Pupillometry in children: a good method for assessing listening effort

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Abstract

The additional cognitive effort required during listening activity, for example in case of inadequate acoustic conditions, may lead to a general worsening of cognitive performances, especially in children, who are still developing adult-like language skills which may help them compensating for inaccurate speech recognition. For this reason, it is increasingly important to have a more objective method for assessing listening effort. Pupillometry could be a good solution for evaluating the effect that background noise has on children' cognitive abilities, particularly in the case of hearing-impaired children. As it has been proved that eye pupil dilation can be considered a psychophysiological marker of cognitive effort, pupillometry may indeed be a practical and reliable method for this type of evaluation. This review aims to provide more information on this technique and how to use it when assessing listening effort in children.

Keywords: pupillometry; children; listening effort; pupil dilation

Introduction

Additional effort may be needed during listening activity, for example in case of reverberation, background noise, disturbances in the audio-signal transmission and listening impairments such as hearing loss.

The additional effort required in order to understand the auditory message in inadequate conditions may detract from other kinds of cognitive activities, and this can result in an overall worsening of cognitive performances.

Listening effort relate to "the resources or energy actually used by a listener to meet cognitive demands". (Peelle 2018)

In a 2016 study the authors defined mental effort as "the deliberate allocation of mental resources to overcome obstacles in goal pursuit when carrying out a task" and, in particular, listening effort as "A specific form of mental effort that occurs when a task involves listening." (Pichora-Fuller 2016)

Therefore, it is essential to consider and evaluate listening effort, especially in children, since they are particularly susceptible to be affected from it.

The analysis of the pupil size may be a useful method to investigate this problem.

However, only a few pupillometry studies have addressed this issue in children (Hepach 2016) however most of the studies relate to adults (Winn 2018).

One of the main objectives of this review is to fill in this gap by providing information about how to explore listening effort in children using pupillometry.

In order to accomplish this purpose, results from researchers concerning listening effort in children will be presented first to go then deeper into the research on the topic by means of pupillometry.

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Pupillary reflex

Pupil size can change in response to different types of stimuli: light stimuli (brightness and darkness), emotional and arousing stimuli (Hess 1960, MacLachlan 2002) and when exposed to cognitive tasks (Hess 1964, Kahneman 1966, van der Wel P 2005), including those requiring listening effort (Zekveld 2010, 2014).

The activity of the locus coeruleus (LC), a nucleus in the pons of the brainstem, underlies the pupil dilation in response to cognitive tasks (Samuels 2008, Wang 2015, Schmidtke 2018): LC is the principal site for the synthesis of the neuromodulator norepinephrine (NE – also known as noradrenaline) which is implicated in higher cognitive processes such as attention, memory, perception and motivation (Aston-Jones 2005, Sara, 2009). LC and body areas affected by its production of NE are described as locus coeruleus-noradrenergic system or LC-NA system.

The LC-NA system includes two states, tonic and phasic, which correspondingly reflects arousal states and cognitive processes (Aston-Jones 1999, Granholm 2004). Slow changes in pupil diameter in response to a cognitive task, may indicate the fatigue experienced by the participant (McGarrigle 2014). In order to evaluate pupil dilation associated with a cognitive task, the baseline value must be necessarily subtracted from the pupil diameter values during the task. This outcome is also known as “task-evoked pupil response”. The baseline value is defined as the diameter right before the participant engages in a task and it is usually measured 2 seconds before the beginning of the trial/experiment (Schmidtke 2018, Borghini 2018).

As task-evoked responses are usually the object of analysis in studies using pupillometry, it is possible to not consider the effects of emotional factors except in extreme cases, like severe anxiety or fear symptoms (Eckstein 2017) because emotional states affect baseline pupil diameter and not pupil size changes caused by cognitive activities.

As previously said, it is known that pupil constrict in brightness and dilate in darkness and that the magnitude of the opening/closing is determined by the action of two opposite sets of muscles. Even though the response to a certain type of stimuli is the same for everyone (pupil always constricts and never dilates when exposed to brightness), it does not mean that the pupil responses are entirely a reflex: previous studies have shown that high-level cognition affects the way you process the stimulus modulating the pupil response (Mathôt 2018).

