Attentional Effort

An empirical investigation of attentional capacity

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Cognitive psychology has in recent years had an increasing focus on how attention may reflects the degree of processing intensity, also known as attentional effort. The theoretical developments on attentional effort have followed two main trajectories; effort as momentary demands on the attentional system, or degree of appliance reflecting top-down processing. The momentary demands on the attentional system have been operationalized through pupillary dilations, and increasing attentional effort is measured as the increased dilation of the eye pupil. Attentional effort as top-down processing on the other hand, have been investigated through functional imaging. A broad empirical evidence suggests that top-down attentional control is expressed in a distinct neural network, conceptualized as the dorsal network. A recent developmet of theory have suggested that the underlying mechanism regulating both pupillary dilations, and the neural network responsible for attentional control, is mediated by the release of noradrenaline (NE) from the Locus Correulus (LC). This offers a potential bridge between the two different theoretical traditions, unifying them in a joint account of attentional effort. It has further been suggested that the pupillary dilations can be used to predict activity in these neural nodes responsible for attentional processing.This relationship has however never been directly investigated. The current study therefore asessed concurrent pupillometry and fMRI during a sustained visual attention-task where degree of load, and hence attentional effort, on the attentional system was directly manipulated. We investigated how pupillary dilations in combination with parametrical increase of load can be used to predict neural activity in the LC-NE system, as well as activity in the dorsal system. Results reveal that pupillary dilations, in combination of parametrical modulation of load, correctly predicts activity in the dorsal network, as well in the LC. The precent study concludes that pupillary dilations is a valid predictor of neural activity related to attentional effort.

Preface

The current study have been conceived and developed by the author, in collaboration with Dag Alnæs and Bruno Laeng. The author has in collaboration with Alnæs performed pilot-testing of the paradigm, arranged and tested pupillometry-equipment for MR-use. Analysis has been performed by the author, with assistance from Alnæs. Data was collected in May 2013 at the Intervention Centre – Rikshospitalet. Analysis was performed July 2013 at NORMENT, Ullevål university hospital.

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1 Introduction

1.1 Attention and effort

Attention refers to the ability to focus, select and process task-relevant stimuli while ignoring irrelevant or distracting stimuli. William James defined attention as:

> ”…the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or train of thought. Focalization, concentration of consciousness is of its essence. It implies withdrawal from some things in order to deal effectively with others.” (James, 1890, pp 403-404).

Modern psychology has since come a long way in understanding the cognitive and neural mechanisms involved in what is one of the core aspects of attention, as vividly captured by James’ definition: that attention is selective; it involves allocation of processing resources toward some stimuli (internal or external) at the expense of others. Early experimentation documented effects either in auditory attention, as persons were able to perform dicotic listening, or in visual attention, as visual search tasks favored selection of salient stimuli. Theories concerning the ability to select and favor specific stimuli, proposed explanations in form of bottleneck-effects, where only certain objects of the enormous information are allowed to pass through to conscious processing. (Broadbent & Broadbent, 1987; Broadbent, 1958; Deutch, J & Deutch, 1963; Treisman, 1964)

However, there is also a limitation on *how much* the cognitive system is able to select and process at any given time, and thereby the aspect of *capacity* and processing intensity has also gained focus in cognitive psychology. Again the phenomenon may be described in terms of experience and introspection; everyone can relate to the experience that paying attention happens in a matter of degree. From merely paying some attention to the lecture in the start of the semester, to the active listening and memorization two weeks before the exam, there is a degree of appliance, a factor of intensity also known as “attentional effort” (Kahneman, 1973).

One attempt at explaining attentional resource limitations was put forward by Kahneman in his capacity-model of attention (Kahneman, 1973). This proposes that attention is a limited, and task-general resource, which is flexibly allocated depending on the current demands on the attentional system (Kahneman, 1973). The allocation of attentional resources can be described by use of a metaphor: Performing an attentional demanding task is analogous to plugging an electrical appliance (e.g. a toaster) to the electricity grid. When the toaster is turned on, it taps resources (electricity) from the electrical system, using from the available current to perform its task. To compensate for the increased load on the electrical grid, more electricity must be produced to keep up the supply of energy. This can be done until the demands from the grid exceed the capacity of the generator, at which point the system breaks down, and demands can no longer be met. Analogous, as task demands increases, an increase in arousal makes available attentional resources to perform the task at hand, until demands exceed the capacity limit and performance degrades (Kahneman, 1973). Kahneman equated the terms effort and arousal, and the key point of the capacity-model is therefore the ability to adjust the available (but limited) resources through arousal, as task demands changes.

Another key notion of the capacity-model is that effort, and hence resource allocation, is solely determined by the demands of the task. Simplified, Kahneman argues that each cognitive task imposes a given amount of demands on the cognitive system, and one cannot choose to allocate more resources than is needed to perform the task (Kahneman, 1973). However, and following the lecture-example given above, the degree of paying attention also seems to be a matter of intention. As the exam closes in, the expected value of paying attention increases, as the student increasingly values the information given by the lecturer. A more recent conceptualization attentional effort incorporates this notion, and defines effort as the *motivated* activation of attentional systems in r*esponse* to variation in challenges on attentional performance (Sarter, Gehring, & Kozak, 2006). According to this definition, mental effort reflects the voluntarily allocation of attentional resources, to achieve a personal goal (Sarter et al., 2006). Sarter and colleagues thereby expands and refines the concept, relating it to theories of top-down regulation of attention: mental effort, rather than being solely a function of task demands, also depends on the performers' goals and motivation to perform.

Important for the current study is the fact that Kahneman and Sarter suggest two different theoretical perspectives on how to understand to the concept of attentional effort. The capacity model focuses on how external tasks drive the cognitive system, and how arousal can be increased to compensate for insufficient resources as task demands increase.

Sarter and colleague’s definition on the other hand, focuses on how internal goals can be applied to drive attention in a top down manner, to maintain sustained attention towards relevant task at hand. One must assume that these two conceptualizations are tightly connected, as they both relate to the intensity or “effortful” aspects of attention. Even so, they do represent two different theoretical underpinnings, as well as empirical research traditions. Interestingly, recent development of theories regarding the relationship between neural systems involved in regulating arousal and attention may serve as a conceptual bridge between these two different approaches, providing new insight into how arousal, and hence mental effort, as suggested by Kahneman, relates to the brains attentional systems.

The aim of the current study is to investigate this proposed relationship. However, before specific hypothesis can be formulated, the key empirical findings from each research tradition must be reviewed, as well as the new abovementioned theorizing linking these different conceptualizations of effort.

1.2 Kahneman’s capacity-model – pupil dilation as an index of mental effort

In Kahneman’s capacity-model, mental effort is operationalized as arousal. Previous findings had already suggested that arousal was related to task performance (Dodson & Yerkes, 1908) and that degree of arousal was reflected in pupillary dilations, during tasks taxing mental capacity (Bradshaw, 1967; Hess, Eckhard H Polt, 1964). The capacity-model unified these findings, by suggesting that the pupil could be used as an index of arousal, and hence, attentional effort across task domains (Kahneman, 1973). Beatty demonstrated that the pupil dilated in a highly correlated manner in relation to processing demands (Beatty, 1982). Task evoked pupillary dilations, termed pupillometry, reflect dilations of the pupil during task engagement. Recent articles reviewing findings from the field of pupillometry have suggested in summary that the pupillary response can be used to index cognitive demands (Beatty, 1982; Laeng, Sirois, & Gredeback, 2012).

The capacity-model views attentional capacity as a domain-independent resource, which is flexibly allocated depending on the current demands on the attentional system. According to Kahneman, the ideal physiological measure of effort should therefore reflect both within and between differences in task performance. Variation in task difficulty should reflect differences in demands on the cognitive system, and therefore difference in degree of applied effort. As effort reflects utilization of a limited, but general capacity, the measurement should also be sensitive to processing demands across qualitatively different cognitive tasks. Last, the measurement should be sensitive to between-subject differences in task performance at a given level, as attentional capacity, and therefore degree of effort on a given task, varies with cognitive resources (Kahneman, 1973). Pupillometry has shown to be sensitive to all the above-mentioned criteria, thereby providing a reliable measure of exhibited effort (Beatty, 1982).

