Do we rely on good-enough processing in reading under auditory and visual noise?

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Abstract

Noise, as part of real-life communication flow, degrades the quality of linguistic input and affects language processing. According to predictions of the noisy-channel model, noise makes comprehenders rely more on word-level semantics and good-enough processing instead of actual syntactic relations. However, empirical evidence of such qualitative effect of noise on sentence processing is still lacking. For the first time, we investigated the qualitative effect of both auditory (three-talker babble) and visual (short idioms appearing next to target sentence on the screen) noise on sentence reading within one study in two eye-tracking experiments. In both of them, we used the same stimuli — unambiguous grammatical Russian sentences — and manipulated their semantic plausibility. Our findings suggest that although readers relied on good-enough processing in Russian, neither auditory nor visual noise qualitatively increased reliance on semantics in sentence comprehension. The only effect of noise was found in reading speed: only without noise, semantically implausible sentences were read slower than semantically plausible ones, as measured by both early and late eye-movement measures. These results do not support the predictions of the noisy-channel model. With regard to quantitative effects, we found a detrimental effect of auditory noise on overall comprehension accuracy, and an accelerating effect of visual noise on sentence processing without accuracy decrease.

Introduction

Within theory of communication, a noisy channel is considered an inevitable feature of a communication flow [1]. Noise can broadly be defined as any disturbance of the communication channel per se or any additional information that interferes with the target information (e.g., advertisement posts on a website, other talkers around, etc.). Noise can also be classified as internal (caused by aging, diseases, or brain damage) or external (produced by environmental conditions) [2]. External noise may have different modality (auditory, visual), matching or mismatching the modality of the target information under ongoing language processing. In this regard, a street background noise for people who are talking is a modality match, whereas a street background noise for a person who is reading a book is a modality mismatch. In the present study, noise refers to external linguistic information in auditory and visual modality that is presented simultaneously with target visual information.

Overall, previous studies reported a detrimental effect of both auditory and visual noise on reading fluency and comprehension, though their results varied. Eye-movement studies found longer fixations and a greater number of regressions under meaningful [3], [4],

[5] and meaningless background speech [6]; under non-linguistic visual noise such as certain font type or blurred script ([7], [8] in older adults only); and under linguistic visual noise with short phrases appearing on the screen together with target sentences [9]. Interestingly, the evidence for the influence of noise on reading comprehension was mixed across studies. Whereas visual noise studied in [9] did not impede readers' comprehension, auditory noise showed both detrimental and null effects on comprehension accuracy across studies. For example, the detrimental effect of auditory noise was found under background speech and music with lyrics that were in the same language as the reading task in [10] and under non-preferred background music in [11]). No effect of auditory noise was found when the noise was meaningful speech in native and foreign language in [5], under bar noise such as music and voices in [12] and [11]. Altogether, the findings across these studies suggest that a mismatch in noise and signal modalities might be more detrimental for reading comprehension compared to the match in modalities.

While the above studies demonstrated that noise quantitatively reduces reading comprehension accuracy [10], [11] and affects eye-movements (e.g., [3], [4], [5], [6], [7], [8], [9]), they did not address specific qualitative effects of noise on sentence processing such as a greater reliance on semantics that is expected according to the noisy-channel model (e.g., [13], [14], [15]). According to the model, under noise comprehenders are expected to process linguistic input superficially and rely on plausible semantic representations that are not necessarily syntactically accurate. This is to say, comprehenders are predicted to guess relations between words based on their meaning and rely on their real-world knowledge. Some evidence supporting this prediction was reported in [16], where visual noise led to a greater reliance on sentential context. Similarly, in [17] and [18], visual noise stimulated a greater reliance on word-level semantics.

Reliance on semantics during comprehension is also claimed within the good-enough sentence processing model (e.g., [19], [20]) suggesting that people do not always fully process linguistic input and can instead rely on their world knowledge and semantic relations between words. This proposal is supported by comprehension data from garden-path sentences such as *While Mary bathed the baby played in the crib* (e.g., [21], [22]), semantically implausible passive sentences like *The dog was bitten by the man* (e.g., [23], [24]) and semantically implausible active sentences like *A fox shot a poacher* [25]. As we see, good-enough processing is likely to occur when a comprehender is confronted with some difficulty (e.g., [19], [26]), among which syntactic ambiguity, complex syntactic structure and

semantic implausibility were widely studied. We propose that noise can be another source of processing difficulties that trigger reliance on good-enough processing.

The effects of noise can certainly depend on the specific type of noise. Previous studies on the influence of auditory noise on reading considered the following types of auditory noise: meaningful/meaningless speech [6], music with lyrics in a native or foreign language, as well as music without lyrics [10]. With regard to visual noise, most studies used modifications of the written target text such as blurred script [7], [8]. However, visual noise as additional input not overlapping with the target signal was used in previous research less often [9], so our study extends investigations of visual noise to this type. Importantly, auditory and visual noise have not been investigated earlier within the same experimental design, which is another novelty of our study.

To summarize, the present study aimed to test for the first time whether auditory (background babble) and visual (short phrases appearing next to the target sentence) linguistic noise increased reliance on good-enough sentence processing when reading. Our study reports two eye-tracking reading experiments run with the same stimuli but different types of noise (auditory or visual) in monolingual Russian adults. We expected to see the main effect of noise on fixation durations during sentence processing and on comprehension accuracy, as well as the interaction between noise and semantic plausibility predicted by the noisy-channel approach: under noise conditions, participants would rely more on good-enough processing than on syntactically-based processing.

