The effect of background speech on attentive sound processing: A pupil dilation study

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Abstract

Listening to task-irrelevant speech while performing a cognitive task can involuntarily deviate our attention and lead to decreases in performance. One explanation for the impairing effect of irrelevant speech is that semantic processing can consume attentional resources. In the present study, we tested this assumption by measuring performance in a non-linguistic attentional task while participants were exposed to meaningful (native) and non-meaningful (foreign) speech. Moreover, based on the tight relation between pupillometry and attentional processes, we also registered changes in pupil diameter size to quantify the effect of meaningfulness upon attentional allocation. To these aims, we recruited 41 native German speakers who had neither received formal instruction in French nor had extensive informal contact with this language. The focal task consisted of an auditory oddball task. Participants performed a duration discrimination task containing frequently repeated standard sounds and rarely presented deviant sounds while a story was read in German or (non-meaningful) French in the background. Our results revealed that, whereas effects of language meaningfulness on attention were not detectable at the behavioural level, participants' pupil dilated more in response to the sounds of the auditory task when background speech was played in non-meaningful French compared to German, independent of sound type. In line with the initial hypothesis, this suggested that semantic processing of the native language required attentional resources, which lead to fewer resources devoted to the processing of the sounds of the focal task. Our results highlight the potential of the pupil dilation response for the investigation of subtle cognitive processes that might not surface when only behaviour is measured.

Keywords

Pupillometry; irrelevant speech; auditory distraction; attention orienting; semantic; cognition

1. Introduction

In natural conditions, cognitive tasks are rarely performed in a fully quiet environment. Rather, our cognitive systems must deal with a fair amount of task-irrelevant acoustic signals that can alter our cognitive performance (for a review see Szalma & Hancock, 2011). Among these background signals, speech stands out as a unique stimulus because it conveys semantic meaning. Indeed, task-irrelevant speech has been consistently found to impair performance even when no linguistic processing is required by the cognitive task at hand, e.g., in serial recall tasks (Bell, Buchner, & Mund, 2008; Buchner, Irmen, & Erdfelder, 1996; Marsh & Jones, 2010; Salamé & Baddeley, 1982). One of the explanations of the effect of irrelevant speech upon serial recall is that the (linguistic) acoustic signal competes with the target task for attentional resources (e.g., Cowan, 1995; Page & Norris, 2003). However, two central questions remain unanswered. Firstly, it is not yet clear what in speech interferes with attention to the focal task. On the one hand, it is possible that speech interferes with attention due to its particular acoustic properties (e.g., Buchner et al., 1996). On the other hand, the interference might be semantic in nature (Vachon, Marsh, & Labonté, 2020). Secondly, as mentioned above, the interference of irrelevant speech has been mostly studied using memory (serial recall) tasks (e.g., Hanley & Broadbent, 1987; Salamé & Baddeley, 1982, 1987). However, if speech competes with a focal cognitive task for *attentional resources*, it is only logical to assume that it will also impair performance in an attentional task. To our knowledge, however, no previous study has tested the influence of irrelevant speech upon performance in a task directly measuring attention. The main aim of the present study was to test the assumption that speech meaningfulness automatically consumes attentional resources leading to decreases in performance in an auditory attentional task. Furthermore, we took a novel approach to the study of the irrelevant-speech effect by complementing our behavioural results with pupillometry, a technique that is increasingly used to estimate the allocation of cognitive resources to auditory processing (Eckstein, Guerra-Carrillo, Miller Singley, & Bunge, 2017; Marois & Vachon, 2018; Widmann, Schröger, & Wetzel, 2018). By using pupillometry, we intended to enrich the physiological study of the irrelevant speech effect while extending the body of evidence suggesting that pupil size is a reliable index of auditory attention (e.g., Zekveld et al., 2018).

Classically, the effect of irrelevant speech on (non-linguistic) cognitive performance is tested using visual serial recall tasks in which individuals are presented with lists of items (e.g., digits or letters) under different environmental conditions (i.e., in silence, while exposed to task-irrelevant speech, noise, etc.). Later on, participants are asked to remember the presented items. The rationale of this paradigm is that, if performance is worse when listening to speech as opposed to other environmental conditions, speech is interfering with memory performance (e.g., Buchner et al., 1996; Ellermeier & Zimmer, 1997; Elliot & Briganti, 2012; Salamé & Baddeley, 1990). As mentioned above, one of the central questions about the irrelevant-speech phenomenon is whether the nature of the cognitive interference it causes stems from its semanticity or “meaningfulness¹”. In this respect, existing data are not unequivocal. On the one hand, irrelevant speech has been found to disrupt cognitive performance independently of the listener’s familiarity with the irrelevant language in the background; in other words, in non-linguistic cognitive tasks such as serial recall, speech has been found to be detrimental for cognitive performance regardless of its meaningfulness (e.g., Buchner et al., 1996; Marsh & Jones, 2010). On the grounds of these results, proposals such as the interference-by-process hypothesis (e.g. Marsh, Hughes, & Jones, 2009) have put forth the idea that the effect of meaningfulness might only appear if the focal task itself requires some level of complex semantic processing such as reading or writing (Bell et al., 2008; Jones, Miles, & Page, 1990; Keus Van de Poll, Ljung, Odelius, & Sörqvist, 2014; Murphy, Bailey, Pearson, & Albert, 2018). On the other hand, an increasing number of studies has reported that the semantic content of background speech can prime or disrupt performance in tasks that are, in principle, not semantic in nature (Buchner, Rothermund, Wentura, & Mehl, 2004; Marois, Pozzi, & Vachon, 2020; Marsh, Ljung, et al., 2018; Marsh et al., 2017; Marsh, Yang, et al., 2018; Röer, Körner, Buchner, & Bell, 2017; Röer, Bell, Körner, & Buchner, 2019). However, a possible caveat of these previous studies is that most of them included classical focal cognitive tasks which involved the manipulation of digits and/or letters, a fact that casts doubt on their assumed non-linguistic nature. In fact, even if the recall of digits or numbers itself does not require higher semantic processing, these items are themselves semantic entities which involve some kind of linguistic activity (Vachon et al., 2020).