The core findings in relation to pupillometry, is that the pupil dilates in relation to processing of cognitive stimuli (Beatty, 1982). The degree of dilation correlates with task difficulty, hence a more difficult task gives larger dilations (Beatty, 1982), up to a certain point when no more resources are available and performance breaks down. That is, the moment task difficulty exceeds available capacity, no further dilation are observed (Beatty, 1982). The dilation sustains as long as effortful processing is upheld, and returns to baseline when the task is finished or abandoned (Peavler, 1974). This relationship between pupil size and performance have been reported in a wide range of tasks, relating to language comprehension (Hyönä, Tommola, & Alaja, n.d.; Just & Carpenter, 1993), mental arithmetic (Bradshaw, 1968; Hess, Eckhard H Polt, 1964), working memory tasks (Kahneman & Beatty, 1966; Karatekin, Couperus, & Marcus, 2004; Stanners, Coulter, Sweet, & Murphy, 1980), or signal detection (Kahneman & Beatty, 1967; Privitera, Renninger, Carney, Klein, & Aguilar, 2008). Also, participants with higher cognitive capacity in form of intelligence, show smaller dilation to the same task at same level of difficulty, due to less required effort for completing the task (Ahern & Beatty, 2013).

Central to this study, is the pupils *online responsiveness* during *task engagement*. According to Kahneman, the pupillary dilation reveals the momentary demands on the cognitive system (Kahneman & Beatty, 1967). It has been suggested that pupil dilations reflects online capacity utilization by the cognitive system (Just & Carpenter, 1993). Importantly, if the degree of pupillary dilation reflects momentary cognitive utilization during task engagement, it should be highly correlated with neural nodes responsible for these processes. Nevertheless, pupillary dilations have never been explored in relation to the neural properties of attention, but it have been suggested that it potentially can be utilized to predict activity in the neural basis of attention (Laeng et al., 2012). It is therefore central for the current study to elaborate on neural correlates of attentional processing.

1.3 The cortical attentional systems – evidence from fMRI

Following Sarter's definition, effort relates directly to allocation of attentional resources to accommodate internal goals for achievement (Sarter, Gehring, & Kozak, 2006), suggesting that attentional effort is related to top-down control over attentional resources. Current knowledge from the neuroimaging field suggests that top-down control is reflected in a distinct neural system: the dorsal attention network (Corbetta, Patel, & Shulman, 2008; Corbetta & Shulman, 2002).

The dorsal network is located bilaterally of the cortex. The key nodes includes the frontal eye field (FEF), the intra-parietal sulcus (SPS), and the superior parietal lobule (SPL), and has been found to be highly activated during tasks involving top-down visual attentional control (Corbetta et al., 2008; Corbetta & Shulman, 2002). Numerous imaging studies have shown that the network is activated during sustained visual attention and anticipation to movement of visual objects (Hopfinger, Buonocore, & Mangun, 2000; Kastner, Pinsk, De Weerd, Desimone, & Ungerleider, 1999; G L Shulman et al., 1999), response preparation (Constantinidis & Steinmetz, 2001) and short term memory tasks (LaBar, Gitelman, Parrish, & Mesulam, 1999). Further, the nodes show an increase in activity in relation to increased task demands during a visual tracking task (Jovicich et al., 2001). It is thought that the dorsal attentional system is responsible for creating and maintaining endogenous signals based on current goals and preexisting information, and thereby biasing the processing of incoming stimuli (Corbetta et al., 2008; Corbetta & Shulman, 2002).

Relevant for the current study, is that the dorsal system is suggested to interact with a right lateralized ventral attention-system. The ventral network is involved in bottom-up attention and responsible for "interrupting" and facilitation of reorientation of the dorsal system toward unexpected but behaviorally relevant stimuli. The key nodes of the network are the temporoparietal junction (TPJ) and Inferior Frontal Gyrus (IFG) (Corbetta et al., 2008; Corbetta & Shulman, 2002). Evidence from functional imaging studies show that these nodes are activated in relation to invalidly cued targets in the Posner cuing-paradigm (Arrington, Carr, Mayer, & Rao, 2000; Vossel, Thiel, & Fink, 2006), or in situations where targets occur in an unpredictable fashion (Stevens, Calhoun, & Kiehl, 2005). In other words, the ventral system activates when something important outside what currently is in the scope of attention needs processing. On the other hand, during focused attention, the ventral system is suggested to be deactivated (Gordon L Shulman et al., 2003; Todd, Fougnie, & Marois, 2005) Theoretically these systems are assumed to facilitate optimal behavioral adaption, integrating stable task performance with the ability to reorient towards new and potentially more rewarding stimuli (Corbetta et al., 2008). Importantly, tasks that activates the dorsal and ventral network (Corbetta & Shulman, 2002), reflects the same tasks that have been earlier reported to evoke pupillary dilations (Beatty, 1982), which further suggests a link between the two different conceptualizations of effort.

Maintenance of the dorsal network and interruptions from the ventral network have been suggested to stem from the same source, cortical secretion of noradrenaline (NE) from the Locus Coeruleus (LC) (Aston-Jones & Cohen, 2005), which also is suggested to be the source of pupillary dilations mediated by cognitive processing (Samuels & Szabadi, 2008a) for both attentional networks.

1.4 Noradrenaline and facilitation of attentional control

The pupillary response and the neural networks reflect two different approaches to the concept of effort. Recent theorizing concerning the function of the LC-NE system has embedded its role in both facilitating maintenance of top-down control, and interruption for bottom-up processing (Corbetta et al., 2008), hence changes in behavioral states and shifts in the allocation of attention (Aston-Jones & Cohen, 2005; Sara, 2009).

The LC is the main source of NE to areas responsible for higher cognitive function, and has projections throughout all of neocortex, with special dense projections towards parietal cortex, super colliculus, and pulvinar nucleus, key nodes in attentional processing (Corbetta et al., 2008; Foote & Berridge, 1991). The LC receives input from prefrontal areas concerning error monitoring, and goal comprehension, especially the orbitofrontal and anterior cingulate cortex, linking it to monitoring of top-down performance (Aston-Jones & Cohen, 2005).

Early empirical findings concerning the effect of NE on target neurons suggested that NE mostly suppresses spontaneous neural activity, but augments and accentuate activity in synapses where significant stimuli is transferred (Kety, 1970). In combination with LC's widespread distribution of NE in the neocortex, it led to theories viewing the LC-NE-system as a general signal-to-noise enhancer, facilitating the throughput of sensory stimuli (Servan-Schreiber, Printz, & Cohen, 1990).

Later empirical findings have however elaborated on LC-NE function, linking it to mediation between different states behavior (Aston-Jones, Rajkowski, & Cohen, 2000). Building on previous mentioned findings, LC-NE activity has been found to correspond with different states of behavior. During sleep and disengagement, LC firing is almost absent (Aston-Jones & Cohen, 2005). During task engagement, LC show intermediate activation, allowing behavior to be focused at the task at hand (Usher, 1999). During states of high arousal, LC show high degree of activity, and corresponds with behavior of high distractibility. These states are suggested to reflect tonic states of activation, where LC shows stable rates of activity (Aston-Jones & Cohen, 2005).

The key question is however, during intermediate tonic LC-activation, how salient and important stimuli are allowed to gain focus, and temporally interrupt task engaged behavior. There is evidence suggesting that during intermediate tonic LC activation, the LC elicts short bursts of NE-activity when a salient stimulus is presented (Nieuwenhuis, Aston-Jones, & Cohen, 2005). This mode of activation is termed phasic activation, and has been interpret as a reset signal, interrupting activity of task engaged functional networks in the cortex (Sara, 2009). During intermediate tonic firing, the phasic activation reflects a short burst of NE time-locked to the salient stimuli, thereby acting as a temporal filter. As higher secretion of NE leads to increased distractibility, the phasic burst provides a short temporal filter, where attention can shift from focused attention to reorientation towards the salient stimuli for a short time. LC activation then returns to intermediate tonic activation, and task-relevant behavior can continue. These findings have been proposed to reflect the optimal trade-off between two different aspects of behavior: exploitation and exploration (Aston-Jones & Cohen, 2005). Exploitation reflects the ability to use focused attention to exploit the current situation. Exploration on the other hand, is the ability to reorient towards new and potentially more rewarding stimuli (Aston-Jones & Cohen, 2005). An important notion is that phasic LC activity is not related to reward per se, as initiation of reward-related behavior not induced by an external cue does not elicit phasic LC activity (Bouret & Sara, 2005); instead, it is seen when a cue that *interrupts* ongoing behavior is linked to a reward (Bouret & Sara, 2005). Importantly, the behavioral states of exploration and exploitation correspond directly to the two different states of attentional focus: top down and bottom up processing, reflected in the dorsal and ventral attentional system. It is suggested that stable intermediate levels of tonic LC activation mediates sustained attention through the dorsal network, while the phasic burst allows reorientation towards task relevant stimuli, through interruption by the ventral system (Corbetta et al., 2008).

