Effort and pupil behaviour in visual search task

by

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ABSTRACT

Perceptual load is reflected in the size of the eye pupil. High perceptual load decreases processing of irrelevant information because attentional resources are employed in the experimental task. Large scale attentional zoom decreases processing efficiency due to a spread of attentional resources. The relationship between perceptual load, attentional zoom, and distractor processing was investigated with modified version of Beck and Lavie’s (2005) distractor processing paradigm. Both behavioural data (i.e. accuracy and response times) and a physiological measure (pupil change) were recorded concomitantly. Results indicated that pupils dilated more in the high load conditions than in the low load conditions, but failed to show differences due to display size manipulations. Moreover, while behavioural data indicated that distractor processing was reduced in the high load condition, pupil reactions to different distractors were just as strong in both the high and the low load condition. It is argued that the pupil is highly sensitive to fluctuations in effort.

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Introduction

Pupillometry

Emotion. The movements of the human eye pupil has intrigued and puzzled for centuries. As far back as in the middle ages the idea of female beauty being artificially inflatable by applying drops of poisonous atropina bella donna to the eyes. The toxic herb, also called deadly nightshade because of its popularity as a murder weapon, caused the pupils to dilate, which presumable made her more attractive because of the subtle revelation of interest. In addition to interest and curiosity, emotions such as stress, pain, anxiety, sexual arousal have demonstrable effects on pupil size (Wang, 2010).

Cognition. Whereas the relationship between emotional variables and pupil dilation has been a known fact for centuries, it was not until the 1960s the relationship between the pupil and cognitive factors called for serious attention and systematic investigation. The then-available equipment allowed for coarse measurements of the changing pupil sizes to be recorded and fitted into a framework for a working memory load-pupil size relationship. Research on pupillary responses to what would nowadays be described as cognitive load started in the early 1960s. Hess and Polt (1964) investigated the pupillary response of people engaged in solving arithmetic problems. They found a positive correlation between level of difficulty and pupil diameter. Soon afterwards, Kahneman & Beatty (1966) related pupil size variations to memory load. The participants were asked to remember strings of digits presented verbally. After a short interval they were asked to reproduce the digits they had heard. Results show that, during encoding, there was an increase in pupil size for each digit presented, indicating a gradual increase in memory load. Similarly, when reproducing the digits, pupil size decreased for each digit reported, indicating a parallel decrease of load on memory. In trials with more digits involved, the pupil sizes were overall larger during the entire procedure, indicating a somewhat more sustained effect of increased memory load. Based on these studies, Kahneman (1973) theorised that the pupillary response to a task was a primary measure of processing effort. He stipulated three criteria for any physiological indicator of processing load. First, it should be sensitive to any within-task variations in task demands. Increasing the task demands by changing the task parameters should produce increased pupil dilations. Second, it should reflect between-task differences in processing load brought about by qualitatively different cognitive activities. Third, it should register individual differences in processing load as individuals with different abilities perform the same cognitive tasks.

Limitations to load measurements. Having seen that the pupil dilates as a direct response to increased memory load, Peavler (1974) decided to go beyond the capacity limits of the test persons' working memory to investigate how the pupil reacts. He found that, similar to Kahneman & Beatty's (1966) discovery, pupil sizes increased with number of digits. However, when the number exceeded nine, the pupil stabilised. Peavler (1974) noted that, as long as some information processing capacity remained, increasing memory load was reflected in increased pupillary dilation. Once this capacity limit had been reached, additional increases in task demands did not increase pupil diameter further. This could indicate that the working memory is simply being overloaded, and therefore momentarily sustains processing effort. Ambler, Fisicaro, & Proctor (1976) introduced dichotic shadowing to task-evoked pupillary response (TEPR) studies. They found a large response during shadowing with the largest pupillary response occurring at the beginning of the trial, followed by a gradual, negatively accelerated decrease in response. In this study, the data points were not numerous enough to compute the shape of the TEPR curve in response to increased load.

Effort. Clark, Barr, & Dunham (1985), nearly a decade later, also looked at the TEPR curve in relation to increased load and found an inverted U-shaped curve, rapidly increasing at the beginning of the task, levelling off, and finally decreasing toward the end. This study design was also sensitive to different levels of difficulty. The two groups did one of two tasks, either shadowing 100 words per minute (hard task) or 60 words per minute (easy task). The TEPR produced by the hardest task was much larger than the TEPR produced by the less demanding task. The group that did the hardest task had a lower TEPR for the first of three blocks. This could indicate that the processing load for this group was reduced due to omission of the words to be shadowed. Hence, the TEPR appears to reflect the amount of information actually processed rather than the amount of information processing required. Two decades after Peavler's (1974) original study, Granholm, Asarnow, Sarkin & Dykes (1996) had a fresh look at resource limits and memory overload. They found that pupil dilation stabilized at nine digits, the common resource limits. They also found that by exceeding resource limits by going beyond nine digits to be remembered, pupil sizes started to decline. These studies both reflect that the pupillary response measures more reliably how the task is executed than the intrinsic load of the task. The effort made does not necessarily correspond to the intended load manipulation of the task. There is some evidence that the pupil data corresponds better with the effort mobilised to execute a task than with the load of the task itself. For example, preparing for action and perception of difficult response sets leads to more dilation than preparing easier tasks (Moresi et al, 2008).