Therefore, part of the mixed results in the serial recall literature could be due to the different degrees of semantic activation elicited by different sets of to-be-ignored and to-be-

¹ Meaningfulness is understood here as the individual’s ability to understand the language, such that a type of speech that the person can understand would be categorized as meaningful (e.g., the native language), whereas any foreign unknown language or language manipulation that prevents access to the semantic content of speech would be deemed as meaningless (e.g., rotated or backward speech).

remembered items. In order to shed light on this aspect, the recent study by Vachon et al. (2020) included a series of experiments in which participants performed purely non-linguistic tasks (e.g., serial recall of dots or unfamiliar faces) while hearing a sequence of irrelevant meaningful sounds (e.g., letters, digits, etc.) interspersed with semantically deviant stimuli (e.g., a letter within a sequence of digits). Participants performed worse in the recall task when a semantic deviant appeared in the sound sequence. In contrast to the postulates of the interference-by-process hypothesis (Marsh et al., 2009), these results suggest that semantic content affects cognitive performance independently of the nature of the focal task because semantic stimuli are “forcefully” processed, therefore leading to attentional diversion (Vachon et al., 2020).

In view of the evidence mentioned above, it is worth to keep on exploring the effect on meaningfulness upon performance, at least for two main reasons. First, most evidence from the effect of meaningfulness in the irrelevant-speech effect comes from tasks which implied at least some minimal linguistic processing. In order to conclude on the effect of irrelevant speech upon cognitive performance in general, and not only on linguistic interference, more evidence is needed from purely non-linguistic tasks. Second, if we assume that the semantic content of irrelevant speech consumes attention resources causing attention diversion, the effect of meaningfulness should be seen upon attention itself, that is, upon performance in focal tasks measuring attention. As mentioned above, to our knowledge, no study yet has tested this assumption empirically.

Lastly, beyond behaviour, another way to contribute to the investigation of meaningfulness is to look at the physiological level. There is some previous EEG studies providing both direct and indirect proof that semantic information of masked or to-be-ignored sounds can affect electrophysiological activity without visible effects in performance (e.g., Holeckova, Fischer, Giard, Delpuech, & Morlet, 2006; Luck, Vogel, & Shapiro, 1996; Pérez, Carreiras, Gillon Dowens, & Duñabeitia, 2015). For instance, the EEG study by Pérez et al. (2015) measured brain oscillatory activity while participants performed a Go/No go task and listened to irrelevant speech in the background which was either in the native, a second or an unknown language. Whereas no differences in behavioural results were reported, the authors found differences between the conditions, such that synchronization in the theta band was larger in the native (meaningful) as opposed to the foreign (meaningless) condition. These results support the idea that the effects of semantic processing might be visible at the level of the brain, even when no behavioural effect is present.

To our knowledge, though, no previous study has directly tested the effect of meaningfulness of task-irrelevant speech using pupillometry, a technique whose potential to measure variations in mental activity cannot be underestimated. In fact, pupil size is modulated by several cognitive functions and has been related, for instance, to memory (Siegle, Steinhauer, Stenger, Konecky, & Carter, 2003), mental load (Just, Carpenter, & Miyake, 2003; Klingner, Tversky, & Hanrahan, 2011), effort in cognitive control (van der Wel & van Steenbergen, 2018), or to attention (Laeng, Sirois, & Gredebäck, 2012), and also particularly to the allocation of auditory attentional resources (see Eckstein et al., 2017, for a review).

At the physiological level, pupil size is under the influence of the autonomous nervous system, with the contribution of both the sympathetic and the parasympathetic pathways, and is mainly influenced by the activity of the locus coeruleus (LC), a brainstem nucleus which releases norepinephrine (NE) and has been shown to play a fundamental part in regulating mental activity (see Sara, 2009 for a review). The LC-NE system shows two functioning modes which are related to two different types of pupil activity. On the one hand, the tonic mode of the LC-NE system is assumed to modulate baseline pupil size (Aston-Jones & Cohen, 2005; Eldar, Cohen, & Niv, 2013; Jepma & Nieuwenhuis, 2011; Joshi, Li, Kalwani, & Gold, 2016; Murphy, O'Connell, O'Sullivan, Robertson, & Balsters, 2014) and reflects level of arousal or task engagement (Gilzenrat, Nieuwenhuis, Jepma, & Cohen, 2010; Hopstaken, van der Linden, Bakker, & Kompier, 2015). On the other hand, phasic activity in the LC-NE system is linked to the transient, event-related pupil dilation responses (PDR; Joshi et al., 2016; Mather, Clewett, Sakaki, & Harley, 2016; Murphy et al., 2014). Phasic LC activity has been ascribed a central role in the dynamic regulation of attention, such that it would enhance the processing of motivationally significant events through noradrenergic potentiation, acting hence as an attention filter (see for instance the "gain theory"; Aston-Jones & Cohen, 2005; Nieuwenhuis, Aston-Jones, & Cohen, 2005; Nieuwenhuis, De Geus, & Aston-Jones, 2011). Since this phasic activity of the LC-NE system influences the event-related PDR, the PDR can be used as an indirect measure of phasic LC-NE system activity, and hence as an index of attention allocation (Murphy et al., 2014; Qiuyan, Richer, Wagoner, & Beatty, 1985; Wetzell, Buttellmann, Schieler, & Widmann, 2016).

