syntactic, lexical, and semantic sources of information are all used by native speakers of Dutch in visual text processing as examined by means of the TRT test. This is evident from the adverse effects of distorting the stimuli on each of these three linguistic dimensions.
- Of the three sources of linguistic information, only semantics is exploited as much by the non-native subjects as by the reference group. This is suggested by the fact that only in the semantic–distortion condition is their performance affected to the same extent as that of the reference group. The effects of lexical and syntactic distortions were much greater for the native participants than for the non-native participants. The non-native participants' decreased sensitivity to these distortions suggests poor abilities in these specific linguistic domains compared with the native participants.

A tentative conclusion is that in the group of non-native speakers of Dutch, reduced syntactic and lexical processing plays a role in their (reduced) performance on the undistorted TRT task. Apparently, lexical and syntactic knowledge and skills in Dutch are less well developed in the non-native speakers of Dutch than in native speakers. Consequently, the former are less sensitive than the latter to distortions in these two linguistic domains.

These results seem to contrast with those obtained by Golestani, Rosen, and Scott (2009). Using a paradigm with word pairs, they found that a semantically related target word facilitated the recognition of a preceding prime word presented in noise in native but not in non-native speakers. The authors hypothesized a retroactive priming effect in native speakers and semantic interference in non-native speakers. The difference seen with the current results may be due to the different ways in which semantic information was manipulated in their study and in ours. Golestani et al. investigated how the provision of additional semantic information (target words) influences perception of a previously presented prime word. In the distortion-sensitivity approach, the semantic cues that are typically available are distorted. In other words, the Golestani et al. study showed that non-native speakers did not benefit from additional semantic information in a word perception task, whereas this study showed that non-native speakers were hindered in sentence processing as much as native speakers when "regular" semantic information was distorted.

Because performance in both the SRT and TRT is influenced by non-nativeness (see Table 2), it is plausible to assume that the same linguistic aspects that influence the TRT also play a role in the SRT. Our findings contribute to the discussion on the mechanisms underlying the reduced speech understanding in noise of non-native listeners. The present results imply that reduced speech understanding in noise of non-native listeners is at least partly caused by reduced exploitation of knowledge-driven information—to be more specific, of linguistic structures at the lexical and syntactic level, as was suggested by Bradlow and Alexander (2007). The contribution of linguistic skills to speech understanding in noise can be confirmed by application of the present linguistic distortions to the speech stimuli of the SRT. Comparing distortion-sensitivity data for non-native listeners on text stimuli on the one hand and speech stimuli on the other hand might show an additional effect of reduced auditory processing (e.g., Bradlow & Alexander, 2007).

Potential Applications of the Distortion-Sensitivity Approach

As shown by the present data, the distortion-sensitivity approach can be used to examine the role of (specific) linguistic skills in the TRT and yields differentiated results. Hence, this study shows that the distortion-sensitivity approach can also be used in the knowledge-driven domain. Having established this for the non-native group in the current study, the distortion-sensitivity approach can now be used to study the role of linguistic abilities in speech understanding in noise for listeners with hearing impairment. Knowledge of which linguistic skills, in particular, are affected in individuals or groups with hearing impairment might help in the development of rehabilitation programs (e.g., Nippold, Mansfield, Billow, & Tomblin, 2009). Furthermore, an advantage of the distortion-sensitivity approach is that, given appropriate reference data, this approach enables the investigation of an individual subject regardless of whether specific cues are used in a relevant task. In clinical practice, such individual results can be used to give guidelines for rehabilitation programs—more specifically, what skills should be taught to listeners with hearing impairment.

In conclusion, it appears that the distortion-sensitivity approach is a useful tool in examining the role that linguistic abilities play in the reduced speech understanding in noise of listeners with hearing impairment.

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