Pupil Diameter as Implicit Measure to Estimate Sense of Embodiment

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Abstract

We explore pupil diameter (PD) as estimator of Sense of Embodiment (SoE) using data of three user studies. We hypothesize that pupil diameter reflects SoE in a direct and indirect way. If individuals feel strongly embodied, presenting an emotional stimulus like a threat to the surrogate will produce a strong response, as if the stimulus would be presented to their own body. This would lead to a positive correlation between SoE and pupil dilation during the presentation of emotional stimuli. Besides this direct effect, there may also be an indirect effect. It is postulated that higher degrees of embodiment reduce workload when controlling a surrogate. This indirect effect of embodiment through lower workload on the PD would result in a negative correlation between SoE and PD since lower workload results in smaller PD. These direct and indirect effects were partially confirmed by the results of three experiments. We observed that PD and SoE are positive and direct correlated in case of emotional stimuli subjected to the surrogate (e.g. a threat), and that PD tended to be smaller for participants who experienced a condition designed to provide high SoE compared to one designed to provide low SoE.

Keywords: embodiment; pupil diameter; measuring; physiology; teleoperation.

Introduction

SoE is the ensemble of sensations that arise in conjunction with having and controlling a surrogate such as a robotic device, a virtual avatar, or a mannequin (Kilteni, Groten, & Slater, 2012; Falcone, Englebienne, Van Erp, & Heylen, 2022). We consider the SoE as characterized by three components: 1) sense of ownership, namely the feeling of self-attribution of an external object or device (Kilteni et al., 2012; Krom, Catoire, Toet, Van Dijk, & van Erp, 2019). 2) Sense of agency, defined as the feeling of having motor, action and intention control over the surrogate (Kilteni et al., 2012; Lenggenhager, Mouthon, & Blanke, 2009). 3) Sense of self-location, referring to the volume of space where one feels located (Kilteni et al., 2012). Usually, self-location and body-space coincide so that one feels located inside one's own physical body (Lenggenhager et al., 2009) (out-of-body experiences can be an exception (Ehrsson, Spence, & Passingham, 2004)). Due to its complexity, SoE lacks a standard assessment framework.

Generally, measurement of SoE can be divided in explicit and implicit measures. Explicit measures include self-reports and standardized questionnaires (e.g., (Peck & Gonzalez-Franco, 2021)). Implicit measures refer to the body response to certain stimuli and include Heart Rate (HR) and Skin Conductance Response (SCR) (Ehrsson, Wiech, Weiskopf, Dolan, & Passingham, 2007)). While explicit approaches try to address specific components of SoE, implicit measures may not exclusively reflect a specific SoE component. However, explicit approaches are subjective measures and depend on different factors of the user experience, certain biases and language (e.g. see (Joshi, Li, Kalwani, & Gold, 2016)). Therefore, it is recommended to use a combination of explicit and implicit measures to assess SoE.

However, most used implicit measures (if included at all) are HR and SCR and the field may benefit from exploring other physiological measures to assess SoE.

PD, heart rate (HR) and SCR are physiological measures reflecting the functions, behaviours, and reactions of the human body to both changes in the outside environment and inside the body itself.

In J. Culbertson, A. Perfors, H. Rabagliati & V. Ramenzoni (Eds.), *Proceedings of the 44th Annual Conference of the Cognitive Science Society.*

These physiological measures are known to reflect emotional and cognitive state (van Erp, Brouwer, & Zander, 2015; Mathôt, Grainger, & Strijkers, 2017; Wang et al., 2018; Gutjahr, Ellermeier, Hardy, Göbel, & Wiemeyer, 2019), and to compare the type and accuracy of information that they can provide (Hogervorst, Brouwer, & Van Erp, 2014). PD is considered to reflect autonomic arousal raised by emotional stimuli of an individual (Oliva & Anikin, 2018). It is also a good measure of cognitive workload (May, Kennedy, Williams, Dunlap, & Brannan, 1990; Porter, Troscianko, & Gilchrist, 2007; Hampson, Opris, & Deadwyler, 2010), and may even be more sensitive than HR and SCR (Hogervorst et al., 2014). An increased diameter is associated with increased degree of difficulty of a task.