Furthermore, researchers have found out that the light response is also modulated by the stimulus processing and its subjective interpretation: a 2013 study (Nakayama 2013), conducted by Nakayama & Naber, discovered that looking at pictures with a sun elicited a pupil constriction response greater than the one elicited by looking at pictures with the same luminance but without the sun. Other researchers have examined whether the pupil reacts only when looking at visual stimuli or even when imaging situations/things, that is without a real sensory input. Mathot, Grainger & Strijkers (Mathôt 2017) found out that listening to words that reminded to a sense of brightness or darkness (e.g. “sun” or “night”) resulted into pupil size changes, respectively into a constriction and a dilation, which do not occur when listening to neutral words (e.g. “dog”).

Regarding the emotional response, several studies investigated how arousal stimuli can affect the pupil size. It has long been known that anything that increases the processing load of the mind can cause pupil dilation (Beatty 1982, Einhäuser 2017, Laeng 2012). For this reason, this kind of response is usually called arousal-related dilation or effort-related dilation.

Eye Tracking for Pupillometry

Pupillometry is the study of changes in pupil diameter in response to specific types of stimuli. By definition, the pupil is “the opening in the centre of the iris through which light enters the eye” (Miller-Keane 2003).

The size of the pupil is controlled by the iris muscles that let the pupils constrict or dilate. The sphincter muscle is linked to the parasympathetic nervous system, causing the pupil constricts when there is too much light; the dilator muscle, instead, is related to the sympathetic system, leading the pupil to dilate in the darkness. Therefore, pupil diam-

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eter always reflects the combined activity of the sympathetic and the parasympathetic systems (McDougal 2015).

Certain conditions and some medications can alter the function of these muscles provoking an abnormally pupil dilation or constriction. In the absence of these factors, the normal pupil size varies between 1.5 mm and 8mm (Hall 2015) and both pupils are usually of equal size, except for people affected by anisocoria, a condition characterized by unequal pupil sizes.

The eye tracker is the device for measuring pupil diameter and eye positions. Advantages of this non-invasive technique include providing accurate measurement and temporal resolution, and managing to detect even small pupil changes. The camera can track reflections in the cornea caused by near-infrared light directed toward the pupil, this process is called PCCR (pupil centre corneal reflection).

There are two main types of eye tracker: screen-based and glasses. Using the screen-based eye tracker, the subjects do not have to wear anything, but they are required to constantly stare at a screen. Glasses, instead, are directly worn by the subject, who is free to move without the fear of losing the eye image (as the cameras are closer than the screen-based ones and move along with the head).

Apart from pupillometry studies, eye trackers are also used for medical research, observations and testing in different fields (gaming, product development, vehicles simulations) and for educational and learning purposes.

In a 1964 study (Hess 1964), a correlation between pupil dilation and cognitive load was found for the first time. Research participants were asked to solve some mathematical problems and to say the answer out loud. By using a photographic technique, which implied photographing the pupil in 0.5 to 1.0 second intervals, it was possible to determine pupil size changes along time. In general, pupil diameter showed a gradual increase before the answer was given, and this increase was found to be proportional to the difficulty of the mathematical task. Once the answer was given, pupil size decreased immediately to its baseline value. From these results, it seems evident that changes in pupil size reflect a direct activity of the nervous system, as already discussed in previous studies (Shakhnovich 1958).

Hess and Polt study has been the first of a 50 years long series of studies on a broad range of cognitive processes (Beatty 1966, Heitz 2008, Hess 1964, Kahneman 1969, Porter 2007), such as attention (Geva 2013, Ebitz 2014, Mathôt 2013, Laeng 2012), language processing (Ahern 1981, Kahneman 1971, Chapman 2015), listening effort and speech perception.

Listening Effort in School-Age Children

Children are still developing adult-like language skills which may help them compensating for inaccurate speech recognition (Elliott 1989, Sussman 1989).