Important for the current study, is that pupillary dilations and NE-activity have also been suggested to be highly correlated (Koss, 1986). Dilations of the pupil due to cognitive processing are a result of the inhibitory effect on the parasympathetic oculomotor complex, which is mediated by the release of NE from the LC (Wilhelm, Wilhelm, & Lüdtke, 1999). Pharmacological studies in humans (Koss, 1986) and an unpublished investigation of single-cell recordings in the LC of monkeys in relation to pupillary dilation during a signal detection task, confirmed this close relationship findings in monkeys (Aston-Jones et al., 2000) The findings provide indications that activity of the LC-NE system and pupil dilations are highly correlated. This relationship has, however, still not been documented by direct measurement in humans.

1.5 Multiple Object Tracking

The goal of the current study is to investigate the link between pupillary dilations, neural networks responsible for attentional performance, and LC-activation. A task widely used to examine top-down visual attentional control, is the Multiple Object Tracking-paradigm (MOT) (Pylyshyn & Storm, 1988). The task requires the participant to track a number of visual objects on a screen through a tracking interval. In the typical MOT-paradigm, a tracking trials starts with a certain number of objects briefly changing color, designating them as targets. The targets objects then return to their original colors, making them undistinguishable from the distractor objects, before all of the objects start moving, following unpredictable trajectories. The participant's task is to track the target objects during the whole tracking interval, and at the end of the interval report which targets in the screen were the target objects. The MOT-task has several advantages when investigating visual attention, as it allows investigation of sustained divided attention, as compared to cuing-tasks in which brief effects of attentional facilitation, usually to one location, is studied (Scholl, 2009). Central for the current study is that the attentional demands, and therefore degree of effort, can be directly manipulated by varying the tracking load, i.e. by increasing the number of objects to be tracked concurrently.

fMRI-studies using the MOT-paradigm have shown that areas involved in attentive tracking include FEF, anterior IPS, posterior IPS and SPL (Culham et al., 1998; Culham, Cavanagh, & Kanwisher, 2001; Howe, Horowitz, Morocz, Wolfe, & Livingstone, 2009; Jovicich et al., 2001), which are all core regions of the dorsal attention network (Corbetta et al., 2008). During attentive tracking, there is no indication of activation of the ventral network on average throughout the tracking trials, supporting the hypothesis that the ventral network is not recruited or suppressed during sustained top-down control (Shulman et al., 2003; Todd et al., 2005).

Further, several areas of the dorsal attention network increase their activity in a parametric fashion as the number of target objects (tracking load) increases (Jovicich et al., 2001). From the theoretical view of Kahneman’s effort model of attention, the increase of neural activity can be understood as an increase in allocation of attentional resources. Returning to Kahnemans criteria for measuring effort, a parametric linear model accounting for tracking load may not account for individual differences in effort: at a given tracking load different participants may be at different effort-levels because there are differences in the total capacity across participants. Also, it may not account for any momentary fluctuations in effort during tracking, e.g. due moment-to-moment changes in difficulty resulting from the random movement of the objects, or changes in motivational states of the participants. We therefore hypothesize that the pupil may explain variability in BOLD-activity in the dorsal attention network not accounted for by a linear parametric model accounting for the tracking load.

It is also reasonable to assume that the MOT-task will induce activity also in the ventral system during tracking, even if the net activation when averaged over the tracking intervals is zero. During the tracking interval the targets will move among, and sometimes close to the distractor objects, which share identical physical properties of the targets. It have been shown that tracking performance decrease when targets and distractors are close, as opposed to when they are further apart (Franconeri, Jonathan, & Scimeca, 2010), and the ventral network activates to distractors when they share properties of behaviorally relevant stimuli (Fox, Corbetta, Snyder, Vincent, & Raichle, 2006).

Also, a puzzling observation is that none of the above-mentioned fMRI-studies using the MOT-task reported any subcortical activations extending towards the brainstem, and the LC. Given the proposed role of the LC-NE system in mediating behavioral modes related to regulation of the dorsal and ventral attention network, and in attentional resource allocation during high task demands, (Gary Aston-Jones & Cohen, 2005; Sara, 2009), one would expect the LC to be involved during MOT. One possible explanation for the lack of LC activation is that areas' extending towards the brainstem was not included in the analysis (i.e. not included in the fMRI bounding box). Another explanation may again be that there is no net activity when averaging across a tracking trial, hiding actual activity in form of phasic bursts of the LC-NE system. A specific goal for the current study is therefore to investigate whether the participants individual pupil time series can account for activity in the LC-NE system during MOT.

1.6 Summary and hypothesis outline

The study of effortful attentional processing has generated two different empirical traditions. Pupillary responses and cortical activations both reflect effortful processing, but the relationships between them have been remained unexplored. Recent theorizing about the LC-NE system has offered a potential bridge between them, allowing the growth of a more unified understanding of the concept of effort. The goal for the current study therefore to investigate the effortful nature of multiple object tracking, and how it relates to pupillary responses and activation of neural networks responsible for attentional processing.

We therefore hypothesize that pupillary dilations, as an index of attentional effort, will increase when the number of targets to track increases.

Further, we hypothesize that a better predictor for the activity of the brainstem reticular activation system, and more specifically the LC-NE system, would seem to be each individual's pupil time-series. Rather than using number of objects to be tracked, the pupil time series should offer a better moment-to-moment index of resource allocation. Therefore, a key prediction of the present study is that the pupil regressor will correlate with areas of the cortical attentional system that are innervated by the LC-NE system, and more specifically, with core regions of the dorsal and ventral attention network.

Also, we expect to replicate previous findings regarding cortical activity during MOT: Regions of the dorsal attention network will be activated during attentive tracking, and increase parametrically with increased tracking load.

2 Methods

2.1 Participants

Twenty subjects recruited from the student population, took part in the study. All participants had normal, or corrected to normal vision. None of the participants reported any current or previous psychiatric or neurological disorders. Standard procedures at *The Intervention Centre* (Oslo University Hospital) were followed concerning MR-safety. All participants were given information about the scanning procedure, their right to withdraw from the study, and a detailed explanation of the experimental task, before giving their informed consent and entering the scanner. 3 participants were excluded due to noisy pupillometry data resulting from wearing contact lenses or wearing mascara. Data from 17 subjects were included in the final sample with a mean age of 25 years (std=4, 2, range 19-35, 5 males)

2.2 Task presentation

Stimuli were generated using MATLAB® (MathWorks, Natick, MA) and the Psychophysics Toolbox extensions (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997), and presented on a calibrated MR- compatible LCD screen (NNL LCD Monitor®, NordicNeuroLab, Bergen, Norway), at a resolution of 1920x1080 and refresh rate of 60 Hz. The screen was placed behind the scanner's bore, and was viewed through a mirror mounted on the scanner's coil, with an effective viewing distance of 1.2 meters and a field of view measuring 32° visual angle.

Each trial started with the presentation of a white central fixation point (0.2° visual angle) inside a gray square (tracking area) subtending 17 x 17 degrees visual angle, and a brief visual instruction as to whether it was a tracking trial or a passive–viewing-trial. The fixation point sustained through the whole trial. After 1.5 seconds eight circular disks were presented, all stationary and in blue color. After an interval of 1.5 seconds, targets were identified by a change in color (red) for 2.5 seconds, before all objects returned to blue. The objects then started moving in an unpredictable manner, but never overlapping each other, inside the tracking area at a movement velocity of 5.5°/second. In passive viewing none of the objects was designated as targets and therefore they never changed color. During passive viewing trials, participants were instructed to relax and not attend to the objects, but maintain fixation during the whole trial interval. During tracking trials, participants were instructed to covertly attend the designated targets, and maintain fixation at the central fixation point. If the participants lost track of the targets during tracking, they were instructed to track the assumed targets, and always track the number of designated targets at the start of the trial. After an 11 seconds tracking period, the objects stopped moving and a probe was presented by a brief change in color. The participants had to report if the probe was either a target or a distractor.

To avoid pupillary changes due to luminance changes between stimulus displays, all object and text colors, as well as the tracking area, were isoluminant (14 cd/m$^{2)}$, except the central fixation (20 cd/m^2) which remained constant throughout the experiment). The scanner room was kept dimly illuminated throughout the session for all participants.

