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How pupil tracks cognitive processes underlying internally- and externally-directed attention tasks

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Abstract

Pupil dilation has been associated with increased cognitive load or mental effort requirements, which can be modulated by external sensory stimulation as well as internal cognition. Underlying a cognitive task are multiple interplaying processes which can be stimulus-driven, goal-driven or spontaneous. However, what remains unknown is how these multiple processes correlate with pupil size modulations and whether it is possible to dissociate their individual effects. To answer this, we employed behavioural and pupil data from two cognitive tasks performed in internal and external attention conditions, where stimulus-driven attention demands were manipulated for the same set of tasks. Using model-based analysis, we were able to dissociate within conditions, how individual processes affect pupil and also compare their effects between conditions. We made two important and novel findings – first, within both the conditions we were able to dissociate stimulus-driven and goal-driven effects. Second, when compared between the two attention conditions, we found distinct stimulus-driven attention-based effects but similar goal-directed task-based effects. Our results indicate that pupil can be used as a reliable tool to study cognition.

Keywords: cognition; eye tracking; goal-directed; internal attention; model-based approach; pupillometry

Introduction

An emerging interest has been towards understanding how our pupils represent "neuromodulation" in relation to cognition (Aston-Jones & Cohen, 2005). Since a very long time pupil dilation has been associated with cognitive load indicating our arousal and mental effort levels (Hess & Polt, 1964; Kahneman & Beatty, 1966), which can be modulated by our external sensory environment and/or internal focus mechanism. For most of the times we are involved in internal thoughts which are not related to our imminent external sensory environment (Killingsworth & Gilbert, 2010; Study et al., 2007). Such internally-directed thoughts can vary in nature from being goal-driven such as intentional planning (Spreng et al., 2010), problem-solving insights (Salvi et al., 2015, 2020), imagination (Benedek & Jauk, 2018) to abrupt spontaneous thoughts such as day dreaming, mind wandering (Smallwood & Schooler, 2013).

Past studies have shown that internally-directed cognition (IDC) can be differentiated from externally-directed cognition (EDC), which involves relation to external stimulation (Annerer-Walcher et al., 2021; Benedek et al., 2017; Ceh et al., 2021). IDC has been characterized by processes such as decoupling from external stimulus, termed as "perceptual decoupling" (Ceh et al., 2021) and coupling to internal goal-directed cognitive processes. For instance, during tasks which demand internal focus, eye behaviours indicating perceptual decoupling have been observed in order to enhance cognitive resources for better task performance. This has been demonstrated by closing of eyes to reduce visual inflow and longer blink durations (Ritter et al., 2018; Salvi et al., 2015) as well as by averting the gaze from the irrelevant external stimulus (Abeles & Yuval-Greenberg, 2017). When engaged in internal cognition, changes in pupil size (increased mean and variance) have also been observed in relation to imagined brightness changes (Laeng & Sulutvedt, 2014) as well as imagined object size and distance (Sulutvedt et al., 2018). Studies have also indicated that during internally-directed cognition, there is an increased mental effort not only due to encoding of internalized/imagined stimulus information (Benedek et al., 2016; Thompson et al., 2001) in the absence of external stimulus but also due to goal-directed task-in-hand (Annerer-Walcher et al., 2021; Ceh et al., 2021; Benedek et al., 2017; Walcher et al., 2017).

While past findings have established differences between IDC and EDC by comparing summary statistic measures such as mean pupil diameter (PD), PD variance etc. (Annerer-Walcher et al., 2021; Ceh et al., 2021; Benedek et al., 2017; Walcher et al., 2017), it remains unknown whether and how much of these differences are due to individual cognitive processes, which can either be stimulus-driven or goal-driven. To answer the question, we analysed behavioural and pupil data from an existing study (Ceh et al., 2021), that modulated internal/external attention demands by varying task-difficulty levels independently of the stimulus being absent or present. This study identified the state of stimulus absence as internally-directed attention condition and that of stimulus presence as externally-directed attention condition. We refer to the influences of these stimulus-states on pupil response as *stimulus-driven attention-based effects*, similar to (Ceh et al., 2021). Further, the study design used a same set of tasks across the two attention conditions, thus allowing us to investigate the interplaying effects of attention-based and task-based demands on *trial-wise pupil responses*. We believed that it would be informative to analyse temporal