Current situation. After the wave of popularity that the pupillometric method enjoyed in the 1960s and 1970s its popularity as a research method waned (Van Gerven, Paas, Van Merrienboer, & Schmidt, 2004). These days the method enjoys newfound regard, partly due to the latest technological development build into the equipment and the software available for analysis of the results. With the increased sophistication and accuracy of the equipment used today, data can be collected that is sensitive to the subtlest temporal and spatial changes. The latest generation of pupillometry hardware has resolution as fine as .025 mm in diameter on individual measurements (Granholm & Steinhauer, 2004), at rates up to 2000 Hz RS (SR Research, Osgoode, Ontario). Eye tracking allows the researcher to systematically record not only the direction of a subject's gaze, but also the saccades, eye blinks frequency and the diameter of the pupil. The most widely used equipment today is based on non-contact video recording of the pupil. The camera, which could be either stationary or head-mounted, records the movements of one of the eyes while the viewer looks at some kind of stimulus. The vector between the centre of the pupil and the corneal reflection is used to compute the gaze location. The corneal reflection is created with non-collimated light and the edges of the pupil are found using contrast detection between the iris and the pupil, not unlike the "magic wand" function in Photoshop. The contrast of the pupil edges is used to track the pupil contractions and distensions as the viewer performs computer based tasks. An alternative method to calculate pupil size is to count the number of pixels of the pupillary area (Pomplun & Sunkara, 2003). This technique is not employed in the present study because of its more affected by perspective distortion, or gaze direction (Klingner, Kumar, & Hanrahan, 2008).

Noise. The great challenge in eye pupil data analysis is to reduce the substantial amount of data noise that can afflict pupillometric studies. Apart from the most obvious artefacts, like changing light conditions, there is a range of possible sources of error, both external and internal to the viewer. The amount of light or the hue in the visual stimulus itself can influence dilation and constriction responses. In addition, stress, emotional factors and time on task do influence the pupil responses (Granholm & Steinhauer, 2004; Fakuda, Stern, Brown, & Russo, 2005).

Attention

Selection. The richness of information that lies in the surroundings makes it impossible to attend to everything. In fact, most perceptual events never make its way to the human consciousness because of effective cognitive systems that consign it to oblivion forever. Because people are continuously bombarded with all sorts of stimulus it is of paramount importance that there are systems in place for selecting what is to be chosen and what is to be ignored. Although the study of attention has gone through many stages, from introspection (e.g. James, 1890) in the 1890s, to present day neuroimaging approaches, some basic principles remain firm. Attention is needed to select and reject. Modern conceptions of attention emphasize the very processes that enable individuals to filter environmental input and come with complete behavioural and neurological frameworks. Behavioural studies typically investigate what information is attained to and how much one can attend to at the time, how much time is needed to process information and how distractors are dealt with.

In practical terms, attention has three major functions: Orienting towards the target, focusing or target detection, and vigilance or the maintenance of a state of alertness (Posner & Petersen, 1990). In order to carry out these functions, there are cognitive mechanisms in place that cooperate and compete in determining the relative amount of attention to be allocated to all the different potential attentional targets. According to Knudsen (2007), there are four main components of attention: Working memory, competitive selection, top-down attention, and bottom-up attention.

Working memory. The working memory is a highly dynamic form of memory that operates of periods of seconds and temporarily stores selected information for detailed analysis (Baddeley, 2003). It holds a limited amount of information during short time spans while this information is manipulated according to current goals and stored memories. There has been some debate as to whether representations for storage and control functions are strictly separate entities within the working memory or not. Whereas early models of working memory (e.g. Baddeley & Hitch, 1974) propose control functions as a separate component, newer models suggest it be an integral part.

Competitive selection. Modern understanding of the working memory emphasise the role of dynamic, competitive processes, rather than the plain maintenance of information. Consequently, it is today a preference for the term “working memory” instead of short-term memory. Multiple types of information may compete for full control of the circuitry underlying working memory at any moment in time, thus making working memory a competitive process (Knudsen, 2007). Competing representations operate with different strengths, which in turn decide to what degree it will preside over working memory. The information that is held in working memory serves as the basis for decision and the planning of complex behaviours (Genovesio, Brasted & Wise, 2006).

Top-down attention. Attention can be driven volitionally by "top-down" signals derived from current task demands and automatically by "bottom-up" signals from salient stimuli. Braver’s (2002) context representations exert influence on attention via endogenous, or top-down, control. The information held in working memory not only serves as a basis for planning complex behaviour; it also guides the very selection and quality of the information it processes (Miller & Cohen, 2001). One mechanism for improving information quality is simply to direct orienting movements toward the target in question (Knudsen, 2007). In terms of enhancing the quality of selected information, the information held in working memory also controls top-down signals that modulate the sensitivity of neural representations that contribute that information (Miller & Cohen, 2001). Some of this modulation may be conscious, but it may also operate silently. One might deliberately direct attention towards something or be merely influenced by current state of mind. Top-down processing occurs when an individual’s prior knowledge, motivations, expectations, and higher mental functioning affect the perceptual representation (Levitin, 2002). Basically, people are at any given time perceptually fine-tuned to certain kinds of stimuli, while at the same time more disposed to ignore or overlook other bits of information.

Bottom-up attention. The exogenous, or stimulus driven, attentional pathway is called “bottom-up” attention. This network is and acts as a circuit breaker and a short cut to attention for salient stimuli. In contrast to the dorsal top-down network, it is driven by stimulus salience or properties inherent in stimuli (Buschman & Miller, 2007). Behaviourally relevant stimuli, particularly if it is salient or unexpected, are acted upon quickly due to the enhanced speed. Salience is what is striking or new or attention grabbing. However, what is experienced as attention grabbing is not static and not universal. It influenced by both learning and behavioural relevance at the same time. That is, what is salient to a person according to this person’s learning, attitudes and experience *combined* with the top-down signals being channelled from the dorsal system makes up the current salience of any information. Some kinds of stimuli are more or less universally salient, such as the sudden appearance of snakes, which are probably hard-wired as potentially dangerous (Purkis & Lipp, 2007). Other stimuli may be salient more because of individual learning or lifestyle. A mafia member, for instance, will react to certain abrupt arm movements differently than people not accustomed to the use of weapons indoors. Object salience combined with top-down signals for current expectations create salience maps.