Trials were presented in blocks, each block consisting of one trial from each condition (Passive Viewing, Load 2-5). Trials inside blocks were randomized, and the blocks semi-randomized to prevent repetition of task-sequence. A rest period of 11 second always followed after running through 5 blocks. Except for the target designation-period, visual stimulation was identical across conditions, and only tracking load differed during the 11 second tracking interval. Each participant performed 4 runs of the task.

Figure 1

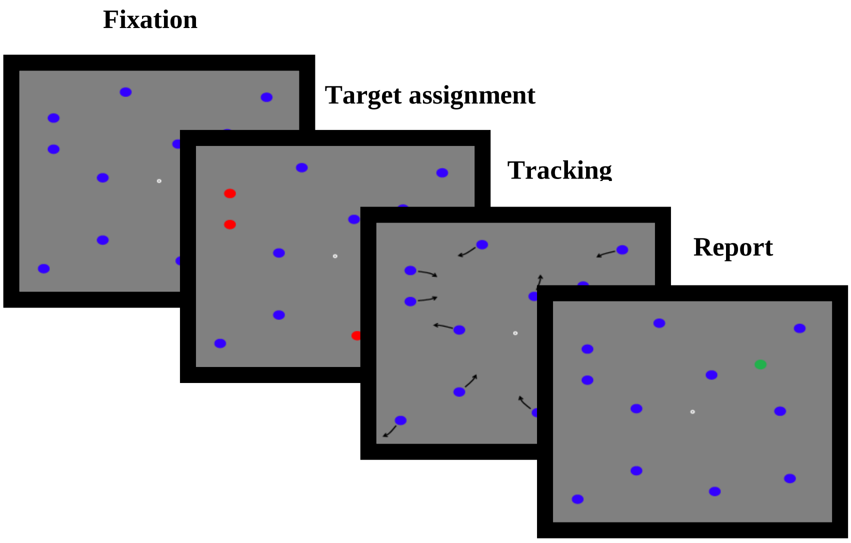

Figure 1: The figure represents a visual display of the applied MOT-paradigm.

2.3 Data acquisition

Pupillometry-data was collected using an MR-compatible coil-mounted infrared EyeTracking system (NNL EyeTracking camera®, NordicNeuroLab, Bergen, Norway), at a sampling rate of 60 Hz and recorded using the iView X Software (SensoMotoric Instruments, SMI GmbH). A trigger from the stimulus computer synced the onset of the pupillometry recording to the start of the experiment.

MR data acquisition was performed with a Philips Achieva 3 Tesla MR-scanner, equipped with an 8-channel Philips SENSE head coil (Philips Medical Systems, Best, Netherlands). Functional data were collected using a BOLD-sensitive T2* weighted echo-planar imaging sequence (36 slices, no gap; repetition time (TR), 2,2s; echo time (TE), 30 ms; flip-angle, 80°; voxel size, 3x3x3; field of view (FOV), 240x240 mm; interleaved acquisition). Since we were interested in areas extending towards the brainstem, the common norm for AC-PCorientation was abandoned, and the slices were oriented to include the whole cerebral cortex, the cerebellum and the brainstem pons, as well as superior parts of the medulla oblongata. To avoid T1 saturation effects, 5 dummy scans were collected and discarded at the start of each functional run. Each run produced 267 functional volumes.

Anatomical T1-weighted images consisting of 180 sagittal oriented slices were obtained using a turbo field echo pulse sequence (TR, 6.7 ms; TE, 3.1 ms; flip angle 8°; voxel size 1x1.2x1.2 mm; FOV, 256x256 mm).

2.4 Preprocessing

Pupillometry data were preprocessed using a custom made MATLAB-script: Data points with physiologically unlikely pupil sizes (2.5 standard deviations from the mean pupil size) and neighboring data points (the preceding and following 50ms), were removed from the data to remove noise due to eye blinks. Trials with less than 50% of the data remaining after removal of outliers were not included for further analysis. Gaps in the pupil time series were replaced by linear interpolation. Inspection of the pupil time series revealed large amount of noise in the vertical pupil diameter measurements, likely resulting from eye lids occluding the pupil. Therefore, only the horizontal pupil diameter measurement was included for further analysis The next preprocessing steps diverged for the analysis of average pupil dilations across tracking trials, and for the creation of pupil time-series regressors for the fMRI-analysis. To investigate average pupil dilations across tracking load, time series for each tracking trial were smoothed using a robust Loess algorithm (smoothing parameter = 0.1) and then resampled in time bins of 100 milliseconds. Baseline pupil diameter was calculated as the average pupil size during the 200ms preceding each tracking onset, and was subtracted from the time series for each tracking period. Trials within each of the load conditions for each participant were then averaged, and then a group average time series and standard errors across subjects for each condition was created. The average pupil dilation from baseline for each load condition was calculated using the time window from 1 to 10 seconds of the tracking period. For fMRI analysis the whole pupil-time series for each run was smoothed using a robust Loess algorithm (smoothing parameter span of 132 samples at 60Hz, 2.2 seconds), z-normalized and then down-sampled to match TR-resolution (2.2 seconds).

The most common approach when reporting pupillometry-data is to use mm pupil dilation. However, since the MRI-environment makes it difficult to keep a constant length between the eye-tracking camera and the eye, the time series was z-normalized, and pupil dilations are therefor reported as z-scores.

fMRI-data was preprocessed using FSL 5.0 (www.fmrib.ox.ac.uk/fsl). The EPI sequences was motion corrected using FMRIB’s linear image registration tool (MCFLIRT), spatially smoothed with a Gaussian kernel of 5 mm FWHM, temporally high-pass filtered (cutoff 120s) to remove slow drifts. The T1-weighted images were scull-stripped using Freesurfers recon-all command (Dale, Fischl, & Sereno, 1999), as this produces more reliable results than the Brain Extraction Tool (BET) included in FSL.

2.5 Data analysis

Effect of load on pupillary dilation, reaction-time and accuracy was analyzed with repeated measures ANOVA. When results violated the assumption of sphericity, Greenhouse Geisser – corrected results were reported.

fMRI-data was analyzed with FEAT (FMRI Expert Analysis Tool) Version 6.00, part of FSL (FMRIB's Software Library, www.fmrib.ox.ac.uk/fsl) using a general linear model (GLM), with four explanatory variables: Passive Viewing (Load 0), Tracking (Load 2-5), Parametric load (the regressor was mean centered to zero, modeling the linear increase with number of objects by weighting the tracking trials with -1, -0.5, 0, 0.5 and 1, for load 2, 3, 4 and 5, respectively), and the individual pupillary time series. The Passive viewing and Tracking regressor modeled the tracking trials as blocks using box-car functions covering the tracking periods. The pupillary regressor contained the individual z-normalized pupil time-series extending the period of the whole experiment. All regressors expect the Pupil time series regressor was convolved using a double gamma HRF.

Motion regressors were included as nuisance variables. To collapse the four sessions into one analysis, a fixed effect analysis was performed over the four sessions for each participant, producing mean COPES (Contrast Parameter Estimates) for each participant and condition, across sessions. These COPES were then entered into a mixed-effects group analysis, before performing the following contrasts: Tracking > Passive viewing, Parametric > 0 and Pupil > 0. Z (Gaussianised T/F) statistic images were thresholded using clusters determined by $Z>2.3$ and a (corrected) cluster significance threshold of $P=0.05$ (Worsley, 2001)

3 Results

3.1 Behavioral results

Figure 2:

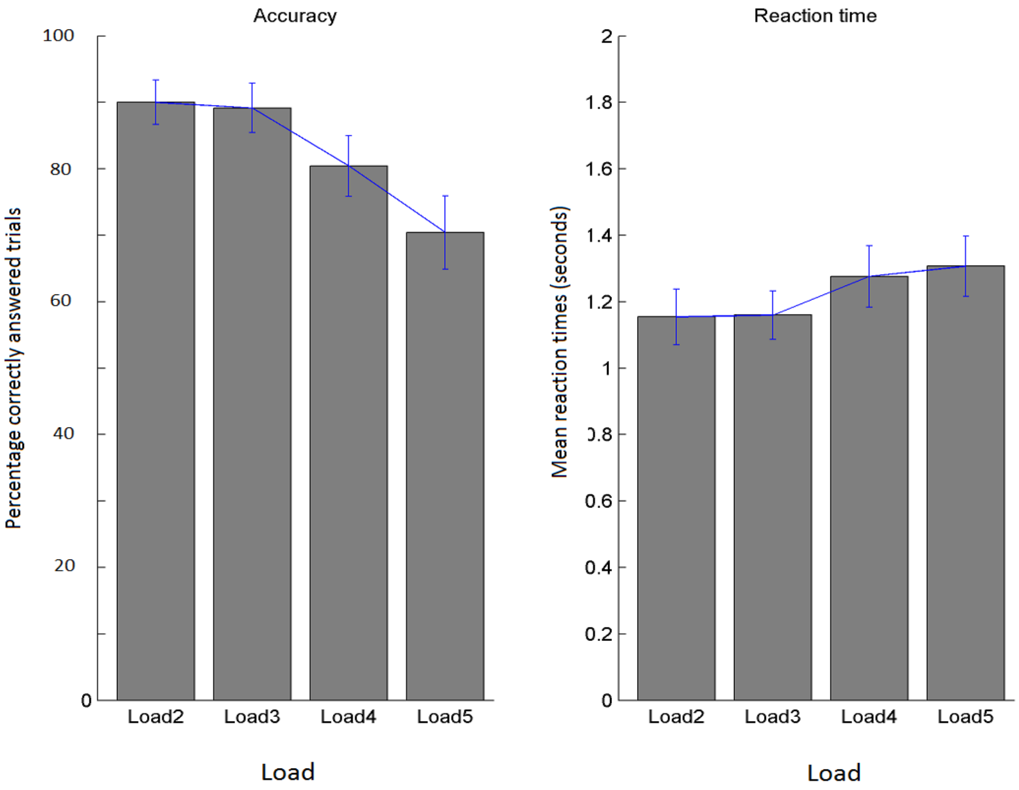

Figure 2: Left side panel shows average levels of correctly identified targets across load conditions. The right side panel shows the mean reaction times.

Repeated measures ANOVAs showed significant effect of tracking load on both correctly identified targets, F (2.44, 31,410) = 10.140, p < 0.001 and reaction time, F (2.277, 31.878) = 7.355, p < 0.02. It was also in both cases significant linear trend for reaction time, F (1, 16) = 16,894 p < 0.001 and accuracy, F (1, 16) = 21.109, p < 0.001. Results suggest that increase of load is associated with significant linear increase of reaction-times, and significant linear decrease in difficulty, indicating that increasing load leads to both lower accuracy and slower reaction times.

3.2 Pupillary results

Figure 3:

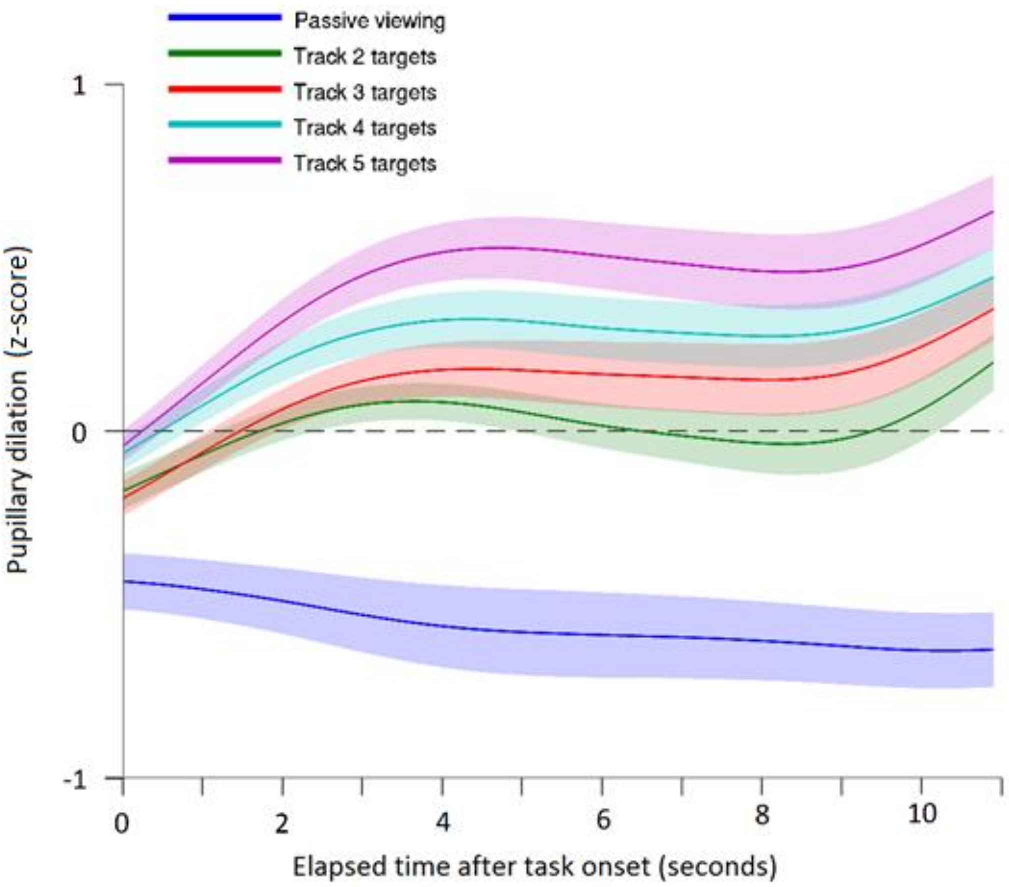

Figure 3 shows the group average pupil time series for the different tracking conditions. Shaded area represents the standard error of the mean (SEM). A repeated measures ANOVA revealed a significant effect of number of targets on mean pupil size change, F (2.045, 32.71) = 5.91, $p < 0.01$. There was a significant linear trend, F (1, 16,) = 9.261, $p < 0.01$, indicating a significant proportional increase in pupil size with tracking load.

3.3 fMRI Results

3.3.1 Activity positively correlated with general tracking

Figure 4:

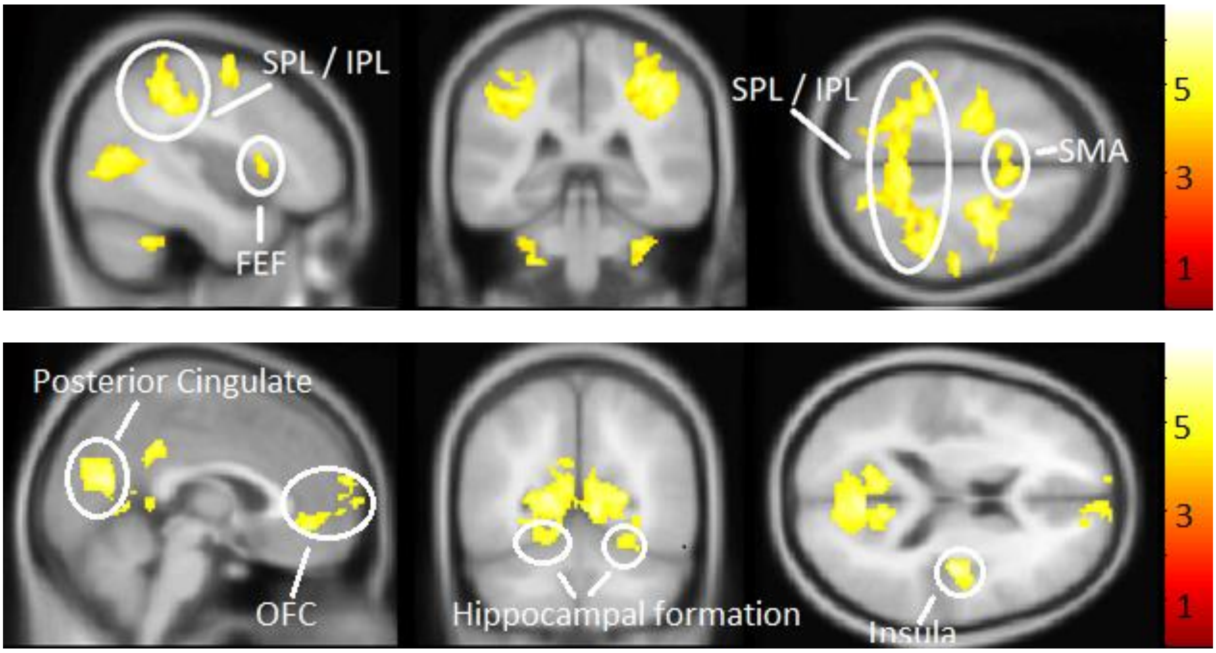

Figure 4: Top display shows activity related to attentional tracking (Tracking > Passive viewing), bottom displays negatively correlated activity (Passive viewing > Tracking). Cluster generating threshold of z>2.3 and (corrected) cluster significance threshold of P=0.05

Table 1: Activity correlated with tracking.