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profile of pupil responses over a trial because mechanisms underlying goal-directed behaviour can be divided, meaningfully, into four sequential stages: encode, plan, compute, response (Anderson et al., 2016; Anderson & Fincham, 2014; Bongers & Dijksterhuis, 2009). Thus, we aimed to determine whether the individual effects of multiple cognitive processes on trial-wise pupil responses exist, and if yes, how can they be dissociated. Further, whether these effects differed between the internal and external attention conditions. Such an analysis remains largely unexplored in the domain of internally vs externally directed attention demands (Annerer-Walcher et al., 2021; Ceh et al., 2021; Benedek et al., 2017; Walcher et al., 2017), and will help answer more closely *how pupil relates to cognition*. To answer our question of study, we employed deconvolution analysis, a model-based approach used previously in pupil studies (Van Slooten et al., 2018; Wierda et al., 2012).

Methods

Participants

In this study, we analysed raw eye tracking (ET) data accessible via the Open Science Framework (https://doi.org/10.17605/OSF.IO/74VNQ). In total, 34 right-handed healthy adults participated in the experiment. Participants had normal or corrected-to-normal vision, and reported no history of ocular, psychiatric, or neurological conditions. A detailed description can be found elsewhere (Ceh et al., 2021). Four subjects were excluded from our data analysis, due to unavailability of raw data (n=1), missing experimental timeline information (n=1), and data loss because of excessive blinking and saccadic eye movements (n=2); resulting in a final sample size of 30 participants (20 females; mean age = 22.7 years, s.e.m. = 0.64).

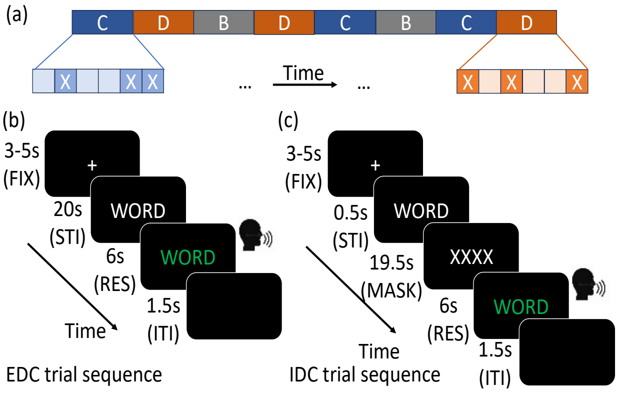

Figure 1. (a) Block sequence of the session consisting of eight blocks, shown here is one of the two possible ways - CDBDCBCD or DCBCDBDC, where C – convergent task, D – divergent task, B – baseline task. A block consisted of six trials of one task type; further any three trials were randomly chosen to be as masked or IDC trials, marked as 'X'. (b, c) A trial sequence from external and internal attention conditions (EDC, IDC); for details, see the experimental design section next.

Experimental Design

Participants performed behavioural tasks under internally-directed and externally-directed attention conditions in an approximately 27.5 min session (Ceh et al., 2021). The two conditions differed with respect to stimulus presentation period (20s) in a trial, where, in IDC the stimulus was masked after a brief presentation (0.5s) imposing internalized attention demands during the following task performance period (19.5s). On the contrary, in EDC the stimulus was visible for complete stimulus presentation period (20s), facilitating complete focus on task performance. Figure 1 demonstrates a trial sequence from both the conditions, IDC and EDC.