To be more specific, we expected both quantitative and qualitative changes in reading under noise. With regard to quantitative effects, we supposed that both visual and auditory noise would increase the cognitive load and that the overall effect of noise on performance in noisy as compared to no-noise condition could be two-fold. On the one hand, participants could read sentences faster and make more comprehension errors in noisy conditions (i.e., the accelerating main effect of noise on reading time and detrimental effect of noise on comprehension accuracy). On the other hand, participants could read sentences slower (i.e., noise slows down reading speed) to compensate for the increased cognitive load and either succeed, thus making a similar number of comprehension errors in the noisy compared to no-noise condition, or still make more comprehension errors. Based on the results of the previous studies (e.g., [9], [10]), we expected that auditory noise would be more salient and harder to suppress due to the modality mismatch (reading vs. listening), which would decrease comprehension accuracy to a greater extent than visual noise.

Apart from quantitative changes, we also expected to find qualitative changes in sentence processing under noise. Previous studies on noisy channel (e.g., [15], [13], [14]) and good-enough sentence processing (e.g., [23], [24], [25]) showed a greater reliance on superficial semantic processing under noise and greater reliance on good-enough processing under processing difficulties. Based on these studies, we hypothesized that external auditory and visual noise would also increase reliance on good-enough processing in our experiments. We expected that the decrease in comprehension accuracy in semantically implausible sentences, reflecting reliance on semantic processing in comprehension, would be greater in noisy compared to no-noise conditions. However, if participants strategically slow down to counteract external noise and to be able to process sentences in noisy and no-noise conditions with comparable accuracy, we expected to observe that they would read semantically implausible sentences slower in noisy conditions and that the accuracy decrease in semantically implausible sentences would not be modulated by the presence of noise.

Experiment 1 (auditory noise)

Method

Participants

Seventy-one adult monolingual speakers of Russian (38 females; $M_{\text{age}} = 22$ years; $SD = 4.9$; range 20 - 40; mean years of education = 14, range 11-20) took part in the experiment with auditory noise. All participants reported normal or corrected-to-normal vision and hearing, and no history of neurological, psychiatric or language disorders. None but one participant had an educational background in Linguistics. All participants signed an informed consent form before participation. The study was carried out in accordance with the Declaration of Helsinki and the code of conduct of the American Psychological Association and was approved by the HSE Committee on Interuniversity Surveys and Ethical Assessment of Empirical Research.

Apparatus

Eye movements were recorded using the Eyelink 1000+ Desktop mount eye-tracker with a chin rest. Stimuli presentation was programmed in the Experiment Builder software (SR Research Ltd.). Sentences were presented in black font (Ubuntu Mono, 30 pt) on a light-grey background. Participants were seated 92 cm away from a 24" monitor with a 1920 x 1080 pix resolution.

Materials

Experimental items (N = 56) were unambiguous Russian sentences with a participial clause attached to one of the two nouns of the genitive noun phrase (NP). We manipulated the plausibility of the semantic match between the participial clause and attachment site (plausible / implausible). Syntactic attachment site of the participle to either the head noun (high attachment) or the dependent noun (low attachment) in the genitive NP was balanced across stimuli, and was unambiguously signaled by case inflection. Table 1 summarizes examples of conditions and comprehension questions. Conditions (1) and (2) were semantically plausible sentences where the participial clause followed the main clause with high and low syntactic attachment correspondingly. Conditions (3) and (4) were semantically implausible sentences where the participial clause also followed the main clause with high and low syntactic attachment correspondingly. Semantic plausibility of the stimuli was evaluated in a preliminary online norming study with 188 healthy monolingual participants. Based on the norming study, we selected participles that were rated as highly plausible with one of the nouns in a noun phrase and highly implausible with the other one (mean rating 4.52, range 3.82-5.00, or mean rating 1.44, range 1.03-2.00). All experimental sentences were followed by a binary-choice comprehension question targeting the attachment site of the participle.

Table 1. Example of an experimental item.

Semantic Plausibility	
Plausible	(1) <i>Дима работал с доктором президента, лечащим маленьких детей.</i> Dima worked with the doctor (Instr, masc) of the President (Gen, masc), *who treat-PART* (Instr, masc) small children.
	<i>Кто лечил маленьких детей? — Доктор / Президент</i> Who treated small children? — Doctor / President
	(2) <i>Дима работал с доктором президента, управляющего целой страной.</i> Dima worked with the doctor (Instr, masc) of the President (Gen, masc) , *who run-PART* (Gen, masc) an entire country.
	<i>Кто управлял целой страной? — Доктор / Президент</i> Who ran an entire country? — Doctor / President
Implausible	(3) <i>Дима работал с доктором президента, управляющим целой страной.</i> Dima worked with the doctor (Instr, masc) of the President (Gen, masc), *who run-PART* (Instr, masc) an entire country.
	<i>Кто управлял целой страной? — Доктор / Президент</i> Who ran an entire country? — Doctor / President
	(4) <i>Дима работал с доктором президента, лечащего маленьких детей.</i> Dima worked with the doctor (Instr, masc) of the President (Gen, masc) , *who treat-PART* (Gen, masc) small children.
	<i>Кто лечил маленьких детей? — Доктор / Президент</i> Who treated small children? — Doctor / President

There were three types of filler sentences (N = 128): 1) fillers imitating experimental sentences with high syntactic attachment; 2) fillers imitating experimental sentences with low syntactic attachment; 3) fillers with a different syntactic structure. Unlike in experimental sentences, questions after fillers targeted other sentence parts (for example, adjuncts, subjects, indirect objects, etc.) rather than the site of participle attachment.