Based on this, pupil size measures are used increasingly within the field of auditory attention, and specially to investigate attentional capture. As opposed to the voluntary allocation of attention to goal- or task-related information, attentional capture refers to the fact

that task-irrelevant surrounding information can catch our attention in an involuntary fashion (Landau, Esterman, Robertson, Bentin, & Prinzmetal, 2007; Yantis & Jonides, 1990). In this line, multiple studies have reported an increase of phasic PDRs to unexpected oddball sounds as compared to expected or standard sounds (Bonmassar, Widmann, & Wetzell, 2020; Friedman, Hakerem, Sutton, & Fleiss, 1973; Marois & Vachon, 2018; Widmann et al., 2018). In addition, several studies have shown that subtle attentional capture effects that were not visible at the behavioural level were present in the form of pupil size changes (Marois et al., 2020; Marois & Vachon, 2018). Due to its sensitivity to involuntary attentional capture, pupillometry presents itself as a promising tool to measure attentional processes related to the perception of irrelevant speech.

This study and hypotheses

The main aim of this study was to measure the effect of meaningful as opposed to non-meaningful irrelevant speech upon a non-linguistic attentional task. Participants heard to-be-ignored speech in the background while performing a focal auditory oddball task while we measured their responses at the behavioural level via reaction times (RTs) and hit rates, and at the physiological level using pupillometry. The task-irrelevant speech was played either in their native language (meaningful condition) or in a foreign language (non-meaningful condition). Concerning our focal task, participants were presented with an auditory oddball discrimination task which allows to quantify voluntary attention and attentional capture (Berti, Grunwald, & Schröger, 2013; Berti & Schröger, 2001; Winkler, Denham, & Nelken, 2009). Specifically, participants listen to an auditory sequence of repeated standard sounds. Rarely and unexpectedly, a different (deviant) sound is introduced in the auditory sequence (Figure 1). Participants are instructed to discriminate if the sounds presented are long or short. The deviant sounds, although not relevant for the duration discrimination task itself, are still expected to capture attention (Schröger & Wolff, 1998).

Firstly, concerning our auditory oddball paradigm to measure attentional capture, we expected to replicate previous results in all our dimensions, such that we hypothesized prolonged RT (e.g., Wetzell, Widmann, Berti, & Schröger, 2006), reduced hit rates (e.g., Escera, Alho, Winkler, & Näätänen, 1998) and increased amplitudes of the PDR in response to deviant compared to standard sounds (e.g., Bonmassar et al., 2020; Marois & Vachon, 2018; Widmann et al., 2018).

Regarding our manipulation of meaningfulness, in terms of behaviour, we considered two possible outcomes based on previous results. On the one hand, if the semantic information of the to-be-ignored speech is processed (Röer et al., 2017; Röer et al., 2019; Vachon et al., 2020), we expected the meaningful speech to consume more attentional resources than the meaningless speech, resulting in reduced distraction effects in the German as opposed to the French condition. On the other hand, according to the interference-by-process hypothesis (Marsh et al., 2009), we considered the possibility that speech meaningfulness would not interfere with attentional capture. This would lead to equal distraction effects in the native and in the foreign language conditions.

Lastly, since pupil size has been shown to be a reliable (Eckstein et al., 2017) and highly sensitive (Marois et al., 2020; Marois & Vachon, 2018) index of the allocation of attentional resources, and if irrelevant speech processing requires attentional resources (Cowan, 1996; Page & Norris, 2003; Vachon et al., 2020), we expected reduced amplitudes of the PDR in response to the sounds of the focal task in the native language as opposed to the foreign language, indicating that attentional resources in the former condition were consumed by involuntary semantic processing. Following the same line of thought, we hypothesized that the effect of attentional capture at the level of the pupil (deviant-standard difference in PDR) would be reduced in the German compared to the French condition.

2. Materials and methods

2.1. Participants

Forty-four German native speakers were initially recruited for the study. One participant did not finish the recording because she was feeling unwell. Two more participants had to be excluded because they repeatedly fell asleep during the experiment, leading to behavioural performance at chance level (hit rate < 60%). Consequently, the data of forty-one participants (24 females; mean age = 27; SD = 6.8; range = 18 – 45 years) was used for analysis. Forty participants were right-handed, and one was left-handed, according to the German version of the Oldfield Scale (Oldfield, 1971).

We only included participants who had neither current knowledge of French nor previous educational contact with this language (school subject, language course, etc.), as reported by the participants themselves. The participants' education level varied, but our sample was mostly made up of undergraduate and graduate students. None of them had a

known history of developmental disorder, and they did not report cognitive impairments of any kind. Their hearing was normal, and their vision was either normal or corrected to normal. Participants gave written consent prior to experiment beginning and, in exchange for participating, they received a compensation in the form of money or credit points. The local ethical committee approved the experiment.

2.2. Stimuli and apparatus

Auditory oddball discrimination task

The stimuli consisted of 10 different animal sounds (cat meow, rooster crow, cow low, fly buzz, goat bleat, horse neigh, kitten purring, lion roar, raven caw, and sheep baa). Two additional animal sounds (seagull cry and elephant trumpet) were used for the training phase. The animal sounds had a duration of 200 ms (short) and 500 ms (long) and were equalized using root mean square (RMS).