Within each condition, the tasks were of varying difficulty levels: a convergent task (anagram generation; CONV) and a divergent task (sentence generation; DIV). In each task, the stimulus was a meaningful four-letter word (example, 'DEAR'); resulting into four main task conditions: convIDC, convEDC, divIDC, divEDC. In CONV task, the participants had to reshuffle the letters to make a different sensible four-letter word (example, 'READ' from 'DEAR'). In DIV task, the participants had to generate a grammatically-correct sensible four-word sentence, utilizing every letter of stimulus-word as the first letter of any one word of the sentence; where each letter had to be used once, however, not restricted to be in the same order as in the stimulus-word (example, 'Robert acquires eye data'). Anagram generation task required convergent thinking (low task-difficulty) as in it the participants had to find correct answer within a narrow solution space of meaningful words, whereas sentence generation task required divergent thinking (high task-difficulty) to generate individualised solution within a broad solution space of meaningful sentences. The motivation behind analysing the effects of attention modulation across varying task-difficulty levels was that it allowed for dissociating multiple cognitive processes exerting mental effort during internal or external attention. Participants also performed a simple memory task as baseline (BASE) for both attention conditions (baseIDC, baseEDC), where they had to memorise the stimulus word.

Figure 1 demonstrates a trial sequence from both conditions IDC and EDC. Each trial started with a fixation cross (3-5s), followed by the four-letter stimulus word in white-coloured font. During IDC trial, the stimulus word was masked (XXXX; for 19.5s) following a brief presentation period (0.5s), whereas during EDC trial, the stimulus word was present for the complete presentation period (20s). Participants were asked to vocalize solutions during a response window (6s), indicated by reappearance of the stimulus word on the screen in green-coloured font (a question mark in baseline IDC and EDC). A blank screen period (1.5s) separated the trials. The experiment session consisted of 48 trials (9 convIDC, 9 divIDC, 6 baseIDC, 9 convEDC, 9divEDC, 6 baseEDC) grouped into eight blocks. For a participant, these eight blocks were arranged in either of the two possible ways: CDBDCBCD or DCBCDBDC, where C – convergent, D – divergent, B – baseline, see Figure 1. A block consisted of six trials of one task type, out of which three trials were randomly masked. More information can be found in (Ceh et al., 2021).

We did not include data from the baseline trials because of two main reasons - firstly, the participants had to memorize the stimulus word which was actively engaging memory-related processes. Instead, we believed that the participants must have passively visualized the stimulus word and given vocal response when instructed to do so. Secondly, the convergent and divergent tasks differed from the memory task with respect to how the start of response window was indicated to the participants. In the former tasks, it was indicated by reappearance of stimulus word in green font, whereas in the latter task by a question mark. Thus, we did not find the baseline task as an appropriate control task (Fetsch, 2016).

Eye tracking data preprocessing

Details about the ET set-up can be found elsewhere (Ceh et al., 2021). We pre-processed pupil data recorded at 500 Hz for each participant as follows (Ceh et al., 2021; Van Slooten et al., 2018): Saccades and blinks were detected using the standard EyeLink software and custom routines for pre-processing eye tracking data in MATLAB (version 9.9; The Math Works, Natick, MA, USA). To ensure that the main analysis was not affected by eye movements, saccades (visual angle more than 1°) and 20ms periods pre and post each saccade were removed from the trial data of the participant. A trial was not included in analysis if 20% of its samples were lost due to saccades and/or blinks. Further, linear interpolation was done for durations of signal loss (due to saccades and blinks) using interpolation window of half width 50ms pre- and post-removal periods. The interpolated signal was low pass filtered at cut-off frequency 5 Hz using third-order Butterworth filter, z-scored per participant, and resampled to 20 Hz. For the main analysis, we employed a fixed duration time series of 30.5s, starting 3s prior to the stimulus presentation till the end of blank screen period. Participants with more than 20% of trials lost were not included in the main analysis (here two such participants; total percentage of removed trials for 30 participants included in the analysis was 0.6597% ± 0.5572% (mean ± SD)).

Analysis

Behavioural data For behavioural data, attention-based effects (IDC vs. EDC) and task-based effects (CONV vs DIV) were analysed using a 2 x 2 repeated measures analysis of variance (rmANOVA) approach for performance accuracy percentage, as done previously (Benedek et al., 2017; Ceh et al., 2021). Correct or incorrect solution for each trial was used for calculating performance accuracy for each participant. No reaction time data was available (https://doi.org/10.17605/OSF.IO/74VNQ).