For this reason, the consequences of listening in acoustically inadequate environments, and the consequent listening effort, are extremely important issues.

In particular, children spend most of the daytime in school classrooms, so it is especially important to ensure adequate classroom acoustic conditions and a proper quality of listening. (Gheller 2020)

Background noise and reverberation, which are commonly present in environment frequented by children, may affect the speech signal, and consequently further cognitive resources are required to compensate for the signal distortion (Hurtig 2015).

In fact, continued exposure to high levels of noise is known to be related to lower scholastic performance (Klatte 2013).

In a 2019 study, (Prodi 2019) 117 primary school aged children were tested in both quiet and stationary-noise conditions. They were asked to carry out speech reception tasks: the response time and the number of correctly recognized words were evaluated. Children had generally greater difficulty in noise condition, and especially recorded response time values increased with background noise, while faster response times were found in quiet condition.

In a previous study (Klatte 2010), the effect of background noise on speech perception and listening performance was tested across age ranges. In this case, both 257 children and 94 adults were asked to distinguish between words with a similar sound and to recognise them, they also had to complete a listening comprehension task, by performing a number of complex oral instructions. All tests were carried out in both quiet and noisy environments. Two types of noise were used: a background speech and a background noise without speech. Children were found to be more affected by noise compared to adults, confirming that listening effort due to background noise is a serious issue, and this is especially true in the case of children. In particular, in this study, speech perception task was affected mainly by noise without speech, while listening comprehension task by background speech.

A 2015 study (Prodi 2015), which analysed the effect of noise on listening performance, tested 530 eight-to-ten years old children. Their intelligibility scores and response times during the speech tests were evaluated. Three types of noises were used to interfere with the speech signal: a babble noise, a typical traffic noise, and a noise signal which had been recorded in a quiet space while a noise was being generated on the upper level. The speech material consisted of target words preceded by a carrier phrase. Two signal to noise ratios (SNRs) were used during the tests (0.6 and 12 dBA). The tests were administered with an automated system, and children were able to answer by using a touchscreen mobile phone. The results demonstrated that the background noise level was related to the increase in the response time, which can be seen as an indicator of listening effort. In the better listening conditions (SNR of 12 dBA) participants' performance was worse, in particular, in the babble and the traffic noise conditions, this did not happen for the third type of noise. In the worst listening condition (SNR of 0.6 dBA), a sort of adaptation to the noise was observed only for the traffic noise. Moreover, younger children appeared to have more trouble in managing the noise intrusion compared to older students, whose performance deteriorated only due to a prolonged exposition. Consequently, their average performance was better for each kind of noise (Prodi 2015).

The effects that detrimental auditory conditions and consequently listening effort have on academic skills have been reported by several studies.

Lewis et al. (Lewis 2016) analysed children's abilities in consonants identification and words and sentences recognition in background noise. In the first experiment of the study, 45 normal hearing kids from five to twelve years of age were tested. Speech stimuli were digitally mixed with speech-shaped noise, and the whole signal was presented by mixing signals of different intensities, in order to create three signal to noise ratios: –5, 0, and 5 dB. Although the interaction between speech recognition results and audio-stimulus type (consonants, real words and sentences) was more complex, speech recognition in general was found to be seriously affected by background noise, since lower values of SNR corresponded to poorer performances. Onset time and total duration were also measured during the tasks, in order to have a measure of listening effort. In general, it was found a decrease in both measurements as SNR increased, especially in the case of correct responses. Furthermore, mean onset times were longer for younger children. This may be because listening effort increases as the age decreases, and therefore it is greater in the younger children, compared to the older ones.

In a 2018 research (Rudner) the authors analysed the combined impact of voice quality, noise and visual cues on listening comprehension and listening effort. 245 eight years old children were tested. All subjects were asked to watch a video in which a virtual talker told a short story and, consequently, they were asked to answer a few questions about the story. In one of the study experiments, children had to perform the task in four different conditions, achieved by combining two different modality of stimulus presentation: with or without visual support and with or without multi-talker babble background noise. No significant interaction effect between task's result and visual support was found, while even a low level of babble noise was associated with a reduction of the comprehension of spoken passages and with an increase in the difficulties found during the task.