The total number of experimental and filler items was equally divided into two sets to be used alternately in the noise and no-noise session. Each stimuli set contained 28 stimuli and 64 filler sentences. In each stimuli set, stimuli were balanced for the grammatical gender of the nouns in the genitive noun phrase: the nouns were feminine in one half of the stimuli and masculine in the other half. Additionally, the stimuli in the two sets were matched for the length of each noun and for the sentence length in syllables. In a Latin square design, four experimental lists for each stimuli set were created.

In the noise session in Experiment 1, stimuli were accompanied with auditory noise. The noise was a three-talker babble made of three popular Russian science podcasts that were merged and overlapped in the version 2.3.3.0 of Audacity(R) recording and editing software [27]. The podcasts covered the following topics: family, cinema and the Chukchi language (a sociolinguistic podcast about a minority language in Russia). In total, there were nine speakers, three of them were females. Any non-speech sounds (such as music, crackling, rustling) were removed from the podcast. All three tracks were overlapped in a single one with 37 minutes length, which was longer than the whole noise session.

The complete set of stimuli, noise, data, and analysis code are available online at the OSF project page <https://osf.io/6dy54/>, DOI 10.17605/OSF.IO/6DY54.

Procedure

The experiment began with a 9-point calibration and proceeded with instructions presented on the screen. The instruction was followed by five practice trials, after which the experimental trials began.

Each trial started with a drift correction (black fixation dot) at the position of the first letter in the sentence. Once the fixation was detected, a sentence appeared in full. If the fixation detection did not succeed, calibration was repeated. When participants finished reading a sentence and were ready to answer a comprehension question, they fixated the red dot in the lower right-hand corner of the screen. Once the eye tracker detected the fixation, a sentence was replaced by a comprehension question with two response options. The position

of the correct option on the screen was pseudorandomized. Participants answered a question by clicking on the selected option. After that, the next trial began.

Sentences were presented in a random order. The lists were assigned to participants pseudo-randomly. Each participant completed the experiment in two sessions: under noise and no-noise conditions. The order of the noise and no-noise session was balanced across the participants. The noise was presented continuously through headphones on the acoustic level of 50 dB during the entire noise session of the experiment, i.e., it accompanied both experimental sentences and comprehension questions. The whole procedure took approximately 50 minutes in total, including a fifteen minutes break between the sessions.

Analysis

Statistical data analysis included calculation of response accuracy and three eye-movement measures: First Fixation Duration (FFD; the only or first fixation on a word) and Gaze Duration (GD; sum of all fixations on a word before the first saccade leaving the word) as early measures, and Total reading Time (TT; sum of all fixations on a word including rereading after leaving the word and returning to it) as a late measure. Eye movement measures were analyzed in two critical regions: participle and the noun preceding it. The analysis was conducted with the R system for statistical computing [28] using lme4 package [29].

Response accuracy was analyzed using a generalized mixed-effects model. The model included plausibility (sum-contrast coded; with 1 for implausible condition), noise (sum-contrast coded; with 1 for noise session), and interaction between plausibility and noise. Random effects structure included random intercepts for participants and items. The full structure of the model was as follows: $accuracy \sim plausibility * noise + (1 | unique.item) + (1 | subject.id)$.

A separate linear mixed-effects model was run for each of the three eye-movement measures. Importantly, the models controlled word form frequency of the participle due to different case endings across conditions: *лечащим* ‘who treat-PART (Instr, masc)’ / *лечащего* ‘who treat-PART (Gen, masc)’ / *управляющим* ‘who run-PART (Instr, masc)’ / *управляющего* ‘who run-PART (Gen, masc)’ (see Table 1). Word form frequency measures were calculated based on the Russian National Corpus [30]. For the second critical region, controlling for word form frequency was not necessary because the noun preceding the participle had the same case form across conditions, e.g. *президента* ‘President (Gen, masc)’ in Table 1. Word length was controlled in the models for both regions.

Hence, the models with each eye-movement measure (log-transformed) as an outcome included plausibility (sum-contrast coded; with 1 for implausible condition), noise (sum-contrast coded; with 1 for noise condition), word length (centered), word frequency (centered, for the participle region only), and two two-way interactions (plausibility x noise, plausibility x accuracy). Random effects structure included random intercepts for participants and items. The full structure of the models was as follows: $\log(\text{eyetrackingmeasure_AOI}) \sim \text{plausibility} * \text{noise} + \text{plausibility:accuracy} + \text{length.centered} + \text{frequency.centered} + (1 | \text{unique.item}) + (1 | \text{subject.id})$.

Results

The overall response accuracy in fillers was 0.95 (by-participant range was 0.84-1.00), which indicated high engagement of participants in the experiment. Thus, no participants were excluded from the analysis. Means and standard deviations for response accuracy and basic eye-movement measures (FFD, GD, TT) are summarized in Table 2.

Table 2. Descriptive statistics of response accuracy and parameters of eye movements at the participle and the noun before the participle across conditions.

	Critical region	Accuracy M (SD)	FFD M (SD), ms	GD M (SD), ms	TT M (SD), ms
Plausible, no noise	Participle	0.74 (0.21)	211 (46)	475 (152)	1000 (575)
	Noun		226 (54)	409 (121)	844 (432)
Plausible, noise	Participle	0.72 (0.21)	245 (41)	415 (192)	1010 (559)
	Noun		237 (44)	321 (110)	928 (456)
Implausible, no noise	Participle	0.52 (0.28)	223 (48)	492 (167)	1168 (710)
	Noun		222 (58)	399 (104)	948 (506)
Implausible, noise	Participle	0.46 (0.27)	237 (40)	432 (202)	1161 (757)
	Noun		234 (37)	324 (96)	981 (514)

Response accuracy

First, response accuracy was lower in the implausible condition compared to the plausible one (Est. = -0.55, SE = 0.03, $z = -15.68$, $p < 0.001$). Second, response accuracy was lower in the noise session than the no-noise session (Est. = -0.09, SE = 0.03, $z = -2.51$, $p = 0.01$). Third, no interaction between plausibility and noise was found (Est. = -0.03, SE = 0.03, $z = -0.81$, $p = 0.42$). In other words, noise did not affect response accuracy in the plausible and implausible conditions differently. The detailed results of the model predictions are presented in Table 3.