The visual Zoom

Location and cueing. Location, or from where a given stimulus originates, is of crucial importance for its fate in the attentional process. In selecting information for intensive analysis stimulus, the location serves as a powerful indicator of the information's relevance. Stimuli are filtered out on the bases of it spatial origin (Colby & Goldberg, 1999). Consequently, the product of this process guides goal-directed behaviour. Attentional bias takes on various forms during attentional selection. It is both feature oriented, like the working memory's top-down influence in selecting aspects to be attended to, and spatially oriented. Thus, bias is also at play when choosing where to allocate attentional resources. This phenomenon has been investigated using test paradigms that instruct research subjects (being animals or humans) to direct their attention to a cued location (e.g. Posner & Petersen, 1990). These experimental tests typically indicate at what location a target stimulus most likely will appear (cueing) and measure the reaction time in correctly detecting presented stimuli. Difference in reaction times for correctly indicated locations (valid cues,) wrongly indicated locations (invalid cues), and non-cued targets (neutral trials) indicate to what degree spatial cueing speeds up or slows down target detection. This is interpreted as location cueing successfully assisting or impeding visual attention. It has been demonstrated that animals increase their sensitivity and their target detection speed at cued locations (Desimone & Duncan, 1995). In addition, neurons discriminately react to cued compared to non-cued target locations. At presentation of target stimuli in the cued location neurons at high levels in the visual pathway increase their discharge rates compared to neurons in non-cued target. It has been demonstrated that making primates direct their attention to a certain location has not only a positive effect on performance, but also increases neuronal activity in the visual cortex (Spitzer, Desimone, & Moran, 1988).

The optimal size of the attended area changes according to current goals and the requirements of the situation. In some situations, the most favourable size of the attended space is large, at the expense of the finer details. Yet other situations will call for attention to fine details and a reduced size of the attentional focus. The cost of this, in turn, is reduced large-span completeness (Eriksen & St. James, 1986). It had been demonstrated behaviourally that there is a decrease in processing efficiency when the size of the attentional focus increases (Castiello & Umilta, 1990).

Perceptual load

The bottleneck. As discussed above, an intricate attentional system accounts for selection and rejection of stimuli. Hence, somewhere en route from senses to awareness the non-attended stimuli are halted. There has been a longstanding debate on whether sensory stimuli are more or less automatically processed or rather filtered out at a later stage of perceptual cognition (e.g. Driver, 2001). Given that there seems to be some kind of “bottleneck” from which only selected information will proceed, the opposing views differ as to where they place this bottleneck. According to early selection theories, capacity limits cause information to be filtered out at a merely perceptual level, so that it is not selected for further processing (i.e. Treisman, 1969). Early studies on the phenomenon of attention relied to a great extent on the method of dichotic listening, in which the test persons were asked to attend to a target sound stream in one ear and ignore the events in the other. These initial studies often concluded information was largely ignored in the unattended ear, leading the researchers to conclude that attention attenuates processing in the unattended ear before its content can be analysed semantically. Proponents of late selection models, on the other hand, claim that perceptual information is automatically processed at this level, but later hindered from controlling higher cognitive processes (i.e. Deutch & Deutch, 1963).

Load and bottlenecks. An effective way of reconciling these models and advance the understanding of perceptual filtering was proposed by Beck and Lavie (2005). They devised a visual search task and measured distractor processing as an index of non-target interference. They opted for comparing the reaction times between trials in which the distractor was congruent with the search target to trials in which the distractor was incongruent. The latter condition is associated with increased reaction times because of the response competition it involves (Eriksen, 1995). In Lavie’s case, the incongruent distractor consisted of a letter that was a potential target letter, but was to be ignored on the basis of being placed on a location that was not to be attended. This would create a conflict between responding to the distractor and responding to the target letter. The congruent distractors, on the other hand, were identical to the actual target and would therefore not induce any conflict. In incongruent trials, the distractor would interfere with the visual search if, and only if, it is processed. In that case, one would expect to see reaction times increase as the individual would have to repress the information from the non-relevant distractor before responding. However, in the case of successfully ignoring the distractor, its identity as congruent or incongruent is of no importance. Consequently, the difference in reaction times between these two conditions was interpreted as a measure of distractor processing.

Perceptual load was manipulated to investigate its effect on distractor processing. There were two kinds of distractors involved, one central distractor, at a location not be attended to at all, and five peripheral distractors within the area the target would appear. In the low load condition, the peripheral distractors were homogenous and would therefore make the target “pop out” more efficiently (Wolfe, 1998). In the high load condition, the peripheral distractors were heterogeneous and similar to the target and would therefore make the search more difficult (Duncan & Humphreys, 1989). Results showed that decreasing the perceptual load of the task *increased* the difference in reaction times between congruent and non-congruent trials. In the low load condition there was perceptual capacity left that “spilled over” and started processing irrelevant stimuli. In the high perceptual load condition, on the other hand, there was no spare processing capacity left, and reaction times were similar regardless of congruency. Thus, it was concluded that it is the load that determines to what point in the perceptual process an irrelevant stimulus will reach before being stopped by attentional processes. Distractors such as objects or faces have the same effect as the original distractor-letter task, although the level of load required to eliminate the congruency effect is higher than for less salient distractors (Lavie, Ro, & Russell, 2003).