Puglisi et al. (Puglisi 2018) evaluated the reading abilities of 94 Italian primary school students (mean age 7.9 years). The tests were performed in five different classrooms, each one with different acoustic parameters. Reverberation time, a measure of the time required for the sound to decay in a closed area from the moment that the sound source

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has stopped (Hurtig 2015), and speech clarity, a measure of the intelligibility of speech in terms of quality of speech transfer to the listeners, were measured in each classroom. Children's reading abilities were assessed in terms of reading speed and reading accuracy: the latter was evaluated considering the number of errors during each reading task. No significant correlation between reading abilities and reverberation time was found, while reading speed scores showed a significant correlation with the speech clarity in the classrooms (Puglisi 2018).

There are very few studies in which listening effort in children is assessed using pupillometry. However, this type of evaluation could be extremely helpful.

Pupillometry in Children

Pupillometry might constitute a useful tool when analysing cognitive load. When exploring listening effort, researchers usually rely on several measures, such as self-reports or Response Times (RTs) (e.g., in a speech recognition task, slower response times are related to an increased listening effort (Gustafson 2014)). However, these measurements are not physiological in nature and in the case of self-reports they only represent the final outcome of the cognitive processes undertaken during the task. Consequently, much of the information related to the processing itself gets lost or depends highly on participant's performance on the task. For this reason, pupillometry can be a good way to investigate which cognitive processes underlie the cognitive behaviour in a moment-to-moment way.

Pupillometry is especially useful when it comes to assessing children. This is because it allows to obtain data from a population where lack of collaboration usually hinders the implementation of cognitive or linguistic measurements. Some studies have proved that it is a consistent measure of cognitive processing in cases where other measurements were not feasible or were not reliable enough (e.g., measures that require a voluntary response). For example, in children before the age of 14 months or at a pre-verbal stage (Hochmann 2014). However, most of the studies that relate to listening effort by means of pupillometry have been conducted with adult population (Zekveld 2010, 2014). This fact might be explained by the issues that may occur when assessing kids.

The application of pupillometry is more difficult when it comes to children (Winn 2018). There are some factors that should be taken into account when designing an experiment related to listening effort and specifically with children.

Children tend to struggle more than adults when it comes to remain stable, which is generally required during pupillometry measurement.

Eye-trackers rely on pupil-detection to provide information about pupil diameter. For this reason, if a big movement is made, a new calibration could be required in order to ensure accurate measurements and a re-calculation of the algorithm needs to be carried out, deriving during this time in data loss. It is therefore important to prevent as much as possible these head movements, otherwise data would become too noisy or valuable information would be lost. In children, avoiding these movements can become a very difficult job, so the decisions regarding how to set the design and what device should be used must be done taking this fact into consideration. The first thing to think about is the type of eye-tracker that would be selected.

A practical way to avoid head movement is to use a chin-rest when using remote eye-trackers (in this type of eye-tracker, no parts of the equipment are attached to the participant's head and stimuli is presented on a monitor). As in this case remaining still is imperative to capture accurate data, it restricts participant's movements. This situation may be uncomfortable for the child, for this reason, it is suggested to use head-mounted eye-trackers when assessing children, because they allow more freedom of movement. Unfortunately, this kind of device needs a more controlled environment in order to avoid that other effects interfere on the results. For example, an uneven illumination of the room could result in changes on pupil diameter not related to the task (Lemercier 2014). A good practice could be to use artificial lights such as "neon lighting" for illuminating the assessment room (Armato 2013, Lanata 2013); in case this is not possible and the assessment is conducted outside of a lab, a light-meter for monitoring light intensity levels between participants is necessary.

There are two additional aspects that need to be considered when designing and interpreting experiments that include children and adults. The first one, mainly related to the design of the study, is that children struggle more than adults to maintain attention along the experiment (Hepach 2016, Winn 2018). A good practice that Hepach & Westermann (Hepach 2016) propose, is to present a stimulus prompting for attention prior to the trial presentation.

