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Bachelor Degree in Psychological Science of Development, Personality, and Interpersonal Relations

Final dissertation

Robustness of cognitive performance to irrelevant speech effects

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Introduction

Executing a comprehension-based cognitive task requires the ability to use different types of executive functions. However, exposition to noise, especially if it is intelligible, disrupts the task by generating cognitive overload. This widely observed phenomenon has been investigated by many researchers for decades under different scenarios (e.g. Salamé & Baddeley, 1986; LeCompte, 1994). The objective of this thesis is to develop an experimental design that involves a classic comprehension task with multiple-choice comprehension questions to measure the disruptive effect of irrelevant speech. A within-subject design has been preferred because it is robust against the impact of inter-subject differences and allows the generation of more outcomes with a smaller number of participants.

In this experiment, participants are asked to accomplish two different reading tasks followed by comprehension tests. The first task takes place in a silent environment while during the second task, the participants are exposed to multi-talker babble noise mixed with sporadic intelligible noise. The disruptive effect of noise is detected using the eye movements of participants, which is derived from the recordings obtained via a Tobii Pro eye-tracker device.

Participants are all non-native English speakers who study at the University of Padua in the English language. The texts used in the experiment are chosen from the World Health Organisation website and have approximately the same length and English level (B2 and B2+).

The organization of the thesis is as follows: in the first chapter, the basic cognitive notions related to speech recognition and the impact of noise are explained. The second chapter introduces the assessment methods used in the experiment. The third chapter gives the details of the experiment design including its objective, methodology, the characteristics of the participants and its procedure. The fourth chapter contains a description of the results expected from the experiment, an indication of its limitations and some suggestions about possible future directions of research on the same subject or using the same experiment design. The thesis ends with the bibliography and acknowledgements.

CHAPTER 1: IMPACTS OF NOISE ON COGNITIVE PROCESSES

Oral communication is essential to human communication in everyday life. It is present in almost every kind of social environment such as streets, classrooms, cafés, and bars. The efficiency of information processing depends mainly on focusing capacity, which relies on "attentional selectivity", which is the ability to ignore task-irrelevant events to focus on task-relevant events (Hughes et al., 2011). Attention must be flexible enough to prevent distractions caused by external stimuli, allowing individuals to concentrate on task-relevant activities. After focusing on the main task, the outcome of the individuals' actions would rely on their capacity to map current events in the environment to possible actions. However, it is commonly accepted (Hughes et al., 2011; Mangun et al., 1995) that the functioning in the auditory modality is slightly different, namely that all the auditory information gets processed without being filtered right from the beginning. Although earlier studies emphasized the impact of speech (Herbert & Welsh, 1976), further studies demonstrated that the impact was not exclusive to speech (Jones et al., 1993). According to this theory, individuals are exposed to a wide range of auditory distractions in the competition for action, where "competition for action" refers to a mental function of language and thought processing that defines the capacity to control attention and select information from outside stimuli (Jones et al., 1993). Although before processing the information the outside stimuli should be filtered out, which gets done by the inhibition system. This competition also constitutes a specific vulnerability that has been investigated by many researchers (Salamé & Baddeley, 1986; LeCompte, 1994) who tried to identify which kind of stimuli can affect the inhibition system.

One of the most important elements that have a great impact on information processing is the phenomenon of noise, described by Pickett as "disorder, any disturbance to the ordered pattern of a message" and "the ultimate limit to communication" (Pickett, 1988, p. 2). Noise refers to random fluctuations that can be observed in various systems (West et al., 1990). Numerous experiments in the psychoacoustics field have been conducted on the negative and positive effects of different types of noise on cognitive processes. Researches have shown that background noise has very specific impacts, especially when it includes speech (Salamé & Baddeley, 1986; LeCompte, 1994). For example, Banbury et al. (1998) have shown that background noise originating from office equipment (such as photocopy machines, computers, air conditioning devices, phones etc.) in an open-plan office environment disrupts only mental arithmetic tasks, while the same background noise with additional speech component disrupts both mental arithmetic and memory tasks, irrespective of its meaning. This can be explained by the fact that the presence of speech increases mental workload (Smith et al., 2009).