An important point to make about perceptual load, as it is conceptualised in this context, is that it refers to the number of different-identity items that need to be perceived or the level of attention required (Lavie, 2000). Perceptual load is not to be confused with difficulty of perception, as in perceiving a target with low contrast or small size; it refers to the number of potentially relevant objects for selection. High perceptual load eliminates distractor processing whereas increased task difficulty typically increases distractor processing (Lavie & DeFockert, 2003). Similar results have been encountered using different sorts of task and different distractors. With respect to the bottle neck debate, Lavie´s (2000, 2003, 2005) results indicate that the whereabouts of the perceptual bottleneck depend on the task being executed. When the perceptual load is high, the filtering takes place earlier in the process than when the perceptual load is low. This is evidenced by significantly less distractor processing in high load tasks.

The eccentricity effect

Not only the size of the attended area, but also the size and eccentricity of the target influence the efficiency of the visual search. The eccentricity effect causes targets at peripheral location to be processed more slowly and less accurately than those appearing near the fixation point (Carrasco, Evert, Chang, & Katz., 1995). Detection of both feature and conjunction targets becomes increasingly less efficient as the target appears at greater eccentricity from the central fovea (Carrasco et al., 1995).

There are several possible explanations why this is the case, relating to both cortical magnification factor, and to the distribution of receptor cells in the fovea and the surrounding areas of the retina. A pair of rays that hit the retina close to the centre of the fovea is separated by an angle that is different to the angle that separates the same pair of rays hitting the retinal periphery (Holden & Fitzke, 1998). Therefore, the scale relating degrees in the visual field to distance differs between the various loci of the retina (Holden & Fitzke, 1998). The farther removed a stimulus projection is from the centre of the fovea, the greater the eccentricity and the smaller the size of the projection in the visual cortex.

In addition to the magnification factor, retinal architecture itself imposes constraints on processing and leads to what is called the eccentricity effect. The ratio of different photoreceptor cell types differs throughout the fovea, with cone cells dominating the centre and rod cells dominating the periphery. The corresponding cortical areas for visual input are also unevenly distributed with a disproportionally large percentage of of all cone receptors, along with the retinal ganglion cells they are connected to, subserving the central vision (Miller & Newman, 1998).

The relationship between eccentricity, size, and magnification, is comprised in the cortical magnification factor (Daniel & Whitteridge, 1961). Melmoth, Kukkonen, Mäkelä, & Rovamo (2000) took both contrast and size in to account when investigating the effect of eccentricity on face perception. They found that in all conditions contrast sensitivity first increased and then saturated, as a function of stimulus size. The effect of eccentricity is also non-linear, in that the magnification falls off quickly with increasing eccentricity, and thereafter slows down. By cortically magnifying the stimuli, the eccentricity effect is neutralised (Carrasco & Frieder, 1996). Reversely, the formula can also be used in order to neutralize the effect of increasing image size. Thus, the m-scaling technique allows for manipulation of the attentional aperture without alteration of the cortical projection constant.

Age and pupil responses

Pupil size substantially decreases with old age, a phenomenon referred to as senile miosis (Winn, Whitaker, Elliot, & Philips, 2004). It has also been suspected that also the pupil reaction amplitude diminishes with age. Van Gerven et al. (2004) suggested that the small amplitude of pupillary response in older adults may not be sensitive to small changes in cognitive load. Piquado, Isaacowitz and Wingfield (2010) demonstrated that pupillary responses from older adults can still provide meaningful when the particular properties of the employed age group’s pupil properties was taken into account. In their study, pupil reactions were made relative the velocity of pupil light reflex for both age groups involved. This way, they were able to study the effect of sentence complexity and working memory load on both a young adult group and an old adult group with a mean age of 74 years. By the use of this particular technique of relativizing their pupil reaction, they found both absolute and relative differences between the two groups.

The present study

Based on the properties of cognitive load discussed above and its implications for attention and pupil dilation, it was predicted that a) high load tasks would cause increased reaction times, reduced accuracy, and greater pupil dilations than low load tasks, b) having to spread attention throughout a large area would have the same effects on all measurements, c) incongruent central distractors would cause increased reaction times, reduced accuracy, and increased pupil sizes in the low load condition and d) these effects would be greatly reduced in the low load condition.

Methods and Procedure

Participants

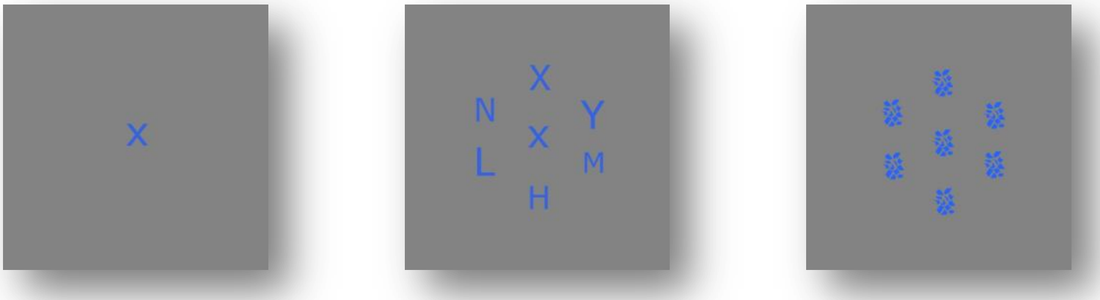
Participants previously recruited for an earlier study were invited back. There were 16 males (mean age 31) and 33 females (mean age 28) from 20 to 49 years of age. They had earlier been screened for dementia, previous or present neurological disease, depression, and substance abuse. All participants had at an earlier occasion completed a task similar to the ones used in the present study. They were rewarded 200 NOK for their participation. Partial or complete data sets from 41 of the original 49 participants were included in the final analysis of the behavioural data, whereas 29 of the data sets were included in the analysis of the eye pupil data. The analysed sample did not differ in age or sex distribution from the original sample.