	K	**Lateralization**	**Peak x y z**	**Value**	**Z-score**
Frontal					
Precentral / SMA / FEF [1]	2345	R	26 10 56	+	6.7
Precentral SMA / FEF	1281	L	-30 -4 56	+	5.7
Medial OFC	231	R	4 64 18	-	5.3
Parietal					
Postcentral / SPL / IPL / IPS [2]	8442	L	-36 -44 66	+	6.3
Superior parietal lobe	401	L	-54 -8 -8	-	6.1
Occipital					
Inferior occipital lobe	799	R	48 -66 12	+	5.9
Middle occipital gyrus	215	L	-36 -76 40	-	5.4

Middle occipital gyrus	451	R	-2 40 -6	-	5.6
Subcortical					
Insula anterior	757	R	34 20 6	+	5.8
Posterior cingulate / Hippocampal formation / Medial occipital lobe[3]	6769	L	-26 -44 -1	-	6.6
Insula posterior	757	R	34 20 6	-	5.8
Cerebellar					
Cerebellum	1046	L	-14 -56 -4	+	6.0
Cerebellum	666	R	28 -44 -48	+	5.8

Table 1: Positive findings are indexed with +, negative activations are indexed with -. SMA: Supplementary motor area, FEF: Frontal eye field, OFC: Orbitofrontal cortex, SPL: Superior parietal lobe, IPL: Inferior parietal lobe, IPS: Inferior parietal sulcus.

1): Findings revealed a large cluster with peak value centered at the FEF. The cluster showed posterior extensions towards the precentral sulcus and SMA.

2): Findings revealed a large cluster centered at superior parts of the postcentral gyrus, with posterior extensions towards SPL, IPL, IPS, and superior parts of the occipital lobe.

3): Findings revealed a large cluster centered at posterior cingulate, with anterior extensions towards the hippocampal formation, and posterior extensions towards the medial parts of the occipital lobe.

3.3.2 Activity positively correlated with increase of load

Figure 5:

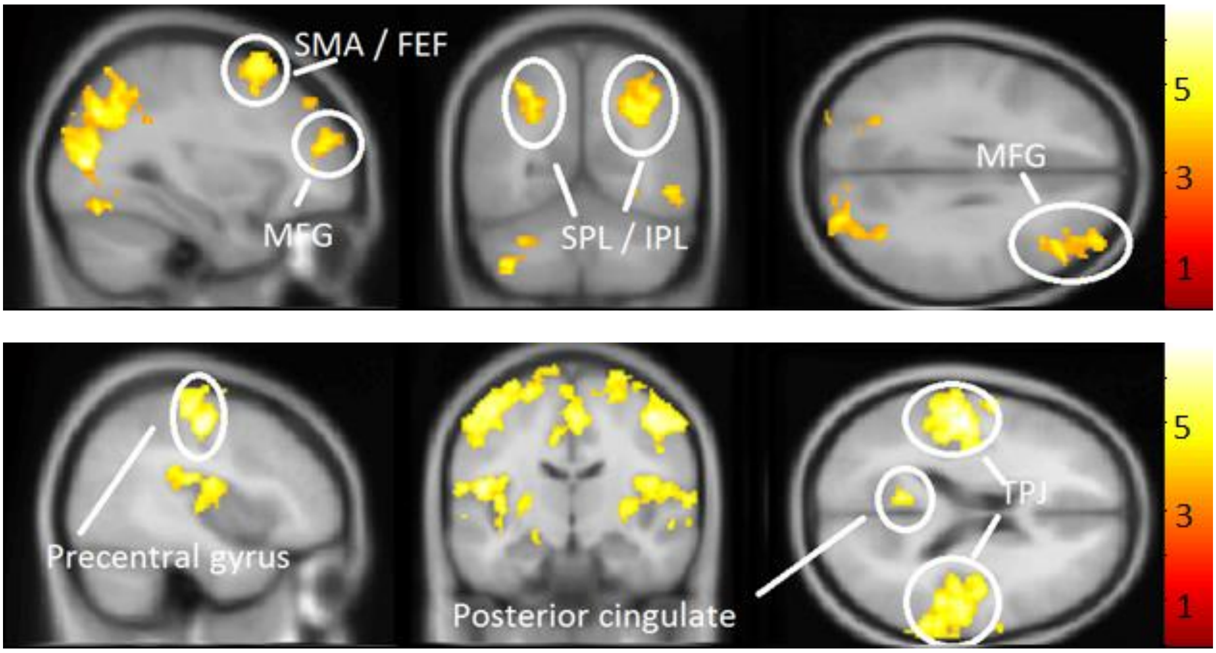

Figure 5: Top display shows areas increasing activity parametrically with tracking load (Parametric > 0)bottom display shows areas that decrease activation parametrically with tracking load (0 > parametric). Cluster generating threshold of z>2.3 and (corrected) cluster significance threshold of P=0.05

Table 2: Activity correlated with increase of attentional load:

	K	**Lateralization**	**Peak x y z**	**Value**	**Z-score**
Frontal					
MFG	376	L	-38 50 10	+	3.7
MFG	1138	R	42 44 14	+	4.6
SMA	423	L/R[1]	-1 14 53	+	4.3
FEF	306	L	-46 3 6	+	4.0
FEF	138	R	46 6 30	+	3.4
mOFC	236	L/R[1]	0 42 -10	-	3.7
vmOFC	357	R	4 14 -8	-	4.3
SFG	179	R	16 -16 72	-	3.9
Precentral gyrus	2002	L	-44 14 56	-	4.4
Precentral gyrus	2534	R	44 -18 48	-	4.6
Parietal					

SPL / IPL / IPS[2]	3423	R	50 -39 52	+	4.8
SPL / IPL	668	L	-42 -44 38	+	4.0
TPJ	1834	L	-55 -29 17	-	4.7
TPJ	1466	R	58 -30 21	-	4.4
<u>Occipial</u>					
Middle occipital lobe	119	L	-40 -82 34	-	4.0
<u>Subcortical</u>					
Insula anterior	153	L	-32 24 0	+	3.7
Posterior cingulate / Hippocampal formation[3]	6769	L	-26 -44 -1	-	6.6
Putamen	210	L	-28 2 14	-	3.9

Positive findings are indexed with +, negative activations are indexed with -. MFG: Middle frontal gyrus, SMA: Supplementary motor area, FEF: Frontal eye field, mOFC: Medial orbitofrontal cortex, vmOFC: ventromedial orbitofrontal cortex, SFG: Superior frontal gyrus, SPL: Superior parietal lobe, IPL: Inferior parietal lobe, IPS: Inferior Parietal Sulcus, TPJ: Temporoparietal junction.

1): Clusters were centered on the x-axis, showing medial bilateral activation.

2): Findings revealed a large cluster centered in the IPL, with extensions towards SPL and IPS.

3): Findings revealed a large cluster centered at posterior cingulate, with anterior extensions towards the hippocampal formation.

3.3.3 Activity positively correlated with pupillary dilation

Figure 6:

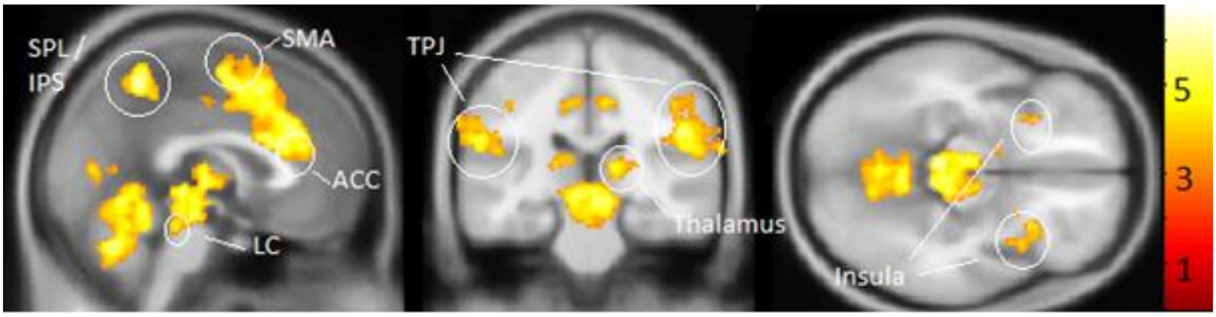

Figure 6: The figure displays areas that correlate with the individual pupil time series. The analysis revealed no significant negative correlations with the pupillary timeseries. Pupillary timeseries > 0. Results shown is based on a cluster generating threshold of z>2.3 and (corrected) cluster significance threshold of P=0.05.