The difficulty of the task is also important in this case: when the task is too challenging for the participant (due to the difficulty of the test or the intelligibility of the signal), pupil diameter decrease instead of increasing. This occurs because the participant gave up trying and have disengaged from the task (Zekveld 2018). Moreover, it is fundamental to investigate the role of working memory in participants when facing listening effort related tasks. We refer to working memory as "the temporary storage of information in connection with the performance of other cognitive tasks" (Baddeley 1983). When assessing listening effort, working memory is an essential component to take into consideration. In a typical listening-effort experiment participants are asked to retain auditory information in memory to recall them after, as a consequence, results can vary as a function of their short-term storage capacity. When comparing pupil diameter between groups of different ages, it is important to keep in mind that memory load in children exceeds sooner than in adults, and when the demand far surpasses participant capacity a decrease in pupil diameter rather than an increasing may show up as observed in some studies using a digit recall task (Johnson 2014, Karatekin 2004). For example, in Johnson et al., study (Johnson 2014), children's pupils reached a ceiling level around the digit 6 and started to constrict after it, whereas adults showed this effect later on. Other studies did not replicate this result, for example Cabestrero et al., showed that the pupil diameter plateaued when resources were exceeded (Cabestrero 2009).

Pupil diameter changes with age. Absolute pupil diameter changes over life-time, and children show larger absolute pupil sizes than older adults (Eckstein 2017). Therefore, in order to make comparisons between pupil sizes, researchers need to register pupil baseline values and compare them to the outcomes instead of comparing absolute diameter values. Pupil baseline values can be obtained by recording the pupil-size for a short period, such as 300 ms before the beginning of the experiment (Hepach 2016). In the case of children, as they have more difficulty than adults to remain still, we might require longer time to make sure we record it.

Pupillometry can be a promising tool to explore the listening effort experienced by children, as it could objectively help to report the necessity of taking care of noise levels in educational environments (schools) and especially in the case of population with hearing pathologies (McGarrigle 2017).

Leaving the limitations behind there are few studies assessing pupillometry in children. yet, most of them focus on topics such as auditory processing and speech perception.

For example, Tamási et al (Tamási 2017) investigated children sensitivity to phonological mismatch: they showed that 30-months-old toddlers' pupil diameters increased when mispronounced words were heard. Another study, conducted by Hochmann and Papeo (Hochmann 2014), analysed infants' response to acoustic stimuli. The authors shown that infants' pupil size increased when exposed to a deviant sound condition, as an evidence of children sensibility to differences between acoustic stimuli.

The studies presented here are an example of how researchers use pupillometry to investigate aspects related to speech and auditory perception in children, however, up to date studies addressing only listening effort in children by means of pupillometry remain scarce there are only a few exceptions (McGarrigle 2017, Steel 2015) yet, further studies that replicate their findings are needed.

Using pupillometry to measure listening effort in children

As already explained in the first section, most of the studies that investigated the effect of noise on listening effort in children with hearing loss have evaluated and analysed children's self-reports, response times

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(RT) and accuracy performance using a dual-task paradigm (tasks that require the participant to do two tasks at the same time) (Peelle 2018). Although it has been shown that verbal tasks reflect better than visual tasks the effects of noise in relation to hearing status, pupillometry measures has been suggested as a tool that allows to better explore the topic of listening effort in children (McGarrigle 2019). However, up to date just a couple of studies have assessed listening effort by means of pupillometry on children, and just one of them applies to listening effort in terms of cognitive effort (McGarrigle 2017).

McGarrigle and colleagues (McGarrigle 2017) used pupillometry to assess listening effort and its consequent fatigue in a group of 41 normal-hearing children aged 8 to 11 years. According to the authors, "listening fatigue" is related to "the tiredness that results from sustained effortful listening".