E-prime scripts

Modified versions of Lavie´s (2005) tasks were used to create the four experimental tasks. To make the scripts suitable for eye-tracking, they were made self-paced, requiring the participant to initiate each trial. This step ensured that the participant was at all times prepared for upcoming task and reduced carry-over effects from task to task. The displays were made equiluminant throughout the whole task in order to rule out any pupil diameter changes caused by changing luminance from the screen. The original task consists of a 1000 ms display of a fixation cross, a 100ms stimulus display, followed by a 1900ms blank screen. The letters are bright yellow on a black background. In the present experiment, the 1000ms fixation cross was followed by 300ms stimulus display and a 3700ms display of masked letters.

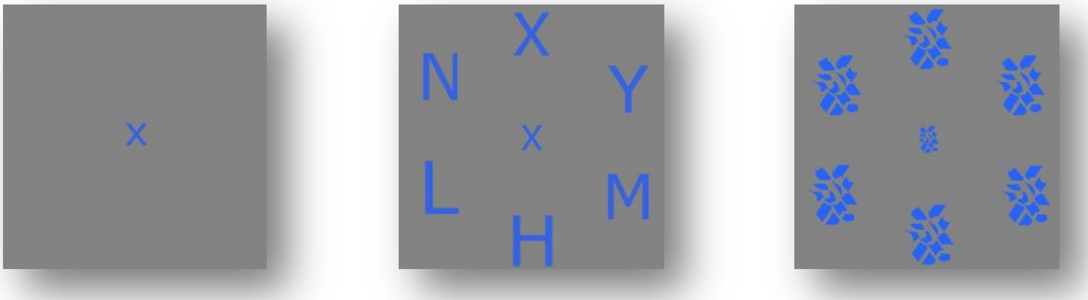
The masked letter display was added in order to ensure constant luminance across all screens and the duration of the stimulus was increased in order to counteract the added difficulty that the masked impose on the task. All screens showed blue (RGB = 39, 100, 255) letters on a charcoal (RGB = 131, 131, 131) background. This colour combination proved to have enough contrast between letters and background without while carrying the same amounts of luminance.

The number of blocks was reduced from three to two in order to reduce fatigue effects, and to keep the participants alert throughout the tasks. In addition to the original load and congruency variables, size was introduced as a third variable. Large versions of both the low load and the high load conditions were constructed, displaying large peripheral letters around the central unaltered distractor. In these versions of the task, size and eccentricity were simultaneously increased using the M-scaling technique, ensuring that the cortical representation remained approximately similar in all tasks. Consequently, any size effect encountered would originate from the increased size of the attentional focus and not from a larger retinal representation of the display.



Fixation cross Stimulus Mask

Figure 1. Small stimuli.



Fixation cross Stimulus Mask

Figure 2. Large stimuli.

Together, the three variables made up mad up a 2x2x3 factorial design, consisting of four different tasks with three congruency conditions in conditions each.

Low load						High load					
Small			Large			Small			Large		
Cong.	Incong.	Neutral	Cong.	Incong.	Neutral	Cong.	Incong.	Neutral	Cong.	Incong.	Neutral

Figure 3. Within-subject variables.

Equipment

Two computers were employed in the recording session, one that ran the e-prime script with the participant's task and one that recorded the eye tracking data. The e-prime script included trigger information that was transferred to the eye-tracking computer throughout the duration of the tasks. These triggers were stored as event markers in the eye-tracker output files. An SMI ® remote contact free eye tracker was used for collecting the eye pupil data. Eye-view software recorded horizontal and vertical aperture of the pupil and gaze position at a rate of 240 Hz. A chin-rest was used to minimise head movements and to ensure an equal distance between the screen and the eyes for all participants.

Procedure

After instructions were given and consent forms signed, participants went through a short trial run of the task they were about to perform. This was done in order to reduce novelty effects, to make necessary adjustments before the recorded session and to calibrate the equipment. The calibration procedure was performed by having the participants gaze at nine different locations across the computer screen. The eye-tracker could thereby infer the gaze position for all participants. The order of the different experimental tasks was counter-balanced in order to distribute any temporal changes evenly. Technical problems at the data collection stage consisted largely of tracking difficulties. Progressive glasses, heavy squinting, and thick make-up on the upper eyelashes turned out to be the greatest challenge to correct pupil tracking.

Data preparation

The Eye-view software output was converted from .idf files to text files using the integrated idf-converter. Thereafter, the data had to go through a series of steps before being suitable for analysis in SPSS. In order to reduce the influence of non-pupil tracking data, eye blinks, gaze diversion, and other sources of error, a MATLAB program was created. The program consisted of the 14 following steps:

Slimming. The raw data of 240 Hz were reduced to every 6th data point, making the final sampling rate 40 data points pr. second. This step was necessary in order to make the amounts of data manageable for the MATLAB software in the following calculations and to reduce processing time.

Removal of non-standard data. Data sets consisting of any other number of trials than the 72 trials in the e-prime script were removed. This step, which was necessary in order to organize the eye data correctly according to trigger information, excluded the largest proportion of the data (see Figure 4.) The main problem was a temporal error in the triggers. With faulty trigger information, the information linking the recorded data to the specific events in the script became unreliable and made accurate analysis impossible. Yet other data sets were incomplete because the eye tracker ceased to record mid-session.