Eye tracking data As a preliminary test for identifying effects related to within-subject factors attention-based and task-based during stimulus presentation on the pupil data, we employed a 2 x 2 rmANOVA for mean pupil diameter (Benedek et al., 2017; Ceh et al., 2021). For each participant, we computed mean pupil diameter across stimulus presentation period (20s) of all trials of individual conditions (convIDC, convEDC, divIDC, divEDC), to capture the overall effects related to the major events of attention modulation and task performance during this period.

Although informative, none of the preliminary ANOVA analyses were able to dissociate and compare the individual effects on trial-wise variations in pupil size. These effects were due to mental effort exerted by two major cognitive processes underlying the internal/external attention task – attention modulation related to stimulus-state (stimulus word absent or present on screen), in short, *stimulus-driven attention effect* and goal-directed activity related to convergent/divergent task performance, in short, *goal-directed task-based effect*. For this, we performed group-level random-effects analysis on the contrast parameter estimates obtained individually for each of the 30 participants, explained below.

For each participant, we performed subject-level deconvolution analysis on the pre-processed pupil data (Van Slooten et al., 2018; Wierda et al., 2012). Data from both the internal and the external attention conditions was incorporated in one model (see equation (1)). The parameters were estimated using ordinary least squares solution. For details on method, refer (Van Slooten et al., 2018). In order to determine time-dependent parameters representing variance in pupil size at time sample *w* of a trial due to factors stimulus-state and task, $\beta_{sti}^{att}(w)$ and $\beta_{tsk}^{att}(w)$, respectively, we estimated the pupil response $\hat{y}_{trl}^{att}(w)$ at a time sample *w* of a trial *trl* of specific attention condition *att* (say, for internal attention $\hat{y}_{trl}^{IDC}(w)$). We did this by modelling each time sample of the trial using the following regressors in the design matrix $X(w)$: 1) a stimulus-state regressor $x_{sti,trl}^{att}(w)$ modelling any event (such as presentation of fixation, stimulus 'WORD' in white font, masked stimulus 'XXXX' in white font, response 'WORD' in green font) in a trial as 1 and blank screen as 0; (Please note that at any given time sample in a trial, only one event takes place.) This regressor captured the unmodulated/sustained variance in pupil size across trials of specific attention demands; and 2) a task-difficulty regressor $x_{tsk,trl}^{att}(w)$ modelling trial-by-trial difficulty levels for convergent and divergent tasks as 1 and 2, respectively. This regressor captured the modulated variance in pupil size due to task-difficulty level across specific attention condition. The task-difficulty data was z-scored for each participant. There was no intercept term as both the dependent and independent variables were mean-centred. Both the above regressors contained 0 for samples from trials of the other attention condition type.

Subject-level model for time sample *w*,

$$\hat{Y}^{att}(w) = X(w) * \beta(w) \qquad \ldots(1)$$

where, $\hat{Y}^{att}(w)$ is 36 x 1 size vector of estimated pupil data at time sample *w* from IDC and EDC trials (9 convIDC, 9 divIDC, 9 convEDC, 9 divEDC; see (2)), $X(w)$ is the design matrix of size 36 x 4 and $\beta(w)$ is the vector of parameter estimates of size 4 x 1.

$$\hat{y}^{att}_{trl}(w) = \beta^{IDC}_{sti}(w)x^{IDC}_{sti,trl}(w) + \beta^{IDC}_{tsk}(w)x^{IDC}_{tsk,trl}(w) + \cdots$$
$$\beta^{EDC}_{sti}(w)x^{EDC}_{sti,trl}(w) + \beta^{EDC}_{tsk}(w)x^{EDC}_{tsk,trl}(w) \quad \ldots(2)$$

For group-level inference, we performed the random effects analysis using one-sample t-test on contrast parameter estimates obtained from subject-level inference of each included participant (Penny and Holmes, 2003). Our main aim was to dissociate and compare the individual effects on trial-wise variations in pupil size due to stimulus-driven attention and goal-directed task processes. We used linear contrasts for analysing effects within- and between-attention conditions.