1.1 **Executive Functions in reading comprehension**

Executive functions (EFs) are a group of cognitive abilities that organize cognition (Barkley et al., 2012). EFs play a crucial role on the outcome of the individual's cognitive process. Executive functions define the actions of a subject who is exposed to a psychological stimulus (visual, phonological, olfactory, etc.).and involve core processes like working memory, inhibition skills, and switching as well as higher-level skills, including planning (Singer et al., 1999).

Lezak (1982) suggested that EFs have 4 different components; (i) goal formulation, (ii) planning, (iii) carrying out goal-directed plans, and (iv) effective performance. and all of them have their own set of actions that are not related to one other. Conversely, there are different theories looking into EF's: Reynolds and Horton (2008) delineate a distinction between general knowledge and EFs. Their theory is based on the assumption that general knowledge consists of an organized set of facts and actions, while EFs are abilities needed to organize new actions, such as planning and adaptation to the new situation. The authors suggest that EFs are not solely passive recipients of information but also possess the capability to influence motor outputs in response to external stimuli (Goldstein et al., 2015). Another important aspect of EFs is "delayed gratification", which depends on willpower and self-control. This aspect has been investigated by Mischel et al. (1972) mostly using the so-called "marshmallow test" (Mischel et al., 1972; Mischel et al., 1989; Mischel & Ayduk, 2004). This experiment is based on the delay-of-gratification paradigm, which refers to the ability of self-control towards a small and immediate award in order to get a bigger award after a short while. This experiment has been conducted with children (Mischel et al., 2011). It has been shown that children with attention deficit and hyperactivity disorder (ADHD) face difficulty in coping with the impulse of having immediate satisfaction (Swanson et al., 2003).

At the heart of this thesis lies the theory by Miyake et al.'s (2012) model, which is widely accepted and central to the discussion. According to the framework, there are three main executive functions that are interrelated yet separate. *Updating* is the function that actively monitors and updates the working memory. This process allows human cognition to receive all possible information from the environment, and in the end, other functions are involved in the modification of the outcome. The second main function is *inhibition*, which is the ability to filter external stimuli in order to remain focused on the task. The third one is *shifting*, also known as *cognitive flexibility*. It refers to the ability to switch attention among tasks and maintain the focus between different operations (such as trying to remember a piece of information while answering a comprehension question under exposure to some noise). These three functions are crucial for investigating the impact of noise on cognitive processes during the execution of reading and subsequently answering the tasked comprehension questions.

1.2 **Irrelevant speech effect**

The phenomenon of Irrelevant Speech Effect (ISE) can be defined as impairment of the cognitive performance under exposure to irrelevant background speech (LeCompte, 1994). It is typically investigated via tests of serial recall, such as the performance of short-term memory for a to-be-recalled list of digits, letters, or words on the screen, under exposure to semantic noises to-be-ignored. It has been discovered that impairment results not only from the presence of speech, but also from reverse speech[1], the sound of a single letter, and the repetition of sounds and music (Senan et al., 2018). After the inclusion of other newly discovered factors, the name of the effect was eventually changed to "Irrelevant Sound Effect", without altering the acronym of ISE.

According to the Working Memory model proposed by Salamé and Baddeley (1982), during a reading task, the text being read is encoded into a phonological representation and stored as sub-vocal speech in phonological memory. However, all speech input, including task-irrelevant speech, enters the phonological memory storage. As a result, phonological codes from all sources are recorded in the same storage, leading to the corruption of phonological representations by task-irrelevant background noise (Yan et al., 2018).

Baddeley (1966) used word sequences as to-be-ignored stimulants, some of which were phonologically very similar to the to-be-recalled digits, and showed that phonological similarity has a much higher impact on cognitive performance than semantic similarity if the task requires the use of short-term memory for serial recall. Interestingly, this trend reversed in the context of long-term memory (Salamé & Baddeley, 1982).

ISE has been approached from these different angles in order to answer different questions. One of these questions was whether selective attention and its impact on the cognitive performance depend on the location of the sound source (Spence et al., 2000). To investigate the cross-modal spatial attention, participants were exposed to the same auditory stream composed of various types of irrelevant semantic noise. The noise was presented first from the direction of the visual display and later from behind the participants' heads. Results indicated that selective attention was less accurate when an irrelevant sound stream originated from the frontal target visual display. Participants found it significantly harder to ignore noise coming from the direction of their visual focus (Buchner et al., 2008).

