Augmented Metacognition: Exploring Pupil Dilation Sonification to Elicit Metacognitive Awareness

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Abstract
Metacognitive awareness enables people to make conscious decisions about their own cognitions, and adapt to meet task performance goals. Despite the role of metacognition in task performance, technologies that effectively augment metacognition are scarce. We explore a novel approach to augment metacognition based on making the eye's pupil dilations, which associate with a variety of cognitions, audible via sonification in real-time. In this exploratory study, we investigated whether pupil dilation sonification can elicit metacognitive awareness. Our findings suggest that correlations between a variety of cognitions, e.g., attentional focus and depth of thinking, and sounds generated by the sonification can emerge spontaneously and by instruction. This justifies further research into the use of pupil dilation sonification as a means to augment metacognitive abilities.

Author Keywords
Augmented Metacognition; Biofeedback; Embodied Information; Metacognition; Pupil Dilation; Sonification.

Introduction
Awareness about your own thinking, or *metacognitive awareness*, enables you to adapt cognitions to meet

task demands [12]. It can help compensate for lower IQ [31], improve learning [33], and benefit self-confidence [18]. However, technologies that augment metacognition are scarce [16]. We propose that by making pupil dilations audible in real-time with a *pupil dilation sonification* [cf. 35], correlations can emerge between the sounds generated by the sonification, and the cognitions that associate with changes in pupil dilation [8, 21]. When such correlations emerge, changes in the sound can bring changes in cognition into awareness, i.e., elicit metacognitive awareness. In this paper, we explore the potential of pupil dilation sonification to elicit metacognitive awareness; as a first step toward a novel way to augment metacognition.

Metacognition and its augmentation

Metacognition can be defined as the awareness and control of one's own cognitive processes [1]. When changes in cognitive processes enter awareness, decision making about one's cognitive behaviour, e.g., for task performance goals, can take place. For example, awareness about sustained attentional focus can aid in the appraisal of what kind of task requires such focus [cf. 36]. This, in turn, can be used to exert control over one's own cognition in order to effectively adapt to changing task demands [11].

However, *technologies* that effectively augment metacognition are scarce [16]. Typically, closed-loop systems that classify cognitions based on physiological data [23] are used to select and present feedback to support metacognitive awareness and control [25]; and thus, in turn, affect cognition. However, such classification models are error prone [14], and generalise poorly to situations not contained in the data these models are developed from [22]. Even if cognitions could be classified accurately [14], other information that is necessary to enable metacognition [12], such as task performance appraisals, may not be available to the technology [cf. 5, 6, 7]. Overcoming these issues may be necessary to truly enable metacognitive augmentation. This study presents a first step toward that aim. We build on the fact that people themselves have access to the necessary information, as it resides in their own mental environment; and focus on bringing this information into people's awareness; empowering them to adapt and control their cognitive processes.

The pupil dilation-cognition link

Technologically augmented metacognition could be based on the eye's *pupil dilations*. The pupil is a circular opening that dilates and constricts [3] to regulate the amount of light that falls onto the retina [36]. Pupil dilation also associates with the type and amount of allocation of *cognitive resources* [26] and tracks changes in cognition rapidly [24]. Task-evoked pupil dilation associates with the allocation of cognitive resources to a task, e.g., attentional focus [15] and mental effort [8]; task-independent pupil dilation associates with the allocation of cognitive resources to task-irrelevant information, e.g., distractibility [15] and mind wandering [28]. Similarly, the association between pupil dilation and depth of thinking [2] and cognitive load [17] can be explained in this way.

Being able to perceive one's own physiological changes can serve as *embodied information* about the cognitions these changes associate with [30]. For example, mechano- and thermoreceptors in the skin enable us to sense when we are sweating [10], and when engaging in a difficult exam, this may elicit

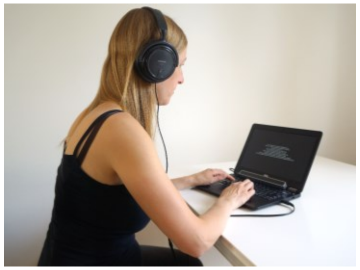

Figure 1 Setup used in the experiment. Participants solve a mathematics problems presented on a computer screen; while listening to a sonification of their own pupil dilation data that is captured and streamed by an eye-tracker in real-time.