First, we performed within-condition analyses for both internal and external attention conditions: the main effect of attention demands on pupil responses was determined by testing parameter estimates of stimulus-state regressor $\beta^{att}_{sti}(w)$ to be significantly different from zero and similarly, the main effect of task-difficulty on pupil responses by testing parameter estimates of task-difficulty regressor $\beta^{att}_{tsk}(w)$ to be significantly different from zero, both the effects indicating how much of variation in pupil size was due to separate factors. Additionally, to determine which of the two effects were significantly contributing to the pupil response at each time sample of the trial, we contrasted the parameter estimates of the two regressors, $\beta^{att}_{sti}(w)\ vs.\ \beta^{att}_{tsk}(w)$, and tested them to be significantly different from each other.

Next, we performed between-conditions analyses to determine whether the two contributing factors of pupil size modulations were significantly different between internal and external attention conditions: we contrasted the parameter estimates of individual regressors, $\beta^{IDC}_{sti}(w)\ vs.\ \beta^{EDC}_{sti}(w)$ and $\beta^{IDC}_{tsk}(w)\ vs.\ \beta^{EDC}_{tsk}(w)$, and tested them to be significantly different from each other.

Results

rmANOVA results

Overall, the participants performed correctly 76.85 % (s.e.m. = 1.88) of all trials. The 2 x 2 rmANOVA (within-subjects factors attention and task) revealed a significant main effect of attention on both performance accuracy ($F_{1,29} = 6.20, p < 0.05$) and mean pupil diameter (z-scored) ($F_{1,29} = 46.79, p < 0.001$). There was lower performance in internal attention task (mean = 74.44%, s.e.m. = 2.67) in comparison to external attention task (mean = 79.26%, s.e.m. = 2.63), indicating that performing tasks without external stimulus input was more difficult and exerted more mental effort due to internalized/imagined stimulus information, which was consistent with past studies (Benedek et al., 2017; Ceh et al., 2021) and also with larger pupil dilation in internal attention task (mean = 0.7433, s.e.m. = 0.05678) in comparison to the external counterpart (mean = 0.1487, s.e.m. = 0.0581).

There was a significant main effect of task on both performance accuracy ($F_{1,29}$ = 17.06, $p < 0.05$) and mean pupil diameter (z-scored) ($F_{1,29}$ = 76.92, $p < 0.001$). The performance in anagram task was higher (or convergent task; mean = 82.40%, s.e.m. = 2.42) in comparison to sentence generation task (or divergent task, mean = 71.29%, s.e.m. = 2.70), indicating that the divergent task was more difficult than the convergent task and increased mental effort due to task difficulty, as reflected in larger pupil dilation in divergent task (mean = 0.7441, s.e.m. = 0.0552) in comparison to convergent task (mean = 0.1479, s.e.m. = 0.0595). There were no significant interaction effects revealed for both the performance accuracy ($F_{1,29}$ = 0.097, p = 0.758) and the pupil ($F_{1,29}$ = 2.00, p = 0.167).

Eye tracking results: Deconvolution analysis

Dissociable and distinct effects of attention-based and task-based processes on pupil size: within-condition

Figure 2 presents the group-level inference results for both the within-condition (Figures 2a, 2b) and between-conditions analyses (Figure 2c). In the internally-directed attention condition (see Figure 2a), when stimulus was presented briefly for about 0.5 s (3s – 3.5s) and then masked 'XXXX' for the remaining period 19.5s (3.5s – 23s), it modulated attention and exerted higher mental effort, i.e., stimulated maintenance and manipulation of internalized/imagined stimulus information in the absence of external stimulus for the convergent and divergent tasks performance. We found that the stimulus-driven attention-based and goal-directed task-based effects were dissociable and showed distinct profiles in a trial. (In Figures 2a, 2b: Grey horizontal bars indicate trial's time samples when parameter estimates (betas) were significantly different from zero at p < 0.05; light grey and dark grey bars for beta values of stimulus-state and task-difficulty regressors, respectively; black horizontal bars indicate time samples when beta values of the two regressors were significantly different from each other at p < 0.05).