In this research, participants have to listen to short passages (13-18 seconds each) and choose among different images the one that corresponded to the passage heard: the stimuli were presented in two different acoustic conditions, one representing the recommended levels of background noise (+15dB SNR) and one representing the typical background noise of a school classroom (-2dB SNR). While executing the tasks, the diameter of participants' pupil was being recorded, along with response times and accuracy. At the end of each trial in both acoustic conditions, participants have to fill a self-report questionnaire about their own perception of fatigue (which includes feelings of tiredness, headache, concentrations problems). The results revealed that there were no statistical differences between the two listening conditions, neither for response times nor for accuracy, while participants showed a larger mean pupil response in typical listening condition than in the ideal one, which is coherent with the idea that a higher noise level lead to higher listening effort.

Another study (Steel 2015) used pupillometry to examine the relationship between listening effort and "binaural fusion" (the process of combining two sounds presented to each ear) in a group of 25 deaf children with cochlear implants: the researchers aimed to explore whether this binaural fusion reduces listening effort or not. They asked participants to listen to acoustic click-trains and to tell whether they heard one single sound or two separate ones. Pupillometric results indicated that pupil diameter was larger when the perception of binaural fusion was lower.

Guidelines for Assessing Listening Effort in Children with Pupillometry

It can be helpful to give some advices on assessing listening effort in children, as there are not so many studies on the topic:

Setting: usually listening-related experiments require the avoidance of background noise (e.g. traffic or voices), so it is preferred to run the experiments in soundproof rooms or cabins. If the study requires background noise, it should be avoided natural environmental noises: instead, it is recommended to use a custom-made sound, built with specific features like constant pitch or volume.

Luminosity: a good lightning system is fundamental for an optimal outcome of the experiment. As light interfere with pupil dilation, it is necessary to keep the light constant: in order to do so, it is suggested to measure the room illumination with a lux meter.

Eye-trackers: it is recommended to use head-mounted eye-trackers with children, as they are easier to use and more comfortable to wear than screen-based eye-trackers. Moreover, unlike the screen-based eye-tracker, this kind of device does not require standing still in order to register pupil data, so it is more practical not only with children but also with other population who struggle with patience and inhibitory abilities, like people with ADHD, ASD or other kind of diseases.

Eye trackers: advantages/disadvantages

The screen-based eye tracker is very common and strongly recommended for observations of screen-based stimuli (e.g. pictures, videos, text, etc). Although desktop eye trackers can be more comfortable for some participants, they are not suitable for some populations. With this type of eye tracker, subjects are asked to look at the screen avoiding moving their head or themselves as much as possible: this demand could be fatiguing and requires patience and inhibitory abilities, a requirement that some populations may find hard to accomplish (e.g. children, people with ADHD, ASD or other kinds of diseases). Also, this type of eye-tracker needs a laboratorial setting.

Glasses, instead, are especially used in outdoor testing and task performance, as they are mobile and small-sized. As it's portable and not strictly necessary to remain still, this kind of eye tracker is not only children-friendly, but also practical for everyone who struggles to reach the laboratory. (Figure1)

Conclusions

Listening effort is strongly related to cognitive resources. In fact, in case of noisy environment, the cognitive system demands additional effort and therefore the cognitive abilities needed to perform a specific task becomes impoverished.

Listening effort has therefore negative effects on cognitive abilities, especially in children (Klatte 2010).

Inadequate acoustic conditions and listening impairments may affect scholastic performance.

It is therefore important to have a more objective method for assessing listening effort. Pupillometry could be a good solution for evaluating the effect that background noise has on children' cognitive abilities, particularly in the case of hearing-impaired children.

While one of the aims of this review were to report the results found up to date on studies that assessed listening effort on children with pupillometry, it is surprising the scarcity of studies revising this question by means of this technique.

This becomes more challenging especially with children, since there are not really clear guidelines and references to be referred.

The results of this review could have direct implications for the scientific community, making clear the importance of assessing listening effort on children by means of a more objective technique and providing guidance for implementing future pupillometry studies.

In particular, studies that analyse the effect of the listening effort on children with hearing impairment by using pupillometry could make an important contribution to promoting and highlighting the problem of classroom acoustics and the necessity of ensuring good listening conditions.

Figure 1. Example of use of eye tracking glasses for pupil size measurement.

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