Combining x and y axis of the eye. The formula “(X+Y)/2” was used to compute a composite measure of pupil dilation, in which X is the measurement horizontally across the pupil and the Y is the vertical measurement.

Conversion from pixels to mm. Thereafter, the data was converted from pixels to millimetres to ease the interpretation. The original data expressed in pixels were divided by 16.72 in order to create mm. data. This figure was computed by manually measuring objects, recording them with the eye-tracker camera at the viewer distance and comparing the measurement data.

Exclusion of non-pupil data. With the data now signifying millimetres, data points not originating from human eye pupils could be identified and excluded. Measurements of less than 1mm. or exceeding 9 mm. were classified as non-valid eye data and excluded based on Beatty and Lucero-Wagoner’s (2000) estimations of the normal pupil range.

Sorting. Data were sorted pr trial, meaning that every data point was assigned to one of the twelve within-subject conditions.

Within-trial outlier exclusion. Mean dilation was calculated for every task for every participant and all data points deviating more than 2.5 SD from the mean were excluded.

Excluding impossible pupil behaviour. Information on the maximum velocity of constriction and dilation of the human eye pupil was used (Murillo, Crucilla, Schmittner, Hotchkiss, Pickworth, 2004). The cut-off values employed in this study allowed for the quick pupil movements associated with younger samples.

Removal of faulty data sets. Trials with less than 50% remaining after the above steps were excluded entirely based on the assumption that they contained more artefacts than valid eye pupil data.

Interpolation of gaps. Smaller gaps, mainly resulting from eye blinks or brief moments of gaze diversion were interpolated.

Across-trial outlier exclusion. Outlier data across all tasks were excluded by calculating the grand mean for all tasks pr participant and deleting data that deviated more than 2.5 SD from the mean.

Base-line correction. Because of the large individual differences in both pupil size and phasic dilation, a fleeting pupil size estimate was created for every individual for each task. The average pupil dilation of the 100 to 300 ms time window of each task acted as a base-line and was subtracted from every data point within the same trial.

Combining data. Data from all the 72 x 2 trials from within each participant were combined into 12 within-subject variable columns.

Calculating mean dilation. For each of these 12 columns, the mean dilation was calculated from the cells representing the time-window from 700 to 2300 milliseconds from stimulus onset.

Data destiny:	%
Included	80%
Excluded as non –standard data	11%
Excluded as faulty data set	2%
Recording error	7%
Total	100%

Figure 4. Exclusion by criterion.

Statistical analyses. There were three types of measures collected, two behavioural (reaction times and accuracy) and one physiological (eye pupil data). These measurements served as dependent variables in the analyses. The three types of dependent measures were submitted to separate repeated measures ANOVAs. The independent within-subject variables were load, size, and congruency and there were no between-subject variables. Post-hoc repeated measures t-tests were performed to significant main effects and interactions to confirm directionality. Some additional t-tests were performed also where no significant main effect was found in the pupil data. This was done because the large amounts of missing data could potentially obscure interesting effects in the ANOVAs.

Results

Behavioural data

Accuracy. Mean accuracy data for correct responses were entered into a repeated-measures ANOVA, with Load (high/low), Size (small/large), and Congruency (congruent/incongruent/neutral) as within-subject independent variables. There were no significant effects involving Size.

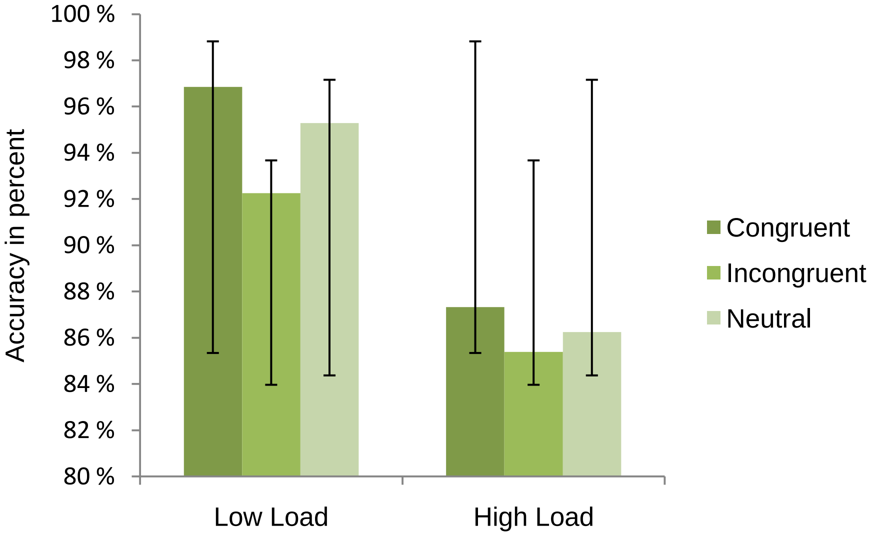


Figure 5. Accuracy by Load. Standard error is shown as vertical bars.

The data was therefore submitted to separate repeated measures ANOVAs at each Size level with Load and Congruency as within-subject variables. For the small display (similar to Beck & Lavie, 2005), there was a significant main effect of Load, $F(1, 42) = 48.9$, $p < 0.0005$, $\eta^2_p = 0.54$. There was also a significant main effect of Congruency, $F(2, 84) = 7.0$, $p = 0.002$, $\eta^2_p = 0.14$, due to lower accuracy in the incongruent condition (88%) than in congruent (93%) and neutral conditions (91%). The Load x Congruency interaction was only marginally significant ($p = 0.068$), but with effects in the expected direction (i.e. larger effect of Congruency under low Load (incongruent – congruent = 6.4%) than high Load (incongruent – congruent = 1.8%). For the large display there was also a main effect of Load, $F(1, 40) = 52.4$, $p < 0.0005$, $\eta^2_p = 0.57$, but the effect of Congruency was only marginal ($p = 0.054$), and there was no interaction between the factors ($F < 1$).