We observed an early steep rise in (z-scored) pupil dilation (see Figure 2a; approx. 3.5s – 6.5s; solid magenta curve) just as the stimulus word was masked at 3.5s, similar profile not present in external attention pupil response (see Figure 2b; solid green curve). This was primarily driven by mental effort due to internally-directed attention processes which start to slowly fade away as soon as the stimulus word information was encoded internally. This was evidenced not only by increasing (approx. 4s – 7s) and decreasing (approx. 7s – 21.5s) beta values of stimulus-state regressor (dashed red curve) but also by insignificant beta values of task-difficulty regressor (4.33s – 6.26s; solid red curve). Intermediately, a tonic (sustained) pupil dilation response (approx. 6.5s - 11.5s) was an outcome of weakening internally-directed attention related to encoding of stimulus word and slowly strengthening goal-directed processes required for task performance where the participant had to search for a solution in the solution space for either the convergent anagram generation task or the divergent sentence generation task, evidenced by increasing beta values of task-difficulty regressor. As soon as solution (either correct or incorrect) was obtained in participant's mind, a gradual constriction of pupil (approx. 11.5s – 23.5s) was observed, which was again an outcome of further weakening internally-directed attention and relatively sustained goal-directed processes required for maintenance of solution in participant's mind until response period starts. This was evidenced not only by significant beta values of individual regressors in the mentioned duration but also by the insignificant contrast between beta values (absence of black horizontal bar indicates insignificance).

Further, a biphasic pupil response of lower magnitude observed in response window (Figure 2a; 23-29s; solid magenta curve), was primarily driven by goal-directed processes required for last stage of the task which was response generation (Jiang et al., 2014; Van Slooten et al., 2018), evidenced by significant beta values of task-difficulty regressor in the mentioned duration. Also, the insignificant beta values of stimulus-state regressor (21.61s – 27s) revealed that the stimulus word appearing in green font to indicate start of response period essentially did not have an effect on pupil response. Overall, in internally-directed attention condition, we found that the mental effort due to stimulus-driven attention-based and goal-directed task-based cognitive processes exerted interplaying yet dissociable effects on the pupil size.

In externally-directed attention condition (see Figure 2b), when stimulus word was presented for the entire presentation period of 20s (3s – 23s) during task performance, we found dissociable and distinct effects of stimulus-driven attention and goal-directed cognitive processes on pupil responses like IDC. However, the mean trial-wise dilation in EDC (solid green curve) was significantly lower in magnitude in comparison to IDC. A two-sample t-test done for mean pupil sizes of IDC and EDC at each time sample across participants revealed significant difference at $p < 0.5$ between mean pupil sizes of the two conditions from 3s – 30s. This was primarily an outcome of insignificant effects of stimulus-state (4.20s – 13.58s; dashed blue curve; for significance see light grey horizontal bars), indicating that when external stimulus was present on screen it required lower mental effort in comparison to when absent. In the presence of external stimulus, the goal-directed processes were facilitated and the participants were easily able to focus on task performance without having to maintain/manipulate imagined stimulus information (Benedek et al., 2016; Thompson et al., 2001), evidenced both by higher task performance accuracy in EDC and by significantly greater beta values of task-difficulty regressor (solid blue curve) than those of stimulus-state regressor throughout the trial, except for a small duration (4.46s – 6.37s; for significance see black horizontal bar) during which the external stimulus-driven attention effects gradually increased (although insignificant) related to processing of stimulus word appearing on screen. Thus, in externally-directed attention condition, we found that the pupil responses were primarily driven by mental effort exerted due to goal-directed processes underlying task performance.

Additionally, both phasic and relatively tonic activity was present during a trial in both the attention conditions. This indicated that the pupil was sensitive differentially to the sequential stages during task performance, from encoding of stimulus till response, as seen in past studies as well (Jiang et al., 2014; Van Slooten et al., 2018; Walcher et al., 2017).