SCR and HR are currently the main assessments of SoE. We are interested in exploring if and how PD is correlated with SoE. When individuals feel strongly embodied, stimulating the surrogate will produce the same effect that could be detected while stimulating their own body (such as arousal, emotional changes, and cognitive workload). PD reflects uncertainty, surprise, and reflects reward prediction errors (Toet, Kuling, Krom, & Van Erp, 2020). Stimulation of the autonomic nervous system's sympathetic branch induces pupil dilation, whereas stimulation of the parasympathetic system causes constriction. We assumed that during an embodiment experience that stimulates SoE, the pupil will be constricted on average (unless a stressful event happens or is introduced in the embodiment experience). In case of an embodiment experience with low SoE, the individual will feel uncomfortable and stressed in embodying the surrogate. This will cause the stimulation of the sympathetic system and pupil dilation.

We report three user studies in which we collected the PD as potential measure of SoE. PD was always collected in combination with other measures (either explicit, implicit, or both).

Hypotheses

H1) We expect a positive correlation between PD and SoE in the presence of emotional stimuli like a threat to the surrogate. We expect higher arousal when participants are more embodied and therewith a larger PD.

H2) We expect a negative correlation between PD and SoE in the absence of emotional stimuli. This is caused by the indirect effect of workload: Higher SoE will reduce workload and lower workload results in smaller PD. For conflicting sensory cues, we expect a lower SoE, a higher workload and thus a larger PD.

Method

Ethical Approval

The ethics committee of the University of Twente approved User Study 1 (RP 2021-111) and User Study 2 (RP 2020-132), while the ethics committee of TNO approved User Study 3 (RP 2021-088).

User Studies

User Study 1. We wanted to validate PD as an implicit approach to measure SoE. To do that, we designed an embodiment experience in which we focused on the manipulation of the sense of ownership and sense of self-location in a between group design with two conditions: one group experienced visuo-tactile synchronous stimuli (embodied condition), while the other experienced asynchronous stimuli (not-embodied).

33 right-handed participants (between 20 and 34 years old, 16 females and 17 males) were recruited from the student body of the University of Twente, with 5 Euro as a raffle. Participants were divided into two groups: 17 participants experienced the embodied condition, while 16 participants the not-embodied one.

As a baseline to compare the novel measure, we recorded SCR and HR as additional implicit measures. Moreover, we collected the answers from a questionnaire (explicit measure) on the SoE (Peck & Gonzalez-Franco, 2021).

The experiment lasted 20 minutes. The embodiment experience was pre-recorded and participants experienced first person perspective (1PP) of a surrogate (a confederate). They were asked to sit in the same rest position described in user study 1. Participants were asked to wear a blue glove in latex on the right hand. A white tissue was used to cover participant's right wrist. In this way, they would not focus on the different features of their skin or clothes compared to the surrogate hand (we placed a white tissue also on the right wrist of the surrogate). Participants were primed with a cup of water that was placed both next to the participants and also next to the surrogate hand. Then, they were asked to wear the Empatica E4 wristband on the left wrist, used to collect SCR and HR. Finally, they put on the HTC VIVE Pro Eye, that was used to collect PD. After the eye tracker calibration, the video was displayed in the HMD and the experiment started. The surrogate was displayed in the same room and position in which the participants were. Participants observed stimuli administered to the hand of the surrogate while synchronous or asynchronous (it depended on the condition) stimuli were administered to their own hand. The experiment consisted of four different stimulation phases all focused on the right hand (see Figure 1): 1) a pen crossing the lunate, 2) a pen alternatively touching the trapetium and the lunate, 3) the experimenter finger touching each fingertip of the participant, and 4) a threat to break the embodiment illusion, namely the experimenter grab the cup of water and pour it only on the surrogate hand.

User Study 2. We investigated if individuals with high kinesthetic intelligence (experimental group) are more resilient to feel embodied with a surrogate compared to individuals with average kinesthetic intelligence (control group) (Falcone, Pradhan, Van Erp, & Heylen, 2021). We identified the experimental group in dancers and gymnasts who practice the discipline at a competitive level.

16 out of 26 right-handed participants (between 20 and 37 years old, 9 females and 17 males) were sampled from staff and student body (control group), while 10 were were sampled from dance/gymnast associations (experimental group).