Table 3. Parameter estimates for the generalized mixed-effects model for the response accuracy.

ACCURACY				
<i>Predictors</i>	<i>Estimate (Log-Odds)</i>	<i>SE</i>	<i>z value</i>	<i>p</i>
(Intercept)	0.48	0.07	7.29	<0.001
Plausibility	-0.55	0.03	-15.68	<0.001
Noise	-0.09	0.03	-2.51	0.012
Plausibility x Noise	-0.03	0.03	-0.81	0.415
Random Effects				
N _{unique.item}	56			
N _{subject.id}	71			
Observations	3950			
Marginal R ² / Conditional R ²	0.081 / 0.135			

Eye-movement measures at the participle

A series of mixed-effects models revealed that plausibility did not affect either early FFD and GD, or late TT fixation duration measures (all $ps > 0.05$), whereas noise did. We found that in the noise session, participles were read slower in FFD (Est. = 0.07, SE = 0.01, $t = 11.02$, $p < 0.001$) and faster in GD (Est. = -0.09, SE = 0.01, $t = -10.24$, $p < 0.001$). We also found the interaction between plausibility and noise in FFD (Est. = -0.02, SE = 0.01, $t = -2.75$, $p = 0.006$), which indicated that in the no-noise condition implausible sentences were processed slower than plausible (the result of the model with nested comparisons $\log(\text{FFD}) \sim \text{noise/plausibility} + (1 \mid \text{unique.item}) + (1 \mid \text{subject.id})$: Est. = 0.04, SE = 0.02, $t = 2.35$, $p = 0.02$). This interaction is also seen in Fig 1.

Fig 1. Interaction between noise and plausibility in FFD at the participle.

Importantly, there was an interaction between plausibility and accuracy in TT (Est. = 0.07, SE = 0.02, $t = 3.23$, $p = 0.001$): participles in implausible sentences were processed more slowly on trials with correct responses (the result of the model with nested comparisons $\log(\text{TT}) \sim \text{plausibility/accuracy} + (1 \mid \text{unique.item}) + (1 \mid \text{subject.id})$: Est. = 0.12, SE = 0.02, $t = 4.08$, $p < 0.001$). As expected, longer word forms were processed slower in GD and TT, and more frequent word forms were processed faster in GD and TT. The results of the model predictions are summarized in Table 4.

Table 4. Parameter estimates for mixed-effects models for eye-movements measures at the participle.

<i>Predictors</i>	FFD				GD				TT			
	<i>Est.</i>	<i>SE</i>	<i>t</i>	<i>p</i>	<i>Est.</i>	<i>SE</i>	<i>t</i>	<i>p</i>	<i>Est.</i>	<i>SE</i>	<i>t</i>	<i>p</i>
(Intercept)	5.36	0.02	228.91	<0.001	5.85	0.03	172.04	<0.001	6.53	0.06	101.47	<0.001
Plausibility	0.01	0.01	1.31	0.190	0.00	0.01	0.15	0.880	0.01	0.02	0.32	0.750
Noise	0.07	0.01	11.02	<0.001	-0.09	0.01	-10.24	<0.001	0.00	0.01	0.46	0.646
Plausibility x Noise	-0.02	0.01	-2.75	0.006	0.01	0.01	0.93	0.351	-0.00	0.01	-0.04	0.972
Plausibility x Accuracy	-0.02	0.01	-1.17	0.241	0.01	0.02	0.63	0.527	0.07	0.02	3.23	0.001
Word length	-0.01	0.00	-1.50	0.133	0.03	0.00	6.90	<0.001	0.04	0.01	8.80	<0.001
Word frequency	-0.01	0.01	-1.79	0.073	-0.03	0.01	-3.20	0.001	-0.02	0.01	-2.44	0.015
Random Effects												
N	56 _{unique.item}				56 _{unique.item}				56 _{unique.item}			
	71 _{subject.id}				71 _{subject.id}				71 _{subject.id}			
Observations	3827				3852				3872			
Marginal R ² / Conditional R ²	0.031 / 0.176				0.039 / 0.220				0.022 / 0.428			

Eye-movement measures on the noun before the participle

Similarly to the participle region, plausibility itself did not affect either early FFD and GD, or late TT fixation duration on the noun preceding the participle (all $ps > 0.05$), whereas noise did. In the noise session, the noun before the participle was read slower in FFD (Est. = 0.05, SE = 0.01, $t = 7.18$, $p < 0.001$) and TT (Est. = 0.03, SE = 0.01, $t = 3.28$, $p < 0.001$), but faster in GD (Est. = -0.13, SE = 0.01, $t = -16.76$, $p < 0.001$). We found the interaction between plausibility and noise in TT (Est. = -0.02, SE = 0.01, $t = -2$, $p = 0.045$), which indicated that in the no-noise condition implausible sentences were processed slower than plausible (the result of the model with nested comparisons: Est. = 0.11, SE = 0.02, $t = 4.08$, $p < 0.001$). Similarly, there was an interaction between plausibility and accuracy in TT (Est. = 0.06, SE = 0.02, $t = 2.59$, $p = 0.01$): nouns before the participle in implausible sentences were processed more slowly, but only on trials with correct responses (the result of the model with nested comparisons: Est. = 0.07, SE = 0.03, $t = 2.33$, $p = 0.02$). As expected, longer word forms were processed slower in GD and TT. The results of the model predictions are provided in Table 5.