Background task-irrelevant speech

The stimuli for the background speech were two short stories taken from a French-German bilingual book compiling contemporary German short stories (Nouvelles allemandes contemporaines - Deutsche heutige Kurzerzählungen Lemercier, 2003). One of the stories told about a male character who walks through a city wondering about his life, and the other spoke about the pawning of a watch and its recovery. We chose a foreign language (French) for our non-meaningful speech signal because of its higher ecological validity as opposed to manipulated speech signals (e.g. backward or rotated speech). The German text was read by a female native speaker of German, and the French text, by a female native speaker of French. Recordings were digitized at 44.1 kHz with a 32 bit quantization. In order to ensure similar loudness across stimuli, we equated them to identical RMS level as the oddball sounds (that is, the signal-to-noise ratio of oddball sound to background speech loudness was 0 dB). The audios were then cut in segments of approximately 145 s (or until sentence end) to block stimuli presentation.

Apparatus

The study was conducted in two labs. Auditory stimulation was sent via two loudspeakers (Bose Companion 2 series III Multimedia speaker system) placed at the left and the right side of a 53,5 cm x 30 cm computer screen. Stimuli were presented with an average

loudness of 67.5 dB SPL (measured with a Phonic PAA3 sound pressure meter from Phonic, Taiwan). We used Octave (Linux, Version 4.4) and Psychtoolbox (Version 3.0.15, Kleiner, Brainard, & Pelli, 2007) to present the stimuli. Response buttons were connected with a RT-Box which provided precise response time measurements (Li, Liang, Kleiner, & Lu, 2010).

In one of the labs, we used an infrared eye-tracker (EyeLink Portable Duo, SR Research Ltd., Mississauga, Ontario, Canada) to record the pupil diameter of both eyes. In the other lab, an EyeLink 1000 eye-tracker with chin and forehead rest (SR Research Ltd., Mississauga, Ontario, Canada) was used. Recording parameters were identical in both labs. The eye-tracker was used in remote mode. Sampling rate of the recording was set at 500 Hz. Distance from the subject's eyes to the eye-tracker was between 50 and 55 cm.

2.3. Task and procedure

The participants' task was to discriminate between long and short animal sounds and to press left (with the left thumb) or right (with the right thumb) in a button pad while native (German) or foreign (French) speech was presented (Figure 1). They were instructed to respond as fast and as accurate as possible and to focus on the discrimination task while trying to ignore the background speech. They were not given any information about the language of the background speech or its meaningfulness, that is, they were not informed that they would hear meaningful (German) and non-meaningful (French) speech in the background. Button press was counterbalanced across participants. For the whole experiment, gaze fixation point was a Lego face ($2.1^\circ \times 1.9^\circ$ visual angle) presented over a grey (RGB 88 88 88) background in the centre of the screen. While performing the task, participants sat comfortably on a chair in an acoustically shielded cabin. During the experiment, the cabin illuminance was of 39.25 lx, and the screen luminance, of 24.2 cd/m² (measured with a MAVOLUX 5032B USB; Gossen Foto- and Lichtmesstechnik GmbH, Nürnberg, Germany). The first block started with a nine-point eye-tracker calibration and validation procedure which was repeated every two blocks.

In order to ensure that participants could do the task, we included a short training block in which participants were exposed to the difference between the two sound durations. Specifically, we presented them with five long and five short trials (eight seagull sounds and two elephant sounds). The training phase was completed without any speech in the background. Participants made virtually no mistakes during the training. In any case before

proceeding, we directly asked if they understood the task, and only proceeded if this was the case.

For the main task, we grouped the animal sounds into five pairs (i.e., cat-rooster, cow-fly, goat-horse, kitten-frog, and raven-sheep). Presentation was blocked to keep trial duration acceptable (< 5 minutes; see below) and to allow participants to take breaks in between the blocks. The experiment consisted of 10 blocks, such that each sound pair was presented twice, i.e., once for every language condition. At each block beginning, participants saw in the screen a short text reminding how the left/right buttons were matched to the long/short sounds, and four practice stimuli (standard short, standard long, deviant short and deviant long) corresponding to the stimuli of the current block were presented once. Participants had to judge their duration and respond with the corresponding button. The fact that participants were already confronted with all types of sounds once in the block-specific instructions should not affect significantly the attention-grabbing power of the deviants, since it has been shown that distraction effects are constant even after the presentation of a few deviants (Wetzel, Widmann, & Scharf, 2021).

The order of the blocks (i.e., of the sound pairs) was randomized within language conditions. Although the order of sounds within the blocks was pseudorandomized according to our oddball manipulation (see below), presenting the same pairs of sounds for both languages allowed us to keep the difficulty of the discrimination task identical across conditions within participants. Participants could take as many breaks as desired in between the blocks.

Figure 1. Schematic representation of the beginning of a block in the auditory oddball discrimination task in the German (a) and in the French (b) conditions. In this case, the cat meow (lighter colour) would be the standard sound (80 % of total), whereas the rooster crow (darker colour) would be the deviant sound (20 % of total). The participants' task was to press the right button when the sound was long (500 ms), and the left button, when it was short (200 ms). The type of animal sound (in the example, cat meow or rooster crow) was not relevant for the task but the deviant (rooster crow) was expected to involuntarily capture attention causing distraction effects at the behavioural level (e.g., prolonged RTs) and increased pupil dilation. As shown in the upper part of the figure, the task-irrelevant speech was continuously playing in the background (English translation of the sentence in the example: "People passed by him, came towards him. He made sure they didn't touch him").