Table 3: Activity correlated with pupillary timeseries:

	K	**Lateralization**	**Peak x y z**	**Value**	**Z-score**
Frontal					
SMA / ACC[1]	9681	R	4 30 26	+	4.1
IFG	97	R	56 8 16	+	3.8
Parietal					
TPJ	1772	L	-57 -33 22	+	3.8
TPJ	668	R	60 29 20	+	4.0
Occipial					
Middle occipital lobe	1772	L	-32 -58 10	+	3.8
Cerebellar					
Cerebellum	4896	R	22 -58 -22	+	4.6
Subcortical					
Brainstem[2]	7612	L	-6 -30 -12	+	4.6
Insula	857	R	38 16 -2	+	4.4
Insula	482	L	-32 14 10	+	3.9

Table 3: Positive finding are indexed with +, results revealed no significant activations negatively correlated with the pupillary timeseries. SMA: Supplementary motor area, IFG: Inferior frontal gyrus, TPJ: Temporoparietal junction.

1): A large cluster is revealed with peak voxel centered at ACC, but with extension backward towards precentral and superior and inferior parietal areas covering Superior Parietal Lobe, and Inferior Parietal Sulcus.
2): A large cluster covering the brainstem, covering the putative LC and superior colliculus, with extensions towards basal ganglia and the right thalamus.

3.4 Summary results fMRI

The central finding for the present study is that the pupil timeseries indeed predicted activity in the brain stem, including the putative location of the LC, and further in the IFG, TPJ, SPL and IPS, reflecting key nodes of the dorsal and ventral system. Importantly, increase of tracking load was associated with a decreased activity in the superior frontal gyrus (SFG) and temporoparietal junction (TPJ).

Furthermore, both tracking, load and pupil timeseries predicted activity in anterior parts of insula.

We also replicated previous findings, showing that both tracking and parametric increase of load modulated BOLD-activity in the frontal eye field (FEF), the Superior parietal lobe (SPL) and the inferior parietal sulcus (IPS), core nodes in the dorsal network. Parametric increase of load positively correlated with bilateral activation of the Middle Frontal Gyrus (MFG)

Furthermore, both tracking in general and increase of load was associated with a decrease of activity in the medial / orbitofrontal areas of the prefrontal cortex (mPFC), inferior parts of the parietal lobe, hippocampal areas, posterior cingulate and lateral parts of the temporal lobe.

4 Discussion

The current study applied the MOT- paradigm to investigate the effect of changes in mental effort on both pupillary responses and brain activity. To our knowledge this is the first study linking online pupillary measurements to brain activity using fMRI in human participants during MOT. The result for the current study supports our hypothesis, and provides converging evidence in line with current literature. As hypothesized, we observed increased pupil dilations with increasing tracking load, supporting the idea that pupil dilations reflect attentional resource allocation, as suggested by Kahnemans model. The fact that increased tracking load was associated with a significant drop in accuracy, and increased reaction-times, confirms that the task indeed taxes a limited resource, and that that the number of load-conditions was appropriate i.e. there was no ceiling effect. Moreover, the individual pupil time series predicted activation of nodes in the dorsal and ventral network, as well as activation of the LC-NE system. Also, we replicate findings from previous studies applying the MOT paradigm, and show that the dorsal attentional network is activated and modulated by attentive tracking.

Recent theorizing links the LC-NE system to the functioning of the cortical attention systems, and also suggests that pupil dilations can be used to index activity of the LC-NE system. Our results support this, as the pupil time series correlates with the brain stem activity, including the putative location of the LC, as well as areas of both the dorsal and ventral attention networks. The following section will discuss our findings in relation to these different networks.

4.1 Cortical attentional-network activation

Both tracking in general and parametric increase of load were, in the present study, positively correlated with activity in the frontal eye field (FEF), superior parietal lobule (SPL) and inferior parietal lobule (IPL), with extensions towards anterior and posterior Inferior Parietal Sulcus (aIPS / pIPS). These nodes reflect core components of the dorsal network, and replicates previous findings regarding MOT (Howe, Horowitz, Wolfe, & Livingstone, 2009). Furthermore are these nodes suggested to play a role in biasing the competition between incoming stimuli, which are competing for attentional capacity. Theorists suggest that the FEF, SPL and IPL/IPS send endogenous signals towards visual sensory areas, biasing visual interpretation. It is further assumed that FEF is able to send endogenous signals without sensory information, but parietal areas depend on visual stimulation for enhancement of processing (Ptak, 2012).This was supported by findings where monkeys performed a difficult visual detection task. Activity in the FEF preceded activity in sensory areas, prior to object recognition (Buschman & Miller, 2007), but activation of the IPS and SPL was only found preceding input from visual sensory areas (Saalmann, Pigarev, & Vidyasagar, 2007). This suggest that frontal areas modulate visual areas prior to visual stimuli, and modulation of parietal areas modulates with a reciprocal connection towards occipital visual areas (Ptak, 2012).

A key finding in the present study is that activity in the SPL and IPS was also predicted by the pupillary regressor. These clusters shows clear overlap with clusters that correlated with tracking in general, but did not overlap with areas modulated by load. This may possibly reflect our measurement of two conceptual different constructs: attention reflected in sustained top-down attention through the tracking period, and “attentional effort”, reflected in the concurrent demands on the attentional system. Our results therefore suggests that the SPL and IPS in general are associated with visual top-down attention, but that there is a local differentiation where specific nodes differs from whether they operate at a general sustained level, or reflect direct online demands on the attentional system. The pupillary timeseries revealed in addition to SPL and IPS concurrent activity in the LC. Our analysis cannot say anything about connectivity between these regions; however the LC-NE system is suggested to send dense modulations towards the parietal areas when performance declines. Seen in the light of LC as a “driver” for attentional capacity (Gary Aston-Jones & Cohen, 2005), we can hypothesize that our results support this connection. The LC-NE system activation will be further discussed below.

However, the central aspect for the current study is that the pupillary timeseries in addition to predicting activity in the dorsal attentional network also positively predicts activity in key nodes in the ventral network (TPJ and IFG), along with the putative LC. The IFG and TPJ have been suggested to be core nodes in the ventral system, mediating attentional shift, and task reset (Corbetta et al., 2008). The ventral system has been shown to respond to behaviorally relevant stimuli during focused attention (Fox et al., 2006) and empirical evidence suggest that the TPJ activates to salient distractors, during sustained attention (Indovina & Macaluso, 2004), along with the IFG (Corbetta et al., 2008). Other studies using

MOT have reported an increase in difficulty, and hence attentional effort, as a function of the proximity between targets and distractors (Franconeri, Jonathan, & Scimeca, 2010). Distractors that share the same physical properties as the targets, are more likely to cause reorientation, and activation of the ventral network (Fox et al., 2006). The activation of the ventral network is suggested to be mediated by a phasic burst from the LC (Gary Aston-Jones & Cohen, 2005), which provides a temporal filter for attentional reorientation. One way to interpret these findings is that the observed pupil-related activation corresponds to when distractors move close to the targets. As the distractors as physically identical to the targets, they represent an irrelevant, but highly salient stimuli. This causes activation of the ventral network, mediated by LC phasic firing. A further interesting finding is that increase of attentional load correlates negatively with activity in the TPJ and IFG, supporting the hypothesis that the ventral network is suppressed during sustained attention, and degree of suppression is a function of attentional load (Corbetta et al., 2008). The present results therefore reveal an interesting dynamic between the dorsal and ventral network; dorsal network activation mediates sustained attention, but when salient distractors move closely to targets, the ventral network activates and suppresses to potentially incorporate the salient distractor.

However, at a cortical level, shifts between the dorsal and ventral system is suggested to be mediated through the MFG. MFG is suggested to be an extended part of the dorsal attentional network (Corbetta et al., 2008) and playing the role of maintaining task goals during attentive tracking (Ptak, 2012). Further is MFG suggested to play a role evaluating how interruptions from the ventral system correspond with behavioral goals. In the present study is only increase of load correlated positively with bilateral activity in the MFG. The MFG have in a large review been linked to sustained spatial attention and working memory functioning (Cabeza & Nyberg, 2000) and especially when several objects in working memory needs to be monitored. (Kerns et al., 2004; Miller & Cohen, 2001; Petrides, 1995). In other words, MFG does not only activate to coordinate how the salient stimuli activating ventral system corresponds with internal goals of achievement, but also to maintain objects activated by the dorsal system, facilitating optimal top-down performance (Corbetta et al., 2008). It is therefore plausible to hypothesize that even though the ventral system deactivates after attentional reorientation, the MFG sustains its activity to maintain top-town control during high degree of attentional load, and not correlate with the pupillary timeseries.