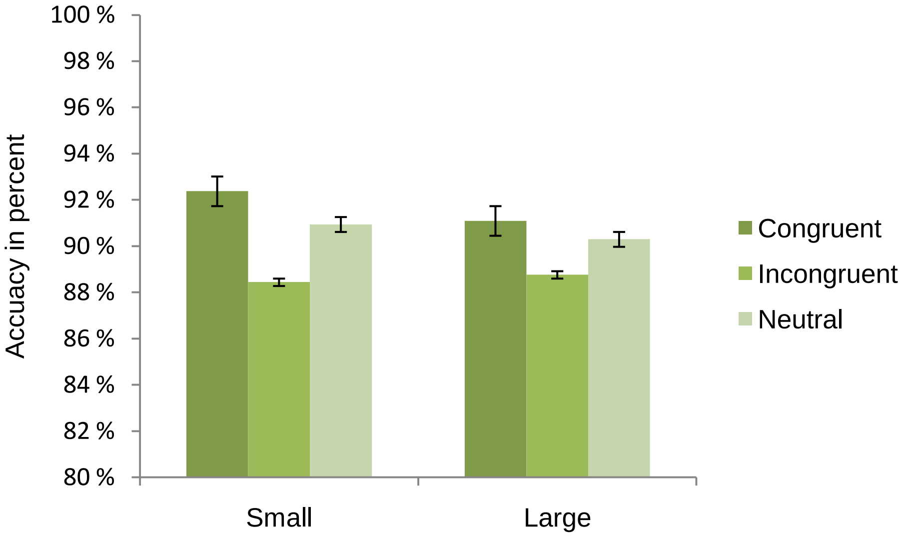


Figure 6. Accuracy by Size. Standard error is shown as vertical bars.

Reaction Times. The mean of median reaction times (RT) were submitted to a repeated-measures ANOVA with Load (low vs. high), Size (small vs. large), and Congruency (congruent vs. incongruent vs. neutral) as within-subject independent variables. There was a main effect of Size, *F*(1, 39) = 7.4, p = 0.01, η^2_p = 0.16, due to longer RTs in the large display conditions (mean RTs were 692 and 716 msec. for small and large displays, respectively), but there were no interactions between Size and the other two factors.

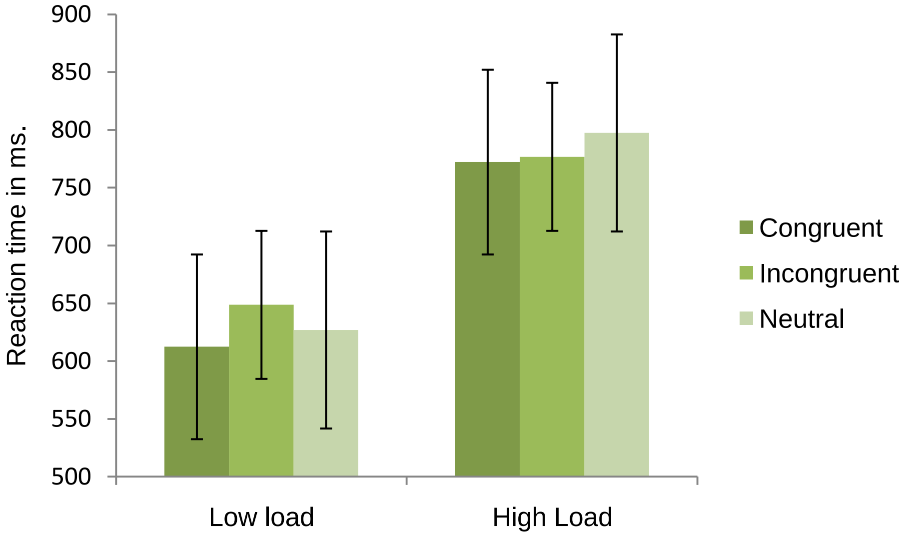


Figure 7. Reaction times by Load. Standard error is shown as vertical bars.

For symmetry with the analysis of accuracy, the data were submitted to separate repeated measures ANOVAs at each Size level with Load and Congruency as within-subject factors. For the small display there was a significant main effect of Load, *F*(1, 41) = 115.3, $p < 0.0005$, $\eta^2_p = 0.74$. There was also a significant main effect of Congruency, *F*(2, 82) = 10.9, $p < 0.0005$, $\eta^2_p = 0.21$ due to shorter RT in the congruent condition (667 msec.) than in incongruent (694 msec.) and neutral conditions (693 msec.). More importantly, there was a significant Load x Congruency interaction, *F*(2, 82) = 9.3, $p < 0.0005$, $\eta^2_p = 0.19$. Post hoc analyses with a paired samples *t*-test revealed that the effect of Congruency was significantly larger in low Load trials (incongruent – congruent = 45.9 msec.) than in high Load trials (incongruent – congruent = 4.2 msec.), *t*(42) = 3.54, p = 0.001.

For the large display there was a significant main effect of Load, *F*(1, 41) = 126.3, $p < 0.0005$, $\eta^2_p = 0.76$. There was a significant main effect of Congruency, *F*(2, 82) = 4.1, p = 0.02, $\eta^2_p = 0.09$ due to shorter RT in the congruent condition (713 msec.) than in incongruent (727 msec.) and neutral conditions (728 msec.). There was also a significant Load x Congruency interaction, *F*(2, 82) = 4.5, p = 0.014, $\eta^2_p = 0.10$. Post hoc analyses with a paired samples *t*-test revealed that the effect of Congruency was significantly larger in low Load trials (incongruent – congruent = 28.6 msec.) than in high Load trials (incongruent – congruent = 0.1 msec.), *t*(42) = 2.31, p = 0.026.