Each block consisted of 50 sounds, namely of 25 short and 25 long sounds. Within each block, we manipulated the frequency of occurrence of the sounds in the pair, such that 80 % of the sounds in a block (i.e., 40 sounds) were uttered by a specific animal (the standard; e.g., a cat), whilst the remaining 20 % (i.e., 10 sounds) were uttered by a different animal (the deviant; e.g., a rooster; see Figure 1). This resulted in the presentation of a total of 500

sounds: 200 standard sounds per language condition (total of 400 standards) and 50 deviant sounds per language condition (total of 100 deviants). According to previous literature, our stimuli number and proportions are sufficient for the achievement of an oddball effect in behaviour and in the pupil (Bonmassar et al., 2020; Wetzell et al., 2006, 2016). The order of stimuli was pseudorandomized per block and participant, such that the only condition to be fulfilled was that at least two standard stimuli preceded a deviant sound. The pseudorandomization was implemented to avoid that single events in the background speech could have a systematic effect upon performance in the discrimination task. Furthermore, in order to prevent effects of sound onset predictability, stimuli were equiprobably presented with five different stimulus onset asynchronies (SOAs): 2400, 2600, 2800, 3000, and 3200 ms. This was balanced within each block per sound type and duration. Each block had a duration of 4.67 minutes.

Finally, language condition was also blocked, such that participants completed the first five blocks with German (or French) in the background, and with French (or German), the other five blocks. This was done in order to avoid transfer effects between the languages. Language order was counterbalanced across participants.

2.4. Self-reported measures

After the task, we asked participants about their subjective perception of task difficulty; specifically, we asked if they found that the task was easier to complete in one or the other language condition, or if they perceived no difference between the languages.

In addition, in order to control for differences between our conditions due to the fact that participants understood German and not French, we also ran a free recall test in order to assess how much participants remembered from the stories. Naturally, this was only done for the German condition, since participants reported null comprehension of the French speech. Participants were directly asked how much they remembered. Responses were rated in a scale from 1 to 6 with the following steps: no details (1), 1 or 2 details (2), 3 to 4 details (3), 5 to 6 details (4), 7 to 8 details (5), and more than 9 details (6) remembered.

2.5. Pupil data processing

We used Marchak and Steinhauer's (2011) method for the calibration of the pupil diameter digital counts, which we subsequently converted to millimetres. In order to remove

blinks and saccades from the recording, we used the blink event marker provided by the eye-tracker and an additional tailor-programmed function targeted at detecting partial blinks from the smoothed velocity time series. Using the latter, we removed pupil changes in diameter exceeding 20 mm/s in an interval ranging from 50 ms before the blink to 100 ms after it (Merritt, Keegan, & Mercer, 1994). We computed the mean of the pupil diameter across both eyes interpolating data segments in one eye when only one of both eyes was closed (as suggested by Kret & Sjak-Shie, 2019).

Recordings were cut in epochs of 2000 ms (including a pre-stimulus baseline of 200 ms). Thereafter, we subtracted the mean amplitude of the pre-stimulus -200 to 0 ms baseline period from each epoch to implement baseline correction (Bonmassar et al., 2020; Merritt et al., 1994; Widmann et al., 2018). Lastly, we computed separate average pupil dilation responses (PDRs) per participant, sound type (deviant and standard) and language condition (German and French) from the mean of both eyes. PDRs were calculated for hit trials only in order to discard the involvement of error-related processes such as arousal increase after perceived errors. Also, we did not include trials where more than half of the epoch duration or the entire baseline duration for both eyes was not available. Data segments where data from both eyes were unavailable were excluded from averaging.

2.6. Data analysis

We excluded from the analysis the two first trials of each block due to the need of forming a rule before a sound can be considered as standard. We also removed the two standard sounds following a deviant to avoid a spill-over effect from the deviant to the standards (Bonmassar et al., 2020; Roeber, Widmann, & Schröger, 2003). This also ensures that enough time is given to the pupil to return to baseline after a deviant occurs (7200 ms, given our minimum SOA of 2400 ms). Participants' responses were considered for further analysis only if they responded in the time window from 300 ms to 2300 ms after sound onset.

The PDR amplitude was computed as the baseline-corrected mean pupil diameter in a 400 ms window centred on the mean peak latency computed across conditions (1076 ms). Trials without a response and with RTs faster than 100 ms were excluded from further analyses. Mean RTs were computed on hit trials only. Trials excluded from PDR analysis (see above) were also excluded from RT analysis and trials excluded from RT analysis (missing, fast, or incorrect response) were also excluded from PDR analysis. Table 1 presents the

number of trials excluded according to these criteria and the final amount of trials analysed per condition.

Table 1. Data exclusion and total amount of trials included in the analysis per language and sound type (Sta = Standard; Dev = Deviant)

		Condition	German		French	
		Sound type	Dev	Sta	Dev	Sta
Total trials			50	200	50	200
Excluded trials	First 2 trials per block and 2 standards after a deviant	Mean	-	105.4	-	105.2
		Median	-	105	-	105
		SD	-	2	-	1.9
		Min	-	100	-	101
		Max	-	109	-	108
	Pupil data artifacts	Mean	0.4	0.8	0.5	0.8
		Median	0	0	0	0
		SD	0.8	1.8	1.2	2.1
		Min	0	0	0	0
		Max	4	9	5	11
	No response in window	Mean	0.5	0.8	0.2	0.3
		Median	0	0	0	0
		SD	2.2	3.8	1.1	1.9
		Min	0	0	0	0
		Max	14	24	7	12
Valid trials	Mean	49.1	93.1	49.2	93.7	
	Median	50	94	50	94	
	SD	2.6	4.9	1.6	3.4	
	Min	34	66	43	81	
	Max	50	100	50	99	

Statistical analyses were performed in R 3.6.3 (R Core Team, 2017). We calculated separate two-way repeated measures Bayesian ANOVAs for each of our dependent variables, namely RT, hit rates and PDR, with sound type and language meaningfulness as independent variables. The levels of our fixed effects were standard and deviant for the sound type, and German and French for language meaningfulness. The Bayesian ANOVAs were implemented with the package *BayesFactor* (Morey & Rouder, 2018).