[1] Reverse speech refers to the utterance of speech in reverse direction.

Another challenge was finding out which noise types could induce this effect. Jones et al. (1992) tested how correctly the participants could recall multiple lists of digits prompted on the screen while being exposed first to the same single-sound noise (for example "aaaaaa") and then to the same repetitive-sound noise (for example "be be be be") in every task. According to their results,these kinds of simple noises were not sufficient to cause an irrelevant speech effect, although they were still distractive compared to a silent environment.

LeCompte (1994) conducted a very similar experiment, except that he used a different repeated sound recording every time a new list of digits was shown to the participants. For example, for the first list, he used the repetitive sound "be be be be", and for the second list of digits he used the sound "aaaaaaa". This approach aimed to determine whether habituation to the disrupting sound significantly reduces the ISE. The experiment showed that habituation to the noise indeed results in a lack of irrelevant speech effect when they use only one repetitive sound for every task. Overall, this experiment demonstrated that the disruptive quality of noise depends on how much it changes from task to task, while the monotony of individual noise recordings decreases the quality of cognitive performance.

The effect of familiarity with the language was also explored using local and globally time-reverse techniques. Saberi and Perrot (1999) discovered that the duration of subdivided segments of a digitized sentence determines the level of the disruptive effect. When subdividing the sentence into 50-millisecond segments and locally time-reversing them, participants still found the speech intelligible, indicating that the reversed segments did not significantly affect the sentence's global intelligibility. However, wider segments with a duration of 100-200 msec rendered the speech dominantly unintelligible.

Ueda et al. (2019) presented to their participants a classic serial recall task while exposing them to disruptive speech in their native or foreign language. The study revealed that the most disruptive kind of speech was the normal and locally time-reversed speech in short segments (50 msec) in the native language of the participant; i.e., speech that is most intelligible and familiar to the participant. Conversely, speech types causing less disruption included those in an unfamiliar language, with or without modification, and those in the native language with locally time-reversed segments of longer duration (100-200 milliseconds), as well as completely backward recordings in the native language. These findings confirmed that the degree of disruption depends on the familiarity and intelligibility of the language of the disrupting speech.

1.3 A special case of ISE: multi-talker babble noise

Among the extensively researched subjects within the realm of the irrelevant speech effect, a significant topic is the impact on cognitive performance inhibition when facing not only single types of semantic noise, but also multi-talker babble noise. In this case, distractive stimulation would be a compilation of semantic noises which consist of unintelligible speech irrelevant to the task, while being possibly relevant in their own context.

Jones & Macken (1995) designed an experiment that emulates the environment of medium-sized open-plan offices. The results showed that the number of errors made by the participants was higher when they were exposed to disruptive speech generated by one or two speakers because of the high intelligibility of the speech. Under such circumstances, participants tend to analyze and process the sentences they hear as disruptive stimuli. However, a notable shift was observed when the disruptive speech emanated from six speakers or more. In this scenario, the occurrence of disruption-related errors notably declined. The phenomenon underpinning this decrease in errors and the subsequent performance enhancement with an increased number of speakers is attributed to the mutual masking of speech among multiple talkers. As more speakers contribute to the background noise, the intelligibility and disturbance of the background speech gradually diminish. This phenomenon is called “babble effect” (Jones & Macken, 1995).

CHAPTER 2: ASSESSMENT OF THE IMPACT OF NOISE ON COGNITIVE PROCESSES

2.1 Assessment via eye tracking

Eye-tracking technology is widely used in the field of psychology, mainly because of its accuracy and practicality. It is a very effective and reliable tool for studying visual information processing. The device operates by utilizing a light source to illuminate the eye in order to create reflections that can capture the eye movements (Punde et al., 2017). It has been developed to detect and track the areas on the screen where the eyes focus via high-speed cameras. Due to its compatibility other types of analysis devices like magnetic resonance imaging, it can also be used with multiple devices (Mele et al., 2012).