Table 5. Parameter estimates for mixed-effects models for eye-movements measures at the region before the participle.

<i>Predictors</i>	FFD				GD				TT			
	<i>Est.</i>	<i>SE</i>	<i>t</i>	<i>p</i>	<i>Est.</i>	<i>SE</i>	<i>t</i>	<i>p</i>	<i>Est.</i>	<i>SE</i>	<i>t</i>	<i>p</i>
(Intercept)	5.32	0.02	239.85	<0.001	5.72	0.03	174.75	<0.001	6.52	0.06	115.06	<0.001
Plausibility	0.01	0.01	0.95	0.343	-0.01	0.01	-1.01	0.311	0.00	0.02	0.08	0.940
Noise	0.05	0.01	7.18	<0.001	-0.13	0.01	-16.76	<0.001	0.03	0.01	3.28	0.001
Plausibility x Noise	0.00	0.01	0.52	0.600	0.01	0.01	0.81	0.416	-0.02	0.01	-2.00	0.045
Plausibility x Accuracy	-0.02	0.02	-1.29	0.198	0.02	0.02	1.29	0.197	0.06	0.02	2.59	0.010
Word length	-0.00	0.01	-0.36	0.719	0.04	0.01	3.53	<0.001	0.05	0.01	5.60	<0.001
Random Effects												
N	56 _{unique.item}				56 _{unique.item}				56 _{unique.item}			
	71 _{subject.id}				71 _{subject.id}				71 _{subject.id}			
Observations	3771				3820				3840			
Marginal R ² / Conditional R ²	0.013 / 0.137				0.072 / 0.284				0.027 / 0.397			

Interim discussion

In Experiment 1 with auditory noise, we found lower comprehension accuracy in implausible than plausible sentences, which indicates a reliance on semantic relations between words more than on syntactic relations and is a sign of good-enough sentence processing during reading. The eye-movement data showed that the duration of online processing of the participle and the preceding noun did not differ in plausible and implausible sentences, when pooling over trials with both accurate and inaccurate comprehension. We suppose that, in general, participants processed implausible sentences fast and superficially, as predicted by the good-enough processing model, without allocating extra processing time to process the semantic implausibility [19]. At the same time, correctly interpreted implausible sentences were read more slowly at both the participle and the preceding noun compared to incorrectly interpreted implausible trials, meaning that shallow good-enough processing is associated with faster reading speed.

We also observed a quantitative effect of auditory noise on overall sentence processing and comprehension. With regard to comprehension, overall accuracy decreased in noise compared to the no-noise condition. With regard to online sentence processing based on eye-movement data, initial lexical processing (shown in FFD increase) of both participle and the preceding noun was impeded in noise. In turn, the syntactic integration [31] of both words (shown in GD decrease) was accelerated under noise. Finally, auditory noise made participants spend more time (shown in TT increase) on processing the noun before the participle. This may imply a general comprehension difficulty that probably led to overall accuracy decrease in noise.

Finally, we found evidence for a qualitative effect of auditory noise on online sentence processing, but not sentence comprehension. In accuracy, there was no interaction between plausibility and noise, so auditory noise did not increase reliance on good-enough processing in sentence comprehension. However, the eye-movement patterns revealed that participles in implausible sentences were initially processed longer (as measured by FFD) than in plausible sentences in the no-noise condition. Similarly, the preceding nouns were processed longer (as measured by TT) in implausible than plausible sentences in the no-noise condition. Hence, participants possibly slowed down in more challenging implausible sentences but only without external noise. However, the slow-down did not result in accuracy increase for implausible sentences in the no-noise condition.

Experiment 2 (visual noise)

Experiment 2 replicated Experiment 1 in terms of stimuli and procedure with the only difference being the type of noise (visual), which in this case matched the modality of stimuli.

Method

Participants

Seventy adult Russian monolinguals (30 females; aged 20-40; $M_{\text{age}} = 23$ years; $SD = 5.5$; mean years of education = 14.5, range 11-22) took part in the experiment with visual noise. None of them participated in Experiment 1.

Apparatus and Materials

The apparatus and materials were identical to those in Experiment 1 with the exception for noise. The noise consisted of short Russian idioms and set phrases from 2 to 5 content words in length, for example *vagon i malen'kaya telezhka* (literally: *a carriage and a small trolley*, idiomatic: *bags and bags of something*), *delat' iz mukhi slona* (literally: *to make an elephant out of a fly*, idiomatic: *to make mountains out of molehills*) etc. In total, 400 frequent and well-known Russian idioms were selected. The complete list of idioms is available online at the OSF project page <https://osf.io/6dy54/>, DOI 10.17605/OSF.IO/6DY54.

Procedure

The experimental procedure was similar to Experiment 1. However, instead of auditory noise, visual noise accompanied the presentation of experimental sentences (but not comprehension questions). For each experimental sentence, 3-4 randomly chosen idioms appeared consecutively at random positions on the screen around the experimental sentence and remained for 300-400 ms each. Visual noise never overlapped with the experimental sentence. A demonstration of a trial with visual noise is provided below in Fig 2.

Fig 2. An experimental trial with visual noise.

Analysis and Results

Statistical data analysis was identical to Experiment 1. The overall response accuracy in fillers was 0.95 (by-participant range was 0.88-1.00). No participants were excluded from the analysis. Means and standard deviations for response accuracy and eye-movement measures (FFD, GD, TT) are summarized in Table 6.