For informational purposes, we computed the corresponding classical frequentist repeated-measures ANOVAs with identical designs as the Bayesian ANOVAs. An alpha level of 0.05 was defined for frequentist statistical tests. Generalized eta square (η_g^2) as an estimate of effect size for repeated measures designs is reported (Olejnik & Algina, 2003).

For the Bayesian ANOVAs, we report Bayes factor (BF_{10}), where larger values suggest more evidence is provided by the data for model reflecting the alternative hypothesis or H_1 (and lower for model reflecting the null hypothesis or H_0). For interpretation, we followed the scale provided by Lee and Wagenmakers (2013), where BF_{10} values larger than 10 are considered as strong evidence in favour of the H_1 , and values between 3 and 10 can be interpreted as moderate evidence in the same direction. BF_{10} values lower than .33 or than .1 are considered as moderate or strong evidence in favour of H_0 , respectively. Finally, values ranging between .33 and 3 can be interpreted as weak or “anecdotal” evidence (Lee & Wagenmakers, 2013). We estimated BFs using 50 000 Monte-Carlo sampling iterations. Effect size of the priors for the fixed and the random effects were set to scaling factors of $r = .5$ and $r = 1$, respectively. Note that these values correspond to default *medium* effect size for the fixed effects and to *nuisance* values for the random effects, according to the *BayesFactor* package (Rouder, Morey, Speckman, & Province, 2012).

In addition, we evaluated main effects and interactions by comparing the models containing a main or interaction effect to the equivalent models stripped of the effect (Inclusion Bayes Factor based on matched models, reported as BF_{Incl} ; Mathôt, 2017).

3. Results

In the following subsections we first report our results for the RT, the hit rate and PDR measures. Table 2 offers a summary of the descriptive statistics for all dependent variables.

The last section briefly describes results on the self-reported measures of task difficulty and recall.

Table 2. Descriptive statistics for all dependent variables as a function of sound type (Sta = Standard; Dev = Deviant) and background language (German; French).

M = Mean; *SEM* = Standard error of the mean

Type/ Language	<i>M (SEM)</i>								
	RT in ms			Hit rate in %			PDR in mm		
	Dev	Sta	Dev-Sta	Dev	Sta	Dev-Sta	Dev	Sta	Dev-Sta
German	782 (17)	703 (14)	79 (7)	94.7 (1.0)	96.8 (.7)	-2.1 (.6)	.195 (.014)	.162 (.011)	.033 (.007)
French	768 (15)	697 (12)	71 (7)	95.9 (.7)	97.6 (.6)	-1.7 (.7)	.220 (.015)	.172 (.011)	.048 (.009)

PDR shows the average baseline-corrected pupil size in the time window of interest.

3.1. RT

Reaction times (RTs) were longer for deviant compared to standard sounds and similar between language meaningfulness conditions (Figure 2; see Table 2 for descriptive statistics). The Bayesian ANOVA preferred the model including the *sound type* effect only ($BF_{10} = 1.04 \times 10^{20}$). The data provide strong evidence for the *sound type* effect ($BF_{\text{Incl}} = 1.29 \times 10^{20}$; $F(1,40) = 159.09$, $p < .001$, $\eta_g^2 = .14$). The data provide evidence against rather than for an effect of *language meaningfulness* ($BF_{\text{Incl}} = 0.60$; $F(1,40) = 1.68$, $p = .20$, $\eta_g^2 < .01$). The data provide moderate evidence against a *sound type* by *language meaningfulness* interaction effect ($BF_{\text{Incl}} = 0.27$; $F(1,40) = 1.11$, $p = .30$, $\eta_g^2 < .001$).

Figure 2. Violin plot showing the probability density of the data in the different languages (German: Brown; French: Cyan) as a function of sound type (deviant: darker colour; standard: lighter colour). The white boxes within the plots represent the interquartile range, and the horizontal line the median. The figure also depicts individual data points that are more than 1.5 times the size of the interquartile range. Panel a) shows RT data. In both language conditions, deviant sounds caused increased RT than standard sounds (distraction effect). There is evidence against an interaction of sound type and language meaningfulness. Panel b) shows hit rates data. Only an effect of sound type was found, such that hit rates for standard sounds was higher than for deviant sounds. Panel c) depicts data for the pupil dilation response (PDR). PDR was increased in response to deviant sounds (compared to standards) and in response to French (compared to German). There is evidence against an interaction of sound type and language meaningfulness.

3.2. Hit rate

Hit rates were higher for standard compared to deviant sounds and similar between language meaningfulness conditions (Figure 2; see Table 2 for descriptive statistics). The Bayesian ANOVA preferred the model including the *sound type* effect only ($BF_{10} = 9.89$). The data provide strong evidence for the *sound type* effect ($BF_{\text{Incl}} = 10.17$; $F(1,40) = 12.91$, $p = .001$, $\eta_g^2 = .04$). The data provide evidence against rather than for an effect of *language meaningfulness* ($BF_{\text{Incl}} = 0.50$; $F(1,40) = 1.19$, $p = .28$, $\eta_g^2 = .01$). The data provide moderate evidence against a *sound type* by *language meaningfulness* interaction effect ($BF_{\text{Incl}} = 0.23$; $F(1,40) = .17$, $p = .68$, $\eta_g^2 < .001$).