Moreover, the eye-tracking technology can be used to measure visual perception (Jarodzka et al., 2021), emotions (Lewandowska et al., 2022), and cognitive effort (Gómez-Merino et al., 2020; Piquado et al., 2010). It is also widely used to diagnose children with autism spectrum in early developmental stages by examining their gazing patterns (Guillon et al., 2014). Notably, autism spectrum disorder encounter in directing their gaze towards the facial features located internally of the speaker (Wan et al., 2019). In contrast, children with typical development tend to fixate on the eyes or the mouth of the speaker, while those with an autism spectrum disorder mostly look at the outer parts of the face (Shic et al., 2014).

2.2 Assessment via text comprehension tests

Comprehension tests are designed to evaluate individuals' ability to comprehend and extract information from a written, visual or auditory material on a specific topic. These tests can also be used to assess the subject's competence level in a language. In the context of a reading comprehension assessment, participants are asked to read and subsequently answer related questions. These questions come in different formats, including multiple choice, fill-in-the-blanks, or open-ended questions, each tailored to assess distinct skills. Multiple choice questions generally contain options that are meant to mislead the participant. Fill-in-the-blank questions are designed to measure how much attention the subject has paid to the details in the text. Open-ended questions, on the other hand, lead the participant to shift focus from the details to the general meaning of the text. These questions allow us to validate the subjects' ability to comment on the text and therefore, are useful for assessing their level of comprehension.

CHAPTER 3: STUDY OF THE IMPACT OF IRRELEVANT SPEECH EFFECT ON COGNITIVE PROCESSES

3.1 Objective of the thesis

The aim of this study is to investigate the impact of different types of noise on cognitive performance. The study utilizes a within-subject design, i.e., comparing the performance of the same subjects under different conditions. This design is preferable for small sample sizes of subjects because it is statistically robust to inter-subject variations. The noise deployed for disruption is designed as a sequential combination of different types of noise to create an irrelevant speech effect. Based on the existing theories (Herbert & Welsh, 1976; Salamé & Baddeley, 1986), the working hypothesis suggests that comprehension scores generated in a noise-free environment should be higher than those obtained under exposure to noise. Moreover, it is expected that intelligible noise would be more disruptive than unintelligible noise because it creates an additional cognitive load during reading.

3.2 Methodology

The experiment consists of two parts, each involving a reading comprehension task. Before the experiment, the subjects will be asked to sign a consent form and fill in multiple questionnaires on language level, reading background and dyslexia background. In the first part, they will be asked to read a text on the screen in a noiseless environment and then answer a set of comprehension questions about the text. In the second part, they will be asked to conduct the same task with a different text while being exposed to multi-talker babble noise via earphones. In both parts, the subjects' gaze will be continuously recorded. The performances of each participant under these two different conditions will be compared both in terms of their comprehension scores and their gaze patterns. Since the texts are designed to be homogeneous with regard to their readability, it would be easy to see the parts of the screen that the participants fixate their gaze on correspond to those parts of the text where they spent more time reading, re-reading and fixate their attention. Knowing the exact timings of noise exposure, it can be also possible to identify the parts of the text read at these moments and to compare them with the gaze map. This way, the impacts of different types of noise on cognitive performance can be measured.

3.2.1 Characteristics of the noise

The noise stimulus deployed in the reading comprehension test is a compilation of noises. In order to prevent participants to accommodate to the noise, the recording involves a sequential combination of intervals involving different types of noise: (i) unintelligible babble noise, (ii) transitory noise (e.g., ambulance sirens, doors slamming, books dropping, …) and (iii) intelligible noise in English. The noise will be conveyed through earphones at an intensity of 65 dB.

3.2.2 The comprehension test

The comprehension texts have been selected from the website of the World Health Organization (WHO) to ensure that they are sufficiently similar in terms of readability, text length, reading time, similarity of the topics and comprehension difficulty, by using two different sources that are made to measure the readability. Moreover, the topics and content of the texts are chosen such that the participants are unlikely to have prior information or extensive knowledge about them.

The characteristics of the chosen texts are given in Table 1.

Table 1. Comparison of the features of the texts used in parts 1 and 2 of the experiment.