4.2 Neural basis for capacity limitations

A central aspect to discuss is also how the attentional capacity-limitation is reflected at a neural level. It have been suggested that the neural organization of the nodes in the dorsal system is the underlying mechanism representing capacity-limitations. There is converging evidence from human and animal studies that the frontal and parietal structures of the dorsal system is organized as spatial maps (Arcaro, Pinsk, Li, & Kastner, 2011; Funahashi, 2013), becoming activated primarily when storing information about objects from particular spatial positions (Franconeri, Alvarez, & Cavanagh, 2013). Theory suggests that these maps represent a form of "cortical real-estate", where attended objects are stored during tracking (Franconeri et al., 2013). This indicates that there is a limited degree of representational space for objects, and decline in performance is a result of targets competing for the same representational space (Franconeri et al., 2013).

Increase of load have further been reported to increase activity in parietal areas of the dorsal network (Jovicich et al., 2001). Our study replicates this finding, and theory suggests that the increased activity reflects an increase of the specificity in the cortical maps (Franconeri et al., 2013). As the task gets more difficult, an increase of activity facilitates specificity within the cortical map, decreasing each object requirement for representational space.

4.3 Central executive network

In addition to findings regarding the neural networks of attention, our results reveal further interesting findings that relate to previous published theory. A shared finding for tracking, load and the pupillary time series, is a clear positive activation of the anterior parts of insula. Insula have been suggested to be a central component in a core task-set system, responsible for initiating and mediating sustained attention, from a central executive perspective (Dosenbach et al., 2006). The central executive network differs from the attentional related networks, as it is suggested to reflect a higher cognitive functioning, facilitating attentional shifts and mediating sustained activity in the attentional systems. This core task-set system is suggested to also include the anterior cingulate cortex (ACC), which in our results only displays activity associated with the pupillary regressor. The ACC is in the literature associated with error performance and online monitoring (Carter, 1998), and it is further suggested to be one of the core components providing input to the LC, signaling increase of NE release in relation to weak task performance. Theoretical interpretations suggests that this is the way the central executive network mediates shifts between top-down and bottom up attention , as the release of NE increases distractibility (Gary Aston-Jones & Cohen, 2005), and gives a short temporal window where attentional shifts can be performed (Sara, 2009). However, ACC have also been shown to correlate positively with increase of attentional load (Davis, Hutchison, Lozano, Tasker, & Dostrovsky, 2000), a finding not present in the current study. A possible reason that increase of load does not correlate with ACC, is that activation of the ACC is better predicted by the pupillary regressor. As ACC is suggested to drive the phasic activation of the LC (Aston-Jones & Cohen, 2005), it should be highly correlated with LC-activation, and predications of LC-activation. We therefore hypothesize that pupillary dilation better predicts activation of the ACC, as it regulates LC in relation to attentional control.

Anterior insula and anterior cingulate cortex is therefore suggested to form a putative task-control network (Dosenbach et al., 2006), as these regions may send top-down signals to the ventral network, and aid mediation between the dorsal and ventral network, through the LC-NE system. Our findings support this interpretation, as we see ACC activation correlated with activation of the LC, IFG, and TPJ, core components of the ventral network, through the pupillary timeseries.

4.4 Default network

A further interesting finding in our data, is that tracking and orientation of attention towards task engagement, is negatively correlated with activation in medial prefrontal cortex (mPFC), posterior cingulate cortex, hippocampus and posterior parts if the insula. These areas reflect key nodes in the default-mode network (DMN), reported to be activated by attentional disengagement (Buckner, Andrews-Hanna, & Schacter, 2008). Findings also reveal that the mPFC, posterior cingulate and the temporoparietal junction (TPJ) is further suppressed as a function of attentional load. This gives supporting evidence for an active suppression of the DMN during attentional top-down control (Corbetta et al., 2008). However, the deactivation centered around the TPJ shows a clear overlap with nodes in the ventral system, which is also suggested to be actively deactivated during top-down control by the dorsal system (Corbetta et al., 2008). This hampers the interpretation, as the activation cannot be clearly attributed a distinct network, but potentially reflects the deactivation of the ventral system, as well as the DMN.

4.5 Study limitations

A central topic to discuss is the validity of including the pupil time series as a regressor, without convolving the regressor using the canonical HRF, as is usually done when modeling BOLD-activity. The common property for both the pupillary response and the hemodynamic response underlying the BOLD-signal is that it reflects neural activity. The hemodynamic response reflects the increased ratio of oxygenated to deoxygenated blood, resulting from the increased metabolism from active neural tissue. . This response is slow compared to the underlying neural activity. Increases in BOLD-activity as measured by fMRI is seen often approximately 2 seconds after stimulus onset (Kwong et al., 1992), and reaches peak activation after 6-12 seconds (Buxton, Wong, & Frank, 1998; Frahm, Krüger, Merboldt, & Kleinschmidt, 1996). The HRF is therefore an approximation on how to convert the model of neural impulses to the observed BOLD-signal. Convolving the pupil time series with an HRF would therefore assume that the pupil response directly reflects neural activity. However, this assumption is problematic since pupil dilations, just as the BOLD-signal, is a more slowly developing response due to underlying neural activity. (Beatty, 1982), with the difference that the pupillary response typically is faster, and reaches peak dilation after 1-3 seconds (Beatty, 1982; Laeng et al., 2011). The actual relationship between the pupillary response and the hemodynamic response is currently unknown. Our choice was therefore to leave the pupillary time series as it is, since the underlying assumption of the HRF may not apply to this regressor.

The pupillary time series is further correlated with activity in the putative LC in the brainstem. Previous findings have suggested a tight link between pupillary dilations and NE activity (Koss, 1986), and the release of NE from LC likely mediates pupillary responses due to cognitive processing (Samuels & Szabadi, 2008). Documentation of LC-activation during fMRI-recording is however not straightforward, as the nucleus only contains 22,000 to 51,000 neurons in human adults (Mouton, Pakkenberg, Gundersen, & Price, 1994). Further is the LC is located close to the pontine raphe nuclei (Parvizi & Damasio, 2003), and in the monkey, neurons in the rostral poles of the superior colliculus can display tonic activity during fixation behavior, preventing the execution of saccades (Buttner-Ennever, Cohen, Pause, & Fries, 1988). A potential interpretation of our LC-activation is therefore that the activation of superior colliculus has been smoothed out during preprocessing to extend to the LC. But interestingly, our LC activation show a clear overlap with an anatomical template for locating of the LC developed using high-resolution MRI (Keren, Lozar, Harris, Morgan, & Eckert, 2009). Further support comes from the theoretical aspect, as pupillary dilations is suggested to be highly correlated with activation of the LC-NE system, in relation to mental effort and increase of cognitive load (Laeng, Sirois, & Gredeback, 2012). Our data also showed a clear lateralization of the brainstem cluster, with higher activation extending towards right thalamus. In humans, a denser concentration of NE towards right thalamus have been documented (Corbetta & Shulman, 2002) further supporting the hypothesis that it is in fact the LC-NE system the pupillary time series reveals.

4.6 Future directions

Findings from the current study suggest both measurement pupillary responses and neural activity relates to the same “effort” concept, and that is mediated by the LC-NE system. The present study does however only provide documentation of correlation between different measurements, leaving the notion of causality unexplored. Recent development of analysis-techniques in fMRI, allows exploration of connectivity between correlated neural nodes (Friston et al., 1997), and the causal relationship between them (Friston, Harrison, & Penny, 2003). Assuming that the current findings replicates across studies, the next step in the exploration of effortful processing will involve documentation of causal connections; both in relation to the LC-NE system, but also in the interaction between the dorsal and ventral network.

4.7 Conclusion

The goal for the current study has been to investigate how two different operationalizations of mental effort potentially can be unified in a common understanding. We hypothesized that pupillary responses could be used as an online predictor of neural activity, unifying empirical evidence from functional imaging with evidence from pupillary studies. The current findings suggests that the pupil is a valid predictor of the neural basis of attentional effort, as it predicts activity corresponding with both dorsal and ventral network, the putative LC-NE system and cortical areas responsible for regulating LC-functioning. Our results supports that during attentive tracing, online fluctuations in attentional effort captured by the pupil, successfully predicts activity in cortical networks responsible for attentional control.

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