3.3. Pupil dilation response

Mean amplitudes of the PDRs were increased in response to deviant compared to standard sounds and also increased in the French (non-meaningful) compared to the German (meaningful) background speech condition (Figure 2 and Figure 3; see Table 2 for descriptive statistics). The Bayesian ANOVA preferred the model including both the *sound type* and *language meaningfulness* effects ($BF_{10} = 1.42 \times 10^6$). The data provide strong evidence for the *sound type* effect ($BF_{\text{Incl}} = 5.88 \times 10^5$; $F(1,40) = 42.25$, $p < .001$, $\eta_g^2 = .06$) and moderate evidence for the *language meaningfulness* effect ($BF_{\text{Incl}} = 5.53$; $F(1,40) = 4.50$, $p = .04$, $\eta_g^2 = .01$). The data provide moderate evidence against a *sound type* by *language meaningfulness* interaction effect ($BF_{\text{Incl}} = 0.25$; $F(1,40) = 1.89$, $p = .18$, $\eta_g^2 < .01$).

3.4. Baseline pupil diameter

The mean pupil diameter in the baseline interval was 4.21 mm ($SE = 0.15$ mm) in the German and 4.19 mm ($SE = 0.14$ mm) in the French background speech condition. The data provide moderate evidence against an effect of language meaningfulness on baseline pupil diameter ($BF_{10} = 0.18$; $t(40) = 0.40$, $p = 0.688$).

Figure 3. Mean group PDR in the standard and deviant sound trials in German (brown lines) and in French (cyan lines). The zero in the x axis (0 s) corresponds to the onset of the relevant sound. Deviant sounds (darker colour) evoked larger amplitudes than standard sounds (lighter colour) in both language conditions. Shaded areas represent 95 % CI. French background

speech caused increased amplitudes in response to standard and deviant sounds compared to German background speech.

3.5. Self-reported measures

Regarding task difficulty, 26 participants (64 %) stated that the task was more difficult in combination with the German speech, 10 participants (24 %) declared that the French was more challenging, and 5 participants (12 %) answered that they perceived no differences in task difficulty.

Regarding the free recall measure, the group mean in the 1-to-6 recall scale was of 2.69 ($SD = 1.16$; range 1 to 5), that is, participants could remember between 1 and 2 details in average.

4. Discussion

The present auditory oddball study used pupillometry and behavioural measures to explore the impact of the meaningfulness of task-irrelevant background speech upon auditory attention. Effects of attentional orienting and distraction by task-irrelevant deviant sound features were reflected in increased amplitudes of the PDR, increased reaction times (RT) and reduced hit rates in response to deviant *versus* standard trials. Phasic pupil dilation responses (PDRs) were observed in response to all sounds of the auditory discrimination task, presumably reflecting the dynamic regulation of attention by task demands. Importantly, the observed PDRs were increased –independently from the presentation of standard or deviant sounds– when non-meaningful speech was presented in the background compared to meaningful speech. Our study brings new insights into the examination of subtle effects of task-irrelevant background meaningfulness upon attention.

First of all, and independent of our language manipulation, we found the expected oddball effect in our sound discrimination task, both at the behavioural and at the pupillometry level. In fact, RTs were larger for deviant as compared to standard sounds, indicating that task-irrelevant sound features involuntarily distract attention resulting in impaired performance at the task at hand (Wetzel et al., 2006). As in previous studies, impairing effects of deviant sound processing were also observed in hit rates, such that participants responded more often correctly to standard sounds compared to deviant sounds (Escera et al., 1998). The pupil was also sensitive to the unexpected change in sound type,

such that PDR was larger in response to the deviant as opposed to the standard sounds. In this sense, our results add up to an increasing list of studies finding a relation between involuntary attention and pupil size (Bonmassar et al., 2020; Eckstein et al., 2017; Marois et al., 2020; Marois & Vachon, 2018; Widmann et al., 2018), a result which underscores the large potential of pupil dilation measures to capture subtle effects related to involuntary attentional capture.

Concerning our language manipulation, our main aim was to test the hypothesis that task-irrelevant semantic stimuli are processed, at least to a certain extent, and therefore consume and divert attention (e.g., Vachon et al., 2020). Accordingly, we expected differences in the allocation of attention between our language conditions to lead to differences in our behavioural (RT and hit rates) and pupil size measures. Nonetheless, we could only provide partial support to this assumption: whereas the effect of meaningfulness was not visible at the level of behaviour, we observed it in the pupil. Indeed, RTs and hit rates in the sound duration discrimination task did not differ as a function of meaningfulness. The fact that the Bayesian analysis tended to favour models not including language meaningfulness suggests that the absence of this effect is not due to a lack of statistical power. Note that we also found evidence against a significant interaction between sound type and language, which indicates that the distraction effect (deviant minus standard sounds) was also not different between the native and the foreign language, neither in terms of RT nor in terms of hit rates. Taken together, our behavioural results suggest that task performance in the auditory task was not modulated by meaningfulness of background speech. Therefore, we were not able to support the idea that semantic (native) speech diverts attention more than other types of non-meaningful speech (e.g., Vachon et al., 2020). If this were the case, we should have seen a difference in performance in the attentional task depending on the accessibility to the semantic content of the speech in the background.

At first sight, this result extends the literature on irrelevant speech effects upon memory serial recall tasks to an attentional task and is in line with previous behavioural research which reported no effect of speech meaningfulness upon performance (Buchner et al., 1996; Jones et al., 1990; Marsh & Jones, 2010). In the same line, our results could be supportive of the idea that the effect of the meaningfulness of task-irrelevant speech might not emerge at the behavioural level when focal tasks are non-semantic (e.g., interference-by-process hypothesis; Marsh et al., 2009).