Text	Word count	Sentence count	Average number of words per sentence	Average number of syllables per word	Readability score (Flesch-Kincaid Grade Level)	Readability score (Flesh Reading Ease)
1	446	18	24.8	1.8	15.3	29.4

2	445	26	17.1	1.9	13.5	28.7

The readability scores of the texts were based on the measures proposed in two different sources. The first score is the Flesch-Kincaid Grade Level (FKGL) (Kincaid et al., 1975) which provides an estimate of the educational level a typical reader must achieve in order to comprehend the text (Kher et al., 2017). A low grade means that the text is relatively easy to read and understand. Specifically, if the score is around 0-5, the text is likely to be very basic and suitable for elementary school students; if the score is around 6-8, the text is suitable for middle school students. The second readability score is determined by the Flesh Reading Ease (FRE) formula (Flesch, 1948), which utilizes instead a 100-point scale. The higher the score, the easier the text is to read. Conversely, the lower the score, the more complex and challenging the text is. Both comprehension tests are followed by 10 multiple-choice questions with 4 alternative answers. Some questions are designed to check whether readers comprehended the core passages and information in the text

3.2.3 Eye tracking device

In this study, the eye-tracking device used to determine the fixation of the participants' gaze on the screen is Tobii Pro X3-120 (Tobii Pro, 2016). It also displays the gaze map as a heat map on the screen. The eye-tracker has a frame rate of 120 Hz.

3.3 Participants

The participants of the planned experiment are expected to be university students aged between 19 and 30 years. The participants will be recruited among university students studying subjects in the English language as non-native English speakers. Consequently, all participants will possess bilingual or multilingual capabilities, and they must meet a minimum English proficiency level of B2, which is a prerequisite for university admission.

To ensure the validity of the findings, it is recommended to involve at least 45 participants. The subjects should be divided into balanced groups with respect to gender and age distribution, and should not include persons with special cognitive disabilities.

3.4 Procedure

3.4.1 Pre-experiment procedure

Before starting the experiment, the participants are asked to read and sign a consent form which provides information about the purpose of the experiment and a summary of the procedure. For confidentiality purposes the subjects will be referred to by their specific ID numbers instead of their names. At any stage of the experiment, they have the right to withdraw. They are also allowed to ask any questions about the procedure, confidentiality and the experiment itself. All data will be stored in a database accessible only by the researchers. After the participants sign the consent form, they are asked to fill out a linguistic background questionnaire, which serves as a self-declaration about the language proficiency in the languages they speak. Then, they are asked to fill out a questionnaire about their reading habits, both in their native and non-native languages. They include questions about do they read English books, how much they can comprehend what is written if they don't know some words, how many books in the last year they have red in their native language etc. This questionnaire provides an indication of their ease at comprehending a text in a short time. This questionnaire was originally created in order to assess the reading habits of a group of Italian students (Crawford Camiciottoli, 2001). According to a study on Finnish children, reading habits can predict how much they are engaged in reading as an extracurricular activity (Leppänen et al., 2005). More competence in reading indicates more extracurricular reading which develops word recognition skills and increases reading speed. Another study (Francisco et al., 2019) verifies that the correlation between reading habits and comprehension skills is positive. It is, however, unknown to what extent high word recognition skills would provide robustness against disruptive noise. That is why this questionnaire was chosen to make a limitation on this variable. Consequently, the participants will have to complete an English proficiency test, that allows the researchers to compare the participants' self-declared English proficiency with their actual level. The English proficiency test is taken off the Cambridge English website (Cambridge University Press & Assessment, n.d.) and is titled "General English Assessment". Lastly, the participants are asked to compile the Vinegrad's Adult Dyslexia Checklist (Vinegrad, 1994) in order to determine whether they have any reading difficulty.

3.4.2 Experiment

After the pre-experiment procedure is completed, the participant is seated in front of computer screens. Firstly, the head position is carefully arranged to make sure that the eye-tracker can follow the gaze most accurately. Before starting the experiment, subjects are told that they will be given a text and they will have to answer comprehension questions after finishing their reading. Nevertheless, no information is provided about the number and nature of the questions. When the first text appears on the screen also the recording of the gaze map starts. The subject is told to pass to the second page after finishing the reading task and to answer the comprehension questions.