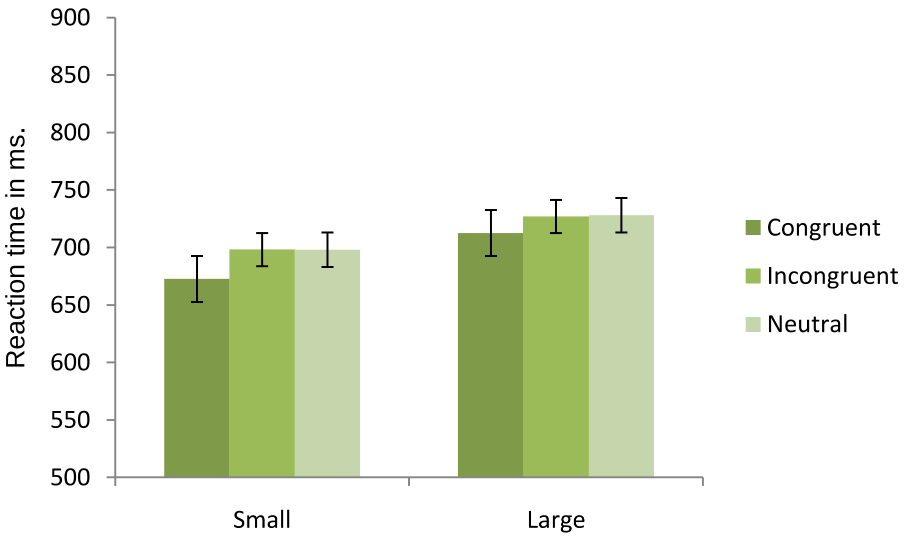


Figure 8. Reaction times by Size. Standard error is shown as vertical bars.

Pupil data

Pupil reactions to stimulus. Pupil dilations peaked on average 1,683 seconds after stimulus onset (SD = 308 ms).

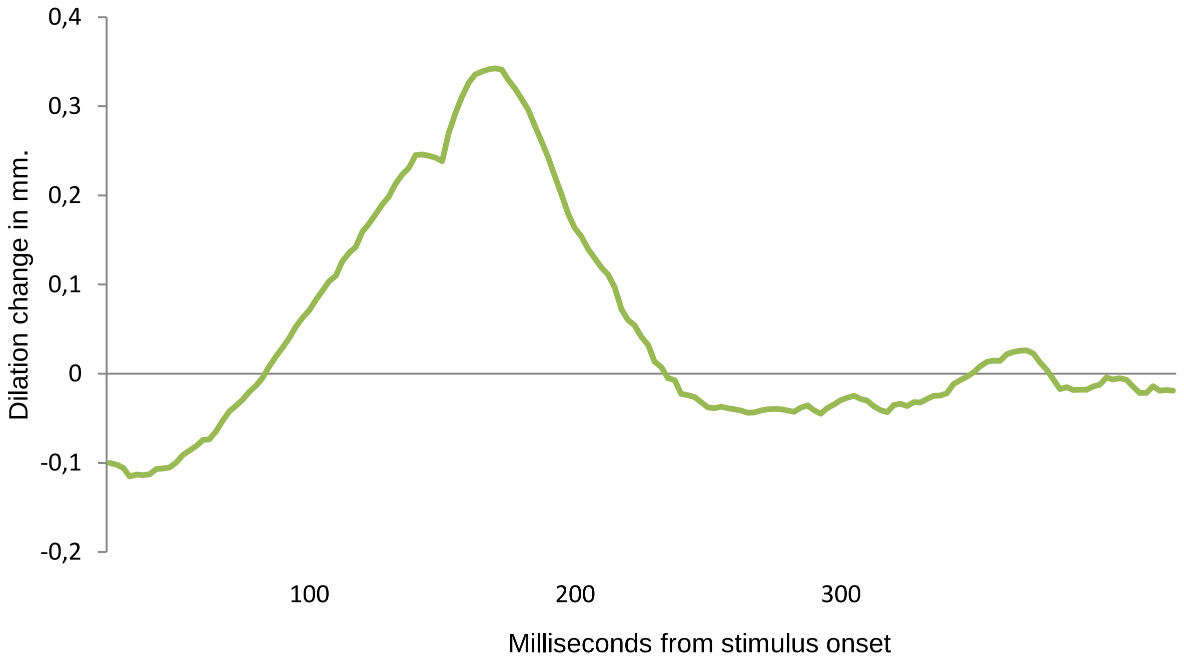


Figure 9. Typical pupil reaction to task.

Fleeting baselines. The fleeting baselines (see “baseline corrections” step in Methods and Procedure) were submitted to a repeated measures ANOVA with task number (1 vs. 2 vs. 3 vs. 4), type of task (easy-small vs. easy-large vs. hard-small vs. hard-large), sex (male vs. female), and age as independent variables. There was no effect for the order of the tasks, type of task, sex, or age.

Correlation with behavior data. A univariate correlation analysis was performed with accuracy data, reaction time, and pupil data as separate variables. There was no significant correlation between any behavioural data (accuracy and reaction times) and pupil dilation for any of the measured variables.

Mean pupil dilation. The mean pupil diameter data (se “calculating mean dilation” step in Methods and Procedure”) were submitted to a repeated measures ANOVA with Load (low vs. high), Size (small vs. large), and Congruency (congruent vs. incongruent vs. neutral) as within-subject factors.