Nonetheless, we did observe an effect of meaningfulness at the physiological level. Specifically, the effect of language was significant upon the PDR and occurred in the expected direction: the pupil dilation in response to the sounds of the attentional task was larger when participants were listening to the foreign as compared to the native speech in the background. The sound-related pupil dilation is mainly modulated by the phasic mode of activity of the LC and is discussed to reflect focused attention to task-relevant or to unexpected motivationally significant stimuli (Sara & Bouret, 2012). Reduced PDR amplitudes in response to task-related sounds in the German condition could indicate reduced allocation of attentional resources to focal (voluntary) sound processing when the speech in the background was meaningful. This is fully in line with the proposal by Vachon et al. (2020): the processing of meaningful speech should consume attention, resulting in reduced availability of resources to devote to task-related sound processing. Descriptively, this hypothesis is also supported by the self-reported measure of task difficulty, which revealed that 64 % of the participants found more challenging to focus on the discrimination task while hearing the German as compared to the French speech. This effect of larger self-disturbance for the native speech is common in the literature, even in studies where no behavioural effect of meaningfulness is found (e.g., Braat-Eggen, Keus Van de Poll, Hornikx, & Kohlrausch, 2019).

In contrast to the effect of meaningful background speech on voluntary attention, the oddball effect at the level of the pupil was not modulated by the meaning of the background speech in the applied experimental situation. This was supported by the Bayesian statistics that revealed a moderate evidence against an interaction of deviant sound processing and language meaningfulness. This indicates that the PDR was capturing differences in voluntary attention allocation to the sounds of the discrimination task between the language conditions, but that meaningfulness did not alter involuntary orienting of attention in the focal task.

Lastly, the Bayesian statistics confirmed that German and French evoked a similar baseline pupil size. Since this measure is supposed to reflect the baseline level of arousal or task engagement (Aston-Jones & Cohen, 2005; Hopstaken et al., 2015), we could infer that the level of arousal or task-engagement was similar in both conditions.

Overall, measuring both behaviour and pupil size gave us the chance to assess the relative sensitivity of our measures towards the effect of meaningfulness. In this sense, our physiological results suggest that subtle effects of semantic content invisible to behavioural

measurements might be better captured by changes in physiological activity (e.g., Holeckova et al., 2006, Pérez et al., 2015). Specifically for pupillometry, our results support the hypothesis that changes in the PDR could be good indicators of attention, also when differences are too subtle to be seen with behavioural indexes (for similar results, see Marois et al., 2020; Marois & Vachon, 2018). As discussed by Marois et al. (2020), one of the possible explanations for the different response sensitivity obtained between behaviour and the pupil could lie on the fact that behavioural disruption implies a whole chain of events from perception to motor output, whereas the PDR represents a time-locked response to the specific stimuli associated to the locus coeruleus-norepinephrine (LC-NE) system (Sara, 2009), that is, in some sense, behavioral measures are considerably noisier compared compared to pupillary measures.

Although our study dealt with a basic research question, we believe it might influence more application oriented-research. In this line, beyond its scientific interest, investigating the effects of speech upon cognitive performance is important, for instance, to understand the factors that influence learning in educational contexts and optimize learning environments. Indeed, the control over auditory attention is essential in educational settings, where the detrimental effects of task-irrelevant noise for learning success are well established (for a review see Klatte, Bergström & Lachmann, 2013). Certainly, our psychophysiological results could also have major implications for clinical research, especially on children. As compared to sensitive electrophysiological responses, the recording of pupil dilation via eye-tracking implies reduced preparation time and a reduced number of trials required for a sufficient signal tracking to noise ratio (e.g., eight deviant trials; Wetzel et al., 2016). Moreover, technological advances in the field of wearable eye trackers make their application more feasible in naturalistic environments. Together with its sensitivity to attentional processes, this could turn the PDR into a suitable instrument for the investigation of the interaction of attention and language meaningfulness in young children or in patients suffering from attention- or language-related disorders such as hearing impaired-patients who have difficulties hearing in noise.

Limitations

Our study did not include any non-linguistic background stimulation, e.g., music or some type of noise. This decision was taken on the basis of a trade-off between task length and scientific value of the results. In this regard, the disturbing effect of (any kind of) speech

as compared to other auditory stimuli while performing non-semantic tasks has been fairly replicated in the literature during the last thirty years (e.g., Buchner et al., 1996; Jones et al., 1990; Marsh & Jones, 2010; Vachon et al., 2020). Although it would have been interesting to quantify the differences between a non-speech and the speech conditions in terms of behaviour and PDRs also in our study, we did not include a further condition to prevent participants' fatigue. Indeed, the cognitive effort needed in order to inhibit the irrelevant speech and keep attention focused on the discrimination task was notable according to the participants themselves, and we wanted to avoid effects of exhaustion in the last part of the experiment.

Finally, although we found the classical oddball effect on hit rates, performance was almost perfect in the focal task, suggesting that the discrimination task was rather easy for the participants and some of the accuracy results might be due to ceiling effects. Future studies could use more challenging focal attention tasks to test the effect of task easiness upon the irrelevant speech phenomenon.

Conclusions

Our study evaluated the effect of task-irrelevant speech meaningfulness on auditory attention using behavioural measures and sound-related changes in pupil size. Through the employment of an auditory oddball discrimination paradigm, we show that the pupil is sensitive to the meaningfulness of task-irrelevant speech: pupil size in response to the sounds of the discrimination task was larger when exposed to non-meaningful background speech as opposed to meaningful speech. Our physiological results suggest that the meaningful speech consumed attentional resources. We highlight the potential of the pupil as a highly sensitive measure of changes in attention allocation.

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