The second part of the experiment starts immediately after the completion of the comprehension questions of the first part. The second text appears on the screen, the noise streaming begins and the recording of the gaze map starts. Again, the subject is told to pass to the second page after finishing the reading task and to answer the comprehension questions.

The study will be counterbalanced, so that a certain number of participants will start the experiment in a silent environment, then move to the noise condition. Others will begin in the noise condition and then transition to the silent environment.

After the experiment, the subjects are asked to submit their comments about the difficulty of the task in both parts of the experiment.

CHAPTER 4: DISCUSSION AND CONCLUSION

4.1 Expected results

Based on the empirical evidence reported in the literature, exposure to disruptive noise during a cognitive task is expected to increase the cognitive load and disrupt cognitive processes such as understanding a text and answering comprehension questions (Salamé & Baddeley, 1982). Therefore, participants are expected to achieve higher scores in the quiet condition.

The heat map derived from the gaze map corresponding to the text comprehension task might differ based on familiarity with the topic, attention, language skills of the participants. It is often the case that reading times and fixations vary considerably within a text, even when readers read in quiet. On the other hand, a more re-reading is expected to be seen on the heat map of the text that has been red under exposure to noise because the subjects are likely to have to re-read those parts of the text where their attention was interrupted by the noise (Jones & Macken, 1995).

4.2 Possible limitations and strategies to reduce methodological pitfalls

This experiment has some limitations because of the excess of variables. One of the most important elements is the measurement of language proficiency. Even though each subject should have a B2 level English, some might have higher English levels than others. As stated before, the participants are not given any information about the number and nature of the questions. Nevertheless, after completing the first part of the experiment, the subject is expected to develop some expectations about the comprehension questions of the second part. Keeping in mind that some of the comprehension questions demand the recalling of very specific numerical answers, it is quite likely that subjects will be more attentive to such numerical details in the second part after answering the questions of the first part and thereby improve their comprehension scores. In other words, a *priming effect* is expected, where the exposure to the stimulus of the comprehension questions of the first part influences the attentive result in response to the second text (Weingarten et al., 2016). Therefore, the priming effect is expected to increase the comprehension scores related to numerical questions, while exposure to noise still can disrupt cognitive performance despite the priming effect. Further comparisons and even additional experiments may be needed to compensate for the priming effect and assess the true impact of noise.

This is the first study to investigate the robustness of ISE on cognitive performances under two different acoustic conditions (quiet and noise). Future studies can focus on the investigation of the differences between monolingual and bilingual subjects in their sensitivity to noise disturbance. Different studies (Ben-Zeev et al., 1977; Bialystok et al., 2010) report that bilingual children generally have a smaller vocabulary per language than monolinguals. Bialystok et al. (2010) further report that bilinguals need longer time to retrieve specific words, although they generally have better control over nonverbal executive functions, such as the ability to selectively attend to relevant information, inhibit distraction, and shift between tasks (Bialystok et al., 2010).

Based on these findings, a new experiment can be designed, where the within-subject test in this thesis will be given to monolingual and bilingual subjects. By exposing both groups to noise, researchers can determine whether bilingual individuals demonstrate higher performance under noisy conditions, thereby suggesting that their enhanced nonverbal executive functions outweigh any vocabulary limitations.

Furthermore, the same experiment can be executed as a between-groups test, involving a control group and an experimental group. Both groups would complete the task in both quiet and noisy environments. This approach offers the advantage of using identical texts to assess comprehension performance, thereby eliminating potential confounding factors such as differences in text readability and difficulty. Consequently, a more accurate measurement of the impact of noise on cognitive tasks can be achieved. Nevertheless, a between-groups design has its own characteristic challenges. The outcome of a between-groups experiment is sensitive to the distribution of subjects with different characteristics (gender, age, mono/bilingual, reading habits etc.) among the two groups. In order to reduce possible biases, one needs to have a balanced distribution of subjects into the control and experiment groups and work with large groups. Large group sizes would allow the experimenter to discard outliers; moreover, inter-subject variations would be better averaged out in large groups. Therefore, the group size to be used in a between-groups experiment should be at least twice as in a within-subject experiment.

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