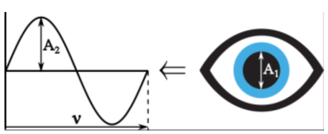

Figure 2 Illustration of the pupil dilation-to-sound mapping. The size of the pupil (A_1) is mapped in real-time to the amplitude (A_2) of a continuously playing sine wave (v=440Hz), and presented to the user during a problem solving task.

metacognitive awareness about the difficulty of the exam [29]. As pupil dilation tracks changes in a variety of cognitions rapidly [8, 24], it could be a rich source of embodied information [11]. However, one can normally not perceive one's own pupil dilations. Therefore, it could be that a technology that makes a person's own pupil dilation perceivable can be used as a basis for a new way to *augment metacognition*.

Using pupil dilation sonification to augment metacognition

We propose a novel way to augment metacognition via *pupil dilation sonification.* We conjecture that perceiving one's own pupil dilations can elicit *metacognitive awareness*. As cognitions change, associated pupil dilations rapidly follow [24]. When these changes are perceived via audible sound, it might enable one to learn correlations between one's own pupil dilations and related cognitions [cf. 21]. These correlations then potentially can function as embodied information about if, when, and what cognitions change during a task [cf. 30], i.e., help elicit metacognitive awareness [11].

In this study, we take the first steps to explore whether, what, and when correlations emerge between sound generated based on pupil dilation and related cognitions *spontaneously*; and we check whether people can experience *instructed* relations between the sound and pupil dilation related cognitive processes.

Method

An exploratory study was conducted to investigate the conjectures developed in the above.

Participants

Twenty people participated (M_{age}=22.68, SD_{age}=5.11, $Range_{age}$=18-38, 16♀, 4♂). Participation required (past) involvement in higher education. They were Dutch. Participants' self-reported mathematical expertise was above average (M=6.58, SD=1.29, Range=2-7). Course credit was offered where appropriate.

Pupil dilation sonification

Sonification [35] was used because of the high temporal resolution of the auditory sense [20] and because it allows us to make pupil dilation changes perceivable in detail [19]. The Eye Tribe eye-tracker streamed the mean pupil size of both eyes at 60 Hz [32] to a custom sonification program made in Cycling '74 Max 7 [4]. To scale the streaming data to a 0-1 range a 15 micrometre minimum pupil size was assumed and a maximum was captured while darkening the room. Signal loss (e.g., due to blinking) was handled by retaining the last data point before signal loss until new data was received. The data stream was resampled at 44.1 KHz and interpolated. See Figure 1 for the setup used.

The pre-processed *pupil dilation* data controlled the *amplitude of a sine wave* (*v*=440Hz, Figure 2). Pupil dilations linearly increased, whereas constrictions linearly decreased the volume of the sine wave. Initial pilot testing suggested that this yielded more clearly discernable results and was less intrusive than other combinations that varied in type, i.e., mapping to volume and frequency, and in wave form, i.e., noise, sine, saw, and square waves. The sounds were presented through headphones. Dimmed lighting conditions (room, screen) were used to minimize interference from the pupil's light reflex [36].

T1	1	2	3	4	5	6	7	8	9	10	11	12
	E	M	M	M	E	M	M	H	E	H	H	E

T2	1	2	3	4	5
	E	M	H	H	E

Table 1 Presentation order of mathematics problems in part one (T_1) and part two (T_2) of the task. Presentation index (numbers) and difficulty level (E=easy, M=medium, H=hard).

T_1	*Did you notice anything particular about the sound*
	If so, what behaviours correlated with the sound
	When did you notice a correlation between the sound and your behaviour
T_2	*Were you able to correlate the change in sound with your state of mind now that you know that it was directly influenced by it*

Table 2 Questions asked after part one (T_1) and part two (T_2) of the Presentation order of mathematics problem solving

Problem solving task

A *mathematics problem solving task* was developed during which the sonification was used. Mathematics involves cognitions that associate with pupil dilation, e.g., attentional focus [8]; and can be manipulated by varying the mathematics problems' difficulty [13]. Participation required (past) involvement in higher education so that three difficulty levels could be based on educational norms: *easy*, problems people can solve after primary school; *medium*, problems people can solve after high school; *hard*, problems at a behavioural sciences undergraduate level. The difficulty of the problems was gradually increased, and interspersed with easy problems (Table 1). Pilot tests suggested this affected the pupil dilation-cognition link more effectively compared to e.g., random presentation.

The first part of the task consisted of twelve mathematics problems (Table 1 and cognition. , T_1). No information was given about the link between the sounds heard and cognition. This was done to explore if and what correlations between the sound and cognitive processes emerge *spontaneously*. The second part was preceded by the instruction that there exists a link between "…the amount of cognitive resources allocated to the task and the changes in volume of the sound". Participants were then instructed to try to solve an additional five problems (Table 1, T_2). This was done to explore whether *instruction* enabled experiencing a given link between the sounds and cognition.

Questionnaire

To explore whether changes in the sounds generated by the pupil dilation sonification elicited awareness about related cognitions *spontaneously*, we asked participants to elaborate on whether, what, and when correlations between their behaviour and the sounds emerged after the first part of the task (T_1). Responses were clustered into categories based on (a) type of response (e.g., deep thinking', 'when staring'), and (b) whether the responses related to cognitions (e.g., 'concentrating'), oculomotor behaviours (e.g., 'blinking'), or no associations. After the second part (T_2) we explored whether changes in the sounds brought changes in the *instructed* relationship between the sound and cognition into awareness, by inquiring about the participant's ability to perceive the instructed correlation. The questions are presented in Table 2.

The *qualities of the sound* itself may also affect the participants. We thus asked to describe the sound itself. Responses were clustered by (a) type (e.g., *'annoying'*), and (b) valence (e.g., *'negative'*). This was done to gather data to help improve future versions of the sonification. To gain some insight into the socio-demographics of the sample, participants were asked to report their age, gender, and education level, but also mathematical ability (very poor=1, very good=10).

Procedure

Participants were seated behind a computer screen and introduced to the study. Information that could reveal the purpose of the study was withheld. Participants reported their socio-demographics and signed informed consent. Task instructions followed, the eye-tracker (9-point calibration) and sonification were calibrated. Participants put on headphones and adjusted loudness to comfortable levels. They then engaged in part one and two of the mathematics problem solving task while hearing the sounds generated by the pupil dilation sonification. After part one and two they filled in the questionnaires, were debriefed, and sent on their way.

Results

The results suggest that people can correlate sounds generated based on pupil dilation with their cognitions.

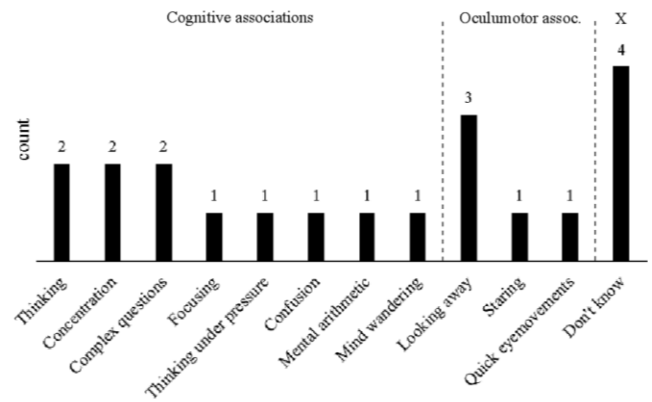

Figure 3 Correlations reported between the sounds generated by the pupil dilation sonification and behaviours.

Eighteen participants (90%) reported they noticed a link between the sound and their behaviour, two (10%) did not. Eleven (55%) suggested a correlation with a cognitive processes, including thinking, concentration, focus, and dealing with complex questions (Figure 3); five (25%) correlated the sound to oculomotor behaviours, such as looking away, staring, and moving the eyes quickly; whereas four participants (20%) did not uncover such correlations *spontaneously*. Relatedly, fifteen participants (78%) reported that the sounds changed when there was a change in cognition or related behaviour (Figure 4); whereas two participants (11%) thought the sound changed due to oculomotor activity only; and two (11%) did not think the sound changed at any particular moment. When *instructed* that the sounds correlate with the amount of cognitive resources allocated, fifteen participants (75%) experienced this correlation, whereas five (25%) did not. These findings indicate that some people are likely to correlate the sounds to oculomotor behaviours, whereas for some it may not be possible to experience such correlations at all. However, most people are able to correlate the pupil dilation sonification sounds with cognitive processes *spontaneously* and by *instruction*, which suggests pupil dilation sonification has the potential to help elicit metacognitive awareness.

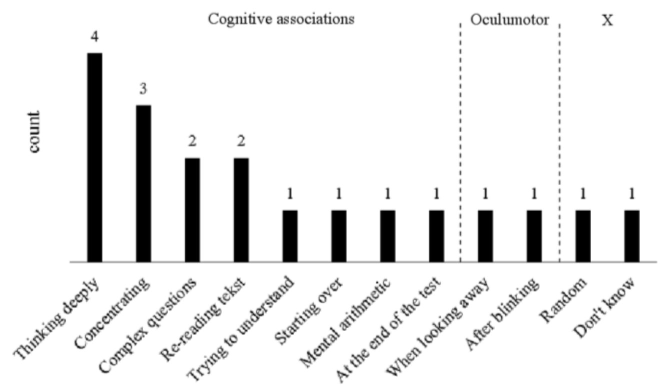

Figure 4 Indication of when the sounds generated by the pupil dilation sonification changed during the problem solving task.

However, there were issues with the quality of the sounds generated by the pupil dilation sonification (Figure 5). Fifteen negative responses (68%), e.g., that the sound was annoying or distracting, seven neutral responses, e.g., that it sounds like a radar (32%), and no positive responses (0%) were reported. Despite its apparent ability help elicit metacognitive awareness, the findings also suggest issues with the use of (our) pupil dilation sonification, which requires further study.

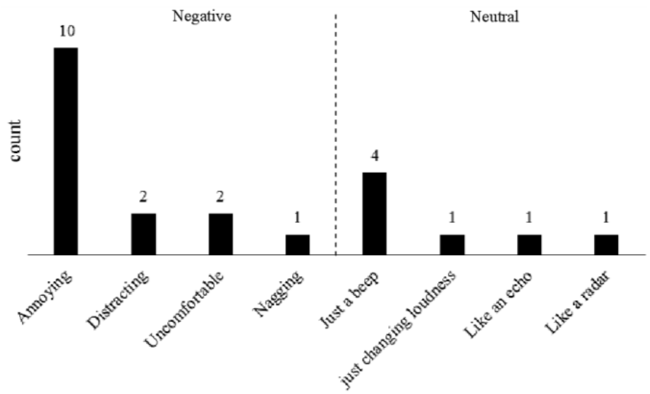

Figure 5 Experiences and attribution to the sound itself.

Discussion and conclusion

In the present study we explored the potential of pupil dilation sonification for eliciting metacognitive awareness. The results showed that most people are able to correlate the pupil dilation sonification sounds with cognitive processes *spontaneously* and by *instruction*. However, some tend to correlate the sounds with oculomotor behaviours, whereas a small minority was not able to perceive a correlation at all. This preliminary evidence suggests that pupil dilation sonification could potentially be a novel way to augment metacognition, but more work is needed.

There are of course limitations. For example, the full range of possible correlations between the pupil dilation sonification sounds and cognition has not yet been explored because a) the mathematics task mostly manipulated task-evoked rather than task-independent pupil dilations [8], and b) light can cause larger dilations than cognition, biasing correlations between sound and oculomotor behaviour [3]. Second, negative responses to the sound itself may have influenced metacognitive awareness (Figure 5), introducing uncertainty about the validity of our approach. Third, caution about any conclusions about using pupil dilation sonification to eliciting metacognitive awareness and augment metacognition is needed as no control group was used and task performance was not measured.

Future work will address these limitations. First, we will explore how to mitigate negative responses to the initial version of the sonification, by a) exploring sparsity, e.g., by sonifying change in pupil dilation, b) using non-intrusive sounds, e.g., café-sounds or waves; but c) it might also require translating pupil dilations to other senses, e.g., haptics or vision [9]. Second, we will explore how to improve the elicitation of metacognitive awareness, by a) developing a sonification that emphasizes differences in task-evoked and task-independent pupil dilations, which signify different cognitions [8]; and (b) test these in a wider range of tasks fully the range correlations between pupil dilation and cognition. Third, replication is advised with a control (fake sonification) to further confirm the theoretical assumptions that underlie our approach.

The contribution of this study is thus preliminary evidence that making pupil dilation audible can elicit metacognitive awareness. Given the role of such awareness in task performance, it may have potential to develop a novel technological approach that can augment metacognition to help people to get the most out of their own cognitive capabilities.

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