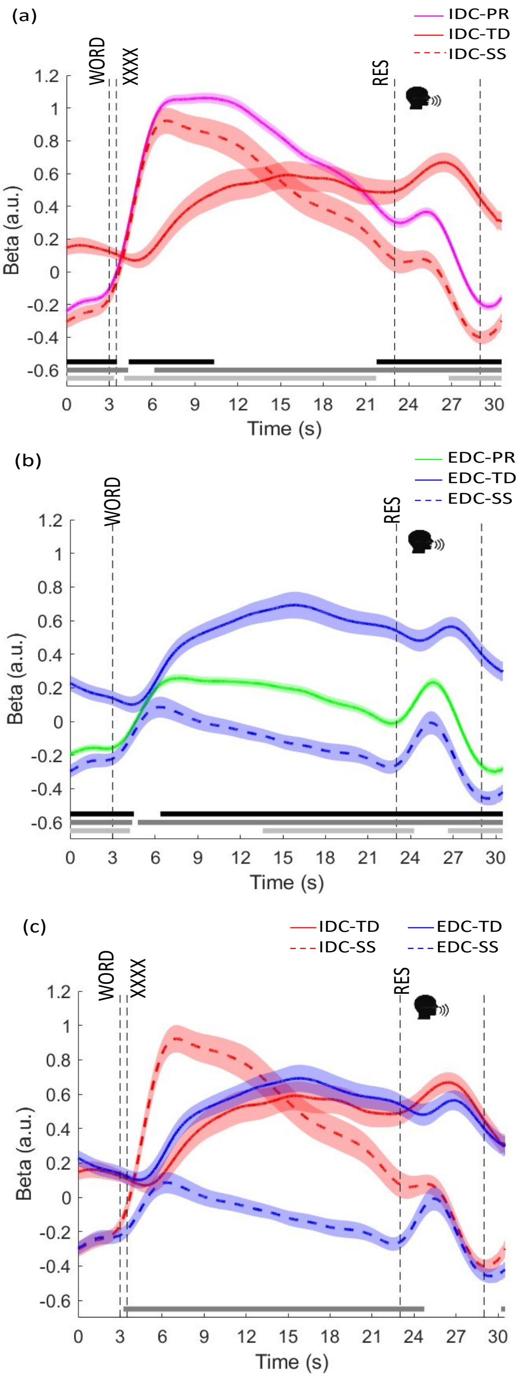

Figure 2. Stimulus-driven attention and goal-directed task effects on pupil response (PR) as dissociable components: Within conditions (a) Mean pupil response (z-scored; solid magenta line) across participants for IDC; Beta values of stimulus-state (SS) regressor (dashed red curve) and task-difficulty (TD) regressor (solid red curve); (b) Mean pupil response (z-scored; solid green line) across participants for EDC; Beta values of SS regressor (dashed blue curve) and TD regressor (solid blue curve). (c) Beta values of SS and TD regressors compared between conditions. All vertical dashed lines represent events in a trial. Shaded areas around curves represent mean ± s.e.m. across participants. All horizontal significance bars indicate time samples where beta values or their contrasts are significantly different from zero at $p < 0.05$.

Distinct effects of attention-based but not task-based processes on pupil size: between-conditions Figure 2c presents the group-level inference results from the between-condition comparisons of stimulus-driven attention-based and goal-directed task-based effects. (Grey horizontal bar indicates trial's time samples when beta parameter estimates representing attention-based effects of the two attention conditions were significantly different from each other at $p < 0.05$). The attention-based effects on pupil responses captured how the absence or presence of external sensory information modulated the participants' mental effort required for processing of stimulus word independent of the task-type. We found these effects to be significantly greater in internally-directed attention condition in comparison to externally-directed attention condition as soon as the stimulus was presented at 3s up till the end of the presentation period at 23 s, indicating higher mental effort requirements in IDC as explained in previous section. This distinction persisted for some time in the response window when the stimulus word reappeared in green font at 23 s, because it was processed with greater uncertainty in IDC as the initial stimulus word presentation was brief (0.5s).