For the first time, to the knowledge of the authors, PD was used as psychophysiological measure of SoE. We combined it with an explicit measure (the SoE questionnaire from (Gonzalez-Franco & Peck, 2018)).

The experiment lasted 20 minutes. Participants were asked to sit in a rest position, putting their right hand on the table as indicated by markers, and the left hand on their left leg. We asked to look at their right hand for the duration of the embodiment experience. Participants wore a blue latex glove on the right hand, and an HTC VIVE Pro headmounted headset (HMD). The HMD has an integrated eye tracker, which we used to measure and record PD. After the eye tracker calibration, a video was displayed in the HMD and the experiment started. The video consisted of a pre-recorded embodiment experience, in which participants experienced the first person perspective (1PP) of a surrogate (in this case a confederate), in the same room and position in which the participants were. The video was recorded using a ZED mini stereocamera. Participants observed stimuli and tasks administered to the hand of the surrogate while the same stimuli and tasks were administered to their real hand. The video and the HMD data were managed and collected with the platform and game engine Unity.

The stimuli and the tasks were administrated in the following order: 1) cross-modal congruency task: we designed two variants (see Figure 2): i)

Figure 1: On the left, the experimenter's perspective during the experiment. The four pictures on the right represents the participant's view during the embodiment experience and, in order, the four phases of stimulation.

in the first case, participants watched the tip of a pen touching the top of their right hand. Only three times out of six the participants' hand was actually touched by the pen. ii) Participants saw the tip of a pen and a brush alternatively touching the hand displayed in the video. Randomizing the order of the stimuli, only three times out of six the visuo-tactile information was congruent (i.e., the participant saw and was touched by the same object). 2) Linking dots: it was designed to test the sense of agency and self-location of the participants in an active task. We realized two drawings with numbers inside black dots, and a small red dot in the center of all of them. We placed a tablet with the drawing in the same position of the one that they watched in the video. They were asked to link the dots in ascending order, sliding their right index on the tablet from one red dot to the other. The experimenter had the role of placing the finger in the proper initial position and telling the participants when to move from one dot to the next one. 3) Threat: it is common to threat the surrogate to break the embodiment illusion and to assess the level of SoE through physiological measures (Ehrsson et al., 2007; Yuan & Steed, 2010; Zhang & Hommel, 2016). We primed the participants with scissors placed both on the real table and the one displayed in the video. Participant watched the scissors being grabbed and then used to hit the table next to the surrogate hand.

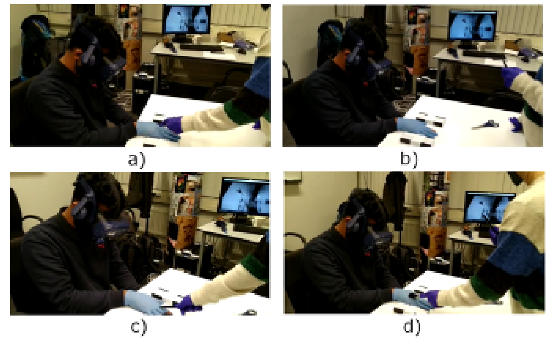


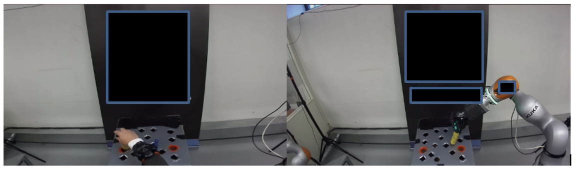
Figure 2: Pictures a) and b) represent, respectively, congruent and incongruent stimuli during the first variant of cross-modal congruency task. Pictures c) and d) represent, respectively, congruent and incongruent stimuli during the second variant of cross-modal congruency task. The screen in the picture was displaying the video of the embodiment experience, that was a reference for the experimenter to provide the stimuli.

User Study 3. We explored the relation between SoE and task performance, learning effect, and cognitive workload. We manipulated two embodiment conditions experienced by two groups: one group experienced sensory cues that support embodiment, while the other group experienced sensory cues that suppress embodiment. Each group had to face the experiment task at two levels: one with their own hand, and another time with a robotic surrogate.