Table 6. Descriptive statistics of response accuracy and parameters of eye movements at the participle and the noun before the participle across conditions.

	Critical region	Accuracy M (SD)	FFD M (SD), ms	GD M (SD), ms	TT M (SD), ms
Plausible, no noise	Participle	0.73 (0.22)	254 (41)	440 (174)	913 (620)
	Noun		244 (48)	323 (104)	777 (437)
Plausible, noise	Participle	0.75 (0.23)	243 (41)	411 (179)	833 (595)
	Noun		243 (45)	315 (119)	728 (425)
Implausible, no noise	Participle	0.43 (0.26)	251(39)	446 (187)	977 (694)
	Noun		241 (44)	323 (108)	846 (502)
Implausible, noise	Participle	0.42 (30)	250 (42)	427 (191)	944 (766)
	Noun		247 (48)	325 (116)	826 (704)

Response accuracy

Statistical analysis of response accuracy with a generalized mixed-effects model revealed lower response accuracy in implausible sentences (Est. = -0.72, SE = 0.03, $z = -21.00$, $p < 0.001$). However, neither noise nor its interaction with plausibility affected response accuracy. The detailed results of the model predictions are presented in Table 7.

Table 7. Parameter estimates for the generalized mixed-effects model for the response accuracy.

ACCURACY				
<i>Predictors</i>	<i>Estimates (Log-Odds)</i>	<i>SE</i>	<i>z</i>	<i>p</i>
(Intercept)	0.41	0.07	5.86	<0.001

Plausibility	-0.72	0.03	-21.00	<0.001
Noise	0.03	0.03	0.96	0.336
Plausibility x Noise	-0.03	0.03	-1.01	0.311

Random Effects

N _{unique.item}	56
N _{subject.id}	70
Observations	4255
Marginal R ² / Conditional R ²	0.129 / 0.189

Eye-movement measures at the participle

Similarly to the Experiment 1, a series of mixed-effects models revealed that plausibility did not affect either early FFD and GD or late TT fixation duration measures (all $ps > 0.05$), whereas noise did, though not in the way expected. Surprisingly, in the noise condition, the critical participle was read faster in FFD (Est. = -0.01, SE = 0.01, $t = -1.96$, $p = 0.05$), GD (Est. = -0.03, SE = 0.01, $t = -4.16$, $p < 0.001$), and TT (Est. = -0.04, SE = 0.01, $t = -4.76$, $p < 0.001$). No interaction between noise and plausibility was found (all $ps > 0.05$). Importantly, there was an interaction between plausibility and accuracy in TT similar to the one in Experiment 1 (Est. = 0.07, SE = 0.02, $t = 3.41$, $p = 0.001$): participles in implausible sentences were processed more slowly, but only on trials with correct responses (the result of the model with nested comparisons $\log(TT) \sim \text{plausibility/accuracy} + (1 | \text{unique.item}) + (1 | \text{subject.id})$: Est. = 0.11, SE = 0.03, $t = 4.05$, $p < 0.001$). As expected, more frequent word forms were processed faster in all measures, and longer word forms were processed slower in GD and TT, though faster in FFD. The detailed results of the model predictions are summarized in Table 8.

Table 8. Parameter estimates for mixed-effects models for eye-movements measures on the participle.

<i>Predictors</i>	FFD				GD				TT			
	<i>Est.</i>	<i>SE</i>	<i>t</i>	<i>p</i>	<i>Est.</i>	<i>SE</i>	<i>t</i>	<i>p</i>	<i>Est.</i>	<i>SE</i>	<i>t</i>	<i>p</i>
(Intercept)	5.47	0.02	295.00	<0.001	5.79	0.04	134.02	<0.001	6.38	0.07	92.40	<0.001
Plausibility	0.01	0.01	1.54	0.123	-0.00	0.01	-0.07	0.944	-0.02	0.01	-1.17	0.241
Noise	-0.01	0.01	-1.96	0.050	-0.03	0.01	-4.16	<0.001	-0.04	0.01	-4.76	<0.001
Plausibility x Noise	0.01	0.01	1.65	0.099	0.00	0.01	0.12	0.905	0.01	0.01	1.19	0.233
Plausibility x Accuracy	-0.02	0.01	-1.30	0.194	0.02	0.02	0.92	0.359	0.07	0.02	3.41	0.001
Word length	-0.01	0.00	-2.79	0.005	0.03	0.00	7.11	<0.001	0.04	0.00	7.70	<0.001
Word frequency	-0.01	0.00	-3.05	0.002	-0.02	0.01	-3.29	0.001	-0.03	0.01	-3.34	0.001
Random Effects												
N	56 _{unique.item}				56 _{unique.item}				56 _{unique.item}			
	70 _{subject.id}				70 _{subject.id}				70 _{subject.id}			
Observations	4196				4200				4207			
Marginal R ² / Conditional R ²	0.007 / 0.140				0.018 / 0.334				0.018 / 0.511			

Eye-movement measures on the noun before the participle

Similarly to the participle region, plausibility did not affect either early FFD and GD, or late TT fixation duration measures on the noun preceding the participle (all $ps > 0.05$), while noise did. In the noise session, the noun before the participle was read faster in TT compared to the no-noise session (Est. = -0.03, SE= 0.01, $t = -3.13$, $p < 0.01$). There was no interaction neither between plausibility and noise, nor between plausibility and accuracy (all $ps > 0.05$). As expected, longer word forms were processed slower in both GD and TT. The results of the model predictions are presented in Table 9.

Table 9. Parameter estimates for mixed-effects models for eye-movements measures at the region before the participle.

<i>Predictors</i>	FFD				GD				TT			
	<i>Est.</i>	<i>SE</i>	<i>t</i>	<i>p</i>	<i>Est.</i>	<i>SE</i>	<i>t</i>	<i>p</i>	<i>Est.</i>	<i>SE</i>	<i>t</i>	<i>p</i>
(Intercept)	5.41	0.02	269.73	<0.001	5.59	0.03	167.85	<0.001	6.34	0.06	99.12	<0.001
Plausibility	0.02	0.01	1.68	0.093	0.02	0.01	1.41	0.158	0.01	0.01	0.75	0.452
Noise	0.01	0.01	1.19	0.234	-0.00	0.01	-0.24	0.811	-0.03	0.01	-3.13	0.002
Plausibility x Noise	0.00	0.01	0.78	0.438	0.01	0.01	1.88	0.061	-0.00	0.01	-0.23	0.814
Plausibility x Accuracy	-0.02	0.01	-1.24	0.216	-0.01	0.02	-0.88	0.380	0.02	0.02	1.11	0.268
Word length	0.01	0.00	1.06	0.287	0.04	0.01	6.32	<0.001	0.04	0.01	4.19	<0.001
Random Effects												
N	56 <small>unique.item</small>				56 <small>unique.item</small>				56 <small>unique.item</small>			
	70 <small>subject.id</small>				70 <small>subject.id</small>				70 <small>subject.id</small>			
Observations	4264				4273				4283			
Marginal R ² / Conditional R ²	0.002 / 0.145				0.026 / 0.273				0.014 / 0.478			

Interim discussion

In Experiment 2 with visual noise, we found the main effect of plausibility on comprehension accuracy, indicating that the participants misinterpreted semantically implausible sentences more often than plausible sentences, relying on good-enough sentence processing during reading. Together with the interaction between plausibility and accuracy in TT during reading the participle, this result suggests that reliance on semantic relations between words and good-enough processing enables faster processing than reliance on syntactic relations between words. These findings were fully in line with Experiment 1.

We found that visual noise accelerated reading of the participle (in FFD, GD, and TT) and of the preceding noun (in TT) compared with the no-noise condition but it did not affect the overall response accuracy. Possibly, the presence of visual noise made participants process sentences even more efficiently while interpreting them with comparable accuracy to the no-noise condition. Importantly, visual noise did not increase reliance on good-enough processing: there were no interactions between plausibility in noise neither in response accuracy nor in reading speed.

General Discussion

The present study aimed to find out whether auditory and visual noise increases reliance on good-enough processing during reading as predicted by the noisy-channel model [13], [14], [15]. Specifically, we conducted two eye-tracking experiments testing whether Russian adults would misinterpret implausible sentences more often in the presence of noise and whether noise would affect fixation durations during reading. Quantitatively, we found that auditory noise impaired comprehension accuracy and had both accelerating and decelerating effects on reading: participles and the preceding nouns were read slower in FFD (also in TT for nouns) but faster in GD. Visual noise, in turn, did not affect comprehension and accelerated reading of both the participle (in FFD, GD, and TT) and the preceding noun (in TT). Qualitatively, we discovered an effect of auditory noise on reading times. Without noise, the participle (in FFD) and the preceding noun (in TT) were read slower in semantically implausible than plausible sentences, although there was no such interaction in comprehension accuracy. On the contrary, visual noise did not have any qualitative effects neither on comprehension accuracy, nor on processing times. Thus, although we found evidence for good-enough sentence processing in Russian, we did not discover greater reliance on good-enough processing mechanisms under noise. We concluded that neither auditory (background babble) nor visual

(short phrases appearing next to the target sentence) noise increased reliance on semantic relations between words during reading, contrary to the predictions of the noisy-channel model.

The main effect of semantic plausibility in comprehension accuracy in both experiments indicates that Russian readers interpreted sentences according to their real-world knowledge and semantic relations between words instead of actual syntactic roles, which resulted in more comprehension errors in the implausible compared to plausible conditions. This result is in line with the predictions of the good-enough processing model [23], [24], [25]. Importantly, in both experiments, we observed that longer total reading time was associated with an accuracy increase only for implausible sentences. This differential effect for implausible and plausible sentences is predicted by the good-enough processing model [32] and indicates that good-enough semantically-based processing is faster than syntactically-based processing.

Auditory noise

In the experiment with auditory noise, we found a quantitative effect of auditory noise on both sentence comprehension and fixation durations, as well as a qualitative effect of noise on fixation durations. Quantitatively, the participants generally made more comprehension errors and exhibited processing difficulties (in longer FFD and TT, although shorter GD measures) under background babble. Qualitatively, their reliance on good-enough processing was not modulated by noise in the response accuracy measure. However, we found a qualitative effect of noise in fixation duration measures: the no-noise condition provoked longer FFD on the participle and longer TT on the preceding noun specifically for implausible compared to plausible sentences. This effect was not observed in the presence of noise.

The overall detrimental effect of noise on comprehension accuracy seen in our experiment was earlier observed in studies with background speech and music with lyrics [10] and with non-preferred music during reading [11]. However, some previous studies that used a babble of voices showed conflicting results. For example, Johansson and colleagues [11] did not find a significant difference in comprehension accuracy during reading under the café noise, nor did Vasilev and colleagues [5] who investigated the influence of native and foreign background speech on reading. The inconsistency of the findings across different studies with auditory noise and its effect on reading might be explained by different noise saliency, instructions and noise presentation. First, audible and clear sentences in [6] and a

homogenous café buzz in [11] differed from the noise in our study (the three-talker babble) that was more salient in terms of the number of speakers and overlapped speeches. Second, participants were instructed to ignore noise in [5], whereas in our study they were not specially instructed to do so. Finally, noise was presented via speakers in [11], while it was presented through the headphones in our experiments.

The general quantitative effect of noise on the eye-movements data in our study partially corresponds to some earlier findings of the studies investigating meaningful speech as auditory noise (e.g., slow-down effect on eye-movements in [3] and [4]). To remind, we observed a slow-down in initial lexical processing (shown in FFD) on both participle and the preceding noun and a slow-down in syntactic and semantic processing of nouns (shown in TT), as well as a speed-up in initial lexical processing and syntactic integration of both words (shown in GD). Similarly, studies of meaningful (e.g., [3], [4], [5]) and meaningless background speech [6] found an increased rereading time and more regressions under noise, which is comparable with an increased total reading time of the nouns in our experiment. We suppose that the overall pattern of fixation durations on the noun and the participle in the presence of noise indicates that the participants were distracted from the stimuli: they required more time for lexical access, then speeded up to pick up their normal word processing speed, but ultimately had to reread words. This online processing behaviour resulted in the increase in comprehension errors in the auditory noise condition. Possibly, the detrimental effect of auditory noise emerged because of the mismatch between the modality of stimuli and the modality of noise. At the same time, opposite to our findings, some studies reported no effect of noise on eye-movements: neither meaningful speech in [5], nor music or café noise in [11] affected eye-movements in their research. The inconsistency in the results between the studies can be explained, as mentioned above, by several factors such as noise type (music, non-music, native or foreign language), noise saliency, experiment instructions and noise presentation.

Most importantly, we did not find evidence for an increased reliance on good-enough processing under auditory noise. Noise had no qualitative effect on comprehension accuracy, meaning that readers showed comparable difference in response accuracy to questions after plausible and implausible sentences in no-noise and in noisy conditions. At the same time, we found that the participants read nouns and participles in plausible and implausible sentences differently under noisy and no-noise conditions. Without noise, readers processed critical words slower in implausible than in plausible sentences, but this effect disappeared in the presence of auditory noise possibly because the participants slowed down in plausible

sentences. In other words, our results might indicate that under noise, simpler semantically plausible sentences were processed as effortfully as more complex semantically implausible sentences. These results are unlike the findings in [4] where the syntactic complexity effect was not modulated by auditory noise.

Visual noise

Contrary to our expectations and unlike the auditory noise, visual noise did not show either a quantitative or a qualitative effect on comprehension accuracy. Our finding goes in line with the previous study on visual noise as short phrases appearing on the screen together with target sentences [9] where the authors also found no effect of noise on comprehension accuracy. Interestingly, our results on eye movements during reading under visual noise contradicted the findings by [9]. We found that in the presence of visual noise readers made shorter fixation than in the no-noise condition. In contrast, previous studies found longer fixations and a greater number of regressions under non-linguistic visual noise such as certain font types or blurred script ([7], [8] in older adults only), and under linguistic visual noise with short phrases appearing on the screen together with target sentences [9]. We suppose that the inconsistency between our results and the findings from some previous studies may be explained by noise saliency and the degree of distraction from the stimuli. In our experiment, visual distraction had rather low saliency and did not overlap with the target stimulus, so its quality was not degraded as with blurred script or certain font types [4], [5]. Thus, short idioms appearing for a short time on the screen around target sentences in our study could provoke readers to focus more on the target stimuli or even facilitated noise suppression due to modality match. Hence, this type of noise in our study accelerated processing, whereas more salient visual noise that was harder to suppress impaired it.

Finally, we found no increased reliance on good-enough processing in the presence of visual noise, as there was no interaction between plausibility and noise neither in comprehension accuracy nor in reading speed. This stands in conflict with previous findings by [16] where the authors reported greater reliance on sentential context in the presence of visual noise, as well as in [17], [18] where a greater reliance on word-level semantics was found. Possibly, the discrepancy is due to the saliency of noise in earlier studies as described above, or due to the modality match with target sentences in our study that facilitated noise suppression.

Limitations and Conclusions

We have to acknowledge several limitations of our study. First, auditory and visual noise was not matched in saliency that could explain their differential effect on reading. Thus, we cannot distinguish whether the facilitating main effect of visual noise on online sentence processing emerged due to insufficient saliency of our visual noise or due to the match between noise and signal modalities. Similarly, the detrimental main effect of auditory noise could emerge both due to its saliency compared to our visual noise and due to the mismatch between noise and signal modalities. Another experiment with a more salient visual noise or less salient auditory noise could shed light on this. Also, we suppose that stronger noise might provoke increased reliance on good-enough processing that was not found in our experiments.

Second, experimental stimuli used in this study cannot allow us to unambiguously interpret the decrease in accuracy in implausible sentences and the respective speed-up in total reading time in line with the good-enough processing model. In the absence of a neuter condition, this effect may also be attributed to the slow-down for correct responses rather than a speed-up for incorrect responses. We believe that comparing plausible and implausible conditions to the baseline for which semantic plausibility does not apply remains prospective for further investigation.

To summarize, we found evidence for the reliance on good-enough sentence processing during reading in Russian. Crucially, we did not find that reliance on good-enough processing increased under noise, contrary to the predictions of the noisy-channel model. Still, we discovered a qualitative effect of auditory noise as a slow-down of semantically implausible sentence processing without noise only, as measured in longer FFD on the participle and longer TT on the preceding noun. Our participants demonstrated different quantitative reading patterns under auditory and visual noise. In the presence of auditory noise, readers were distracted, they slowed down and made more comprehension errors. In visual noise, readers accelerated their processing without comprehension accuracy cost.

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