On the other hand, the goal-directed effects on pupil responses captured how the task-difficulty levels modulated participants' mental effort required for task performance independent of how stimulus information was delivered (Figure 2c). We found these effects to be indistinct across attention conditions (no significant difference across the full trial), indicating equivalent mental effort requirements for task performance.

Discussion

Our deconvolution analysis study on trial-wise pupil responses tested how pupil tracks internally-directed and externally-directed attention. Using an existing eye tracking dataset from a study in the visual domain, which manipulated task and attention demands independently (Ceh et al., 2021), we were able to dissociate the interplaying effects of goal-directed task and stimulus-driven attention demands on the pupil size for both the conditions. Within a condition, we found that these effects exhibited distinct temporal profiles over a trial, indicating that the overall mental effort due to multiple cognitive processes underlying a cognitive task can be dissociated at the level of pupil behaviour (Unsworth & Robison, 2018). We also compared these effects between conditions, where we found that the task-based effects on pupil size were similar across internal and external attention demands. This implied that the goal-directed processes underlying performance of tasks i.e., the manipulation of encoded stimulus word to obtain solution whether from external or imagined stimulus information, required similar mental effort across attention demands (Unsworth & Robison, 2015, 2018). However, the deconvolved (pure) attention-based effects due to manipulation of stimulus-state on the screen exerted significantly higher mental effort required for the maintenance of imagined stimulus word when masked in IDC in comparison to when continuously available in EDC, reflected in greater pupil dilation across IDC trials. Our attention based-effects were in accordance with past studies in this domain, which have shown increased pupil diameter and variance in internalised focus of attention (Annerer-Walcher et al., 2021; Ceh et al., 2021; Benedek et al., 2017; Walcher et al., 2017). However, such studies have reported effects using averaged measures of pupil size across the trials' time samples and without any separation of the effects due to underlying cognitive processes. On the contrary, our results provided a novel contribution to the internal/external attention domain in terms of both dissociating and comparing attention-based and task-based effects on trial-wise pupil responses using deconvolution analysis approach.

In general, observing pupil response variations over a trial provides information on how pupil unfolds during the sequential stages of any given cognitive task (Van Slooten et al., 2018; Wierda et al., 2012). Here, they reflected cognitive processes underlying the convergent and divergent thinking tasks in both internal and external attention demands, which included encoding of stimulus word with or without being present on screen, maintenance and manipulation of stimulus word letters in order to search solution in the solution space, holding up solution in mind until response phase, and finally delivering the vocal response. We found that pupil can reliably and adaptively track the sequential stages under different conditions.

A previous study of internal/external cognition correlating eye behaviour and brain activity over time has analysed covariation of several eye parameters such as fixations, (micro)saccades, blinks, pupil diameter with BOLD-fMRI signal (Ceh et al., 2021). This past study found PD to be evidently strongest in representing not only the attention effects over other eye parameters but also in showing associations (both positive and negative) with temporal activity of several brain regions involved in internal/external cognition, including basal ganglia, calcarine (cuneus) extending to dorsal parts of lingula gyrus, insula, precentral and postcentral gyrus, and inferior occipital gyrus (Ceh et al., 2021). Additionally, the neuroscience findings in the domain have associated distinct anticorrelated brain networks underlying internally-directed and externally-directed cognition (Benedek et al., 2016; Ceh et al., 2021). IDC has been linked with self-generated processes related to the imagined stimulus, and thus to default mode regions such as bilateral inferior parietal cortex involved in suppressing early visual areas during internal attention (Shapiro & Hillstrom, 2002; Singh-Curry & Husain, 2009) when stimulus word has been masked. EDC, on the contrary, has been associated with perceptual coupling to the visually-present stimulus and thus to visual areas (as part of ventral attention network) and dorsal attention network including intraparietal sulcus, superior parietal lobule, precentral gyrus (Corbetta et al., 2008; Corbetta & Shulman, 2002). Thus, these findings indicate that internal and external cognitive processes are dissociable at the level of brain activations as well (Dixon et al., 2014, 2018). Based on this, we believe that these brain-level differences are also reflected at the level of eye behaviour, most strongly via trial-wise pupil responses.

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