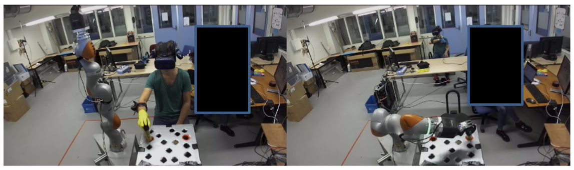
28 right handed participants (16 females and 12 males, between 19 and 49 years old) were recruited from the TNO participant pool. Participants were paid 30€ and their travel costs were reimbursed. Participants were divided into two groups: 15 participants experienced the supportive condition, while 13 participants the suppressive one.

We collected the answers from a SoE questionnaire (Peck & Gonzalez-Franco, 2021) and a cognitive workload one (Hart, 2006). As implicit measures we collected PD. Finally, we evaluated task performance.

The teleoperation setup consisted of a telemanipulator, a haptic control interface and a visual telepresence system. The telemanipulator was the Shadow Hand Lite, equipped with 3D force sensors on its fingertips, mounted on the flange of a KUKA IIWA 7 serial link robot. The haptic control interface was realized by the haptic glove SenseGlove DK1, that tracks finger movements in 11 degrees of freedom and can provide passive force feedback on each finger. The movements of the operator's wrist in space are recorded by an HTC VIVE tracker mounted on the SenseGlove. The visual system consists of a ZED mini stereovision camera with a HTC VIVE Pro Eye relaying the visuals to the operator, while also collecting eye gaze and PD. The setup was slightly different between the two conditions. For the supportive condition, the ZED mini was placed to provide a 1PP, and the operators received the tactile feedback just in the mo-



(a) Frames extracted from the ZED mini recordings during the supportive condition. On the left, the participant's view during the human hand level. On the right, the participant's view during the robotic surrogate level.



(b) Frames extracted from the ZED mini recordings during the suppressive condition. On the left, the participant's view during the human hand level. On the right, the participant's view during the robotic surrogate level.

Figure 3: Frames extracted from the ZED mini recordings during the experiment.

ment in which they grasped and released the peg. In the suppressive condition, instead, the ZED mini was providing a 3PP by facing the operators (i.e., a mirrored perspective of the workspace). Moreover, they had to wear two thick gloves during the task accomplishment with their own hand and, while accomplishing the task using the robotic surrogate, the tactile feedback was continuous from the moment in which they grasped the peg until they released it (see Figures 3a and 3b for an overview of the setup). In both conditions at both levels, participants had to wear the HMD during the experiment.

The experiment lasted 45 minutes. Participants were asked to do a peg-in-hole task, with just two horizontal distant holes. They had 90 seconds to place the peg in the holes as many times as they could. They had to repeat the task 6 times in total, three times by hand and three times by using the robotic surrogate. Half of the participants accomplished the three trials using their own hand first, while the other half by using the robotic surrogate first. After each trial, they had to fill two questionnaires.

Results

For PD analysis, we applied a Hampel filter to remove the outliers, we used the convergency to cover missing data, and we considered the mean of the left and right pupils.

User Study 1. A two samples t-test did not report a significant difference between groups for the three physiological measures (PD, SCR and HR). We did find a significant difference on all the sub-scales of the questionnaire between the group experiencing the supportive and suppressive conditions (Appearance t_{31} = 5,57, $p < .001$, M supportive = 5.48, M suppressive = 3.80; Multisensory t_{31} = 6,43, $p < .001$, M supportive = 5.93, M suppressive = 3.76; Response t_{31} = 4,03, $p < .001$, M supportive = 4.85, M suppressive = 3.51; Embodiment t_{31} = 6,23, $p < .001$, M supportive = 5.53, M suppressive = 3.78; Ownership t_{31} = 6,19, $p < .001$, M supportive = 5.86, M suppressive = 4.03). For the suppressive group, an independent t-test reported a significant difference between the mean of PD during the embodiment experience (M = 4.68mm) and the threat (M = 4.57mm)(t_{15} = 3.22, p = .006). No effects were found for HR and SCR in this group. For the supportive condition, we found a significantly difference between the mean of HR during the embodiment experience (M = 77,41bpm) and the threat (M = 74,43)(t_{15} = 3.21, p = .006). No effects of SCR and PD were found in this group.

User Study 2. A two samples t-test indicated that there was not a significantly smaller mean PD in the control group, that was expected to experience higher SoE (M = 3.87mm), than the experimental group (M = 3.85mm) (t_{20} = 0.47, p = .642). The questionnaire responses did also not report significantly higher mean scores for neither of the three embodiment components. However, within the control group, an independent t-test reported a significantly larger mean PD at the moment of the threat, when participants were expected to experience higher SoE (M = 3.69mm), than during the first part of the embodiment illusion (M = 3.87mm) (t_{14} = 4.52, $p < .001$), i.e. a positive correlation between SoE and PD in the presence of an emotional stimulus. While for the experimental group, we did not find a significant difference of the pupil size between the threat (M = 3.98mm) and the first part of the embodiment illusion (M = 3.85mm)($t_6 = 1.36$, p = .223).

User Study 3. For the supportive condition, we observed a significantly smaller mean pupil dilation when participants accomplished the task with their own hand (M = 4.39mm) than with the robotic surrogate (M = 4.68mm) ($t_{14} = 4.08$, p-value = .001), the embodiment questionnaire responses showed the same effect (Ownership $t_{14} = 4.44$, $p < .001$, M human hand = 5.89, M robotic hand = 3.92; Agency t14 = 9.95, $p < .001$, M human hand = 6.73, M robotic hand = 3.69; Self-location t_{14} = 3.59, p = .003, M human hand = 4.08, M robotic hand = 3.11). Of the cognitive workload questionnaire, only the sub-scale *mental workload* (M human = 2.40, M robot = 4.16)($t_{14} = 3.73$, p = .002) showed an effect. For the suppressive condition, we observed a significantly smaller mean pupil dilation when participants accomplished the task with their own hand (M = 3.68mm) and with the robotic surrogate (M = 4.13mm) ($t_{12} = 4.07$, p-value = .002), the embodiment questionnaire responses showed the same effect (Ownership $t_{12} = 7.55$, $p < .001$, M human hand = 5.70, robotic hand = 2.74; Agency $t_{12} = 6.47$, $p < .001$, M human hand = 5.89, robotic hand = 3.06; Self-location $t_{12} = 2.75$, p = .018, M human hand = 4.17, robotic hand = 3.17). The cognitive workload questionnaire also showed the same effect while using their own hand (M = 19.97) and the robotic surrogate (M = 23.59)($t_{14} = 2.30$, p = 0.040).

Discussion and Conclusion

We hypothesized that PD and SoE are positive and direct correlated in case of emotional stimuli subjected to the surrogate (e.g. a threat) (user study 1 and 2) (H1: we expect a positive correlation between PD and SoE in the presence of emotional stimuli like a threat to the surrogate.). On the basis of our results, we accept H1. The Rubber Hand Illusion presents the same effect: there is no effect as long as there are no emotional stimuli, while there is a large effect when the rubber hand is under threat (Ehrsson et al., 2004, 2007; Petkova & Ehrsson, 2008; Newport & Preston, 2010; Garbarini et al., 2014).

We observed that PD was, or tended to be, larger for participants who experienced a condition designed to provide low SoE compared to one designed to provide high SoE (user study 1 and 3). User study 2 did not confirm this effect due to the design of the experiment: both groups experienced the same supportive embodiment illusion. This finding is in line with the predicted indirect effect of SoE on pupil dilation through workload ((Newport & Preston, 2010; Hogervorst et al., 2014)) (H2: we expect a negative correlation between PD and SoE in the absence of emotional stimuli). We partially accept H2, due to the results of user study 1. Even if the PD of the supportive group was smaller than the suppressive one, we did not find a significantly lower mean. We would expect a negative correlation in case individuals have to perform a task with a certain amount of workload. The responses of the cognitive workload questionnaire from user study 3 confirmed this effect in the suppressive condition, in which participants had to struggle to accomplish the task with their own hand, and even more with the robotic surrogate.

We did not expect a correlation in case of emotional neutral situations were there is no threat or task to be performed with the surrogate. Indeed, in user study 1, the PD was significant just for the control group, even if in contrast with the questionnaire. In user study 2, the threat caused a dilation in both groups.

PD still needs further investigation, especially the indirect effect of SoE on PD through workload. HR and SCR are also under the influence of workload. It would be useful to define the task engagement threshold that allow these physiological measures to be effective measures of SoE. However, even considering the limitations that are in common with the other implicit measures, PD seems to be a suitable and sensitive measure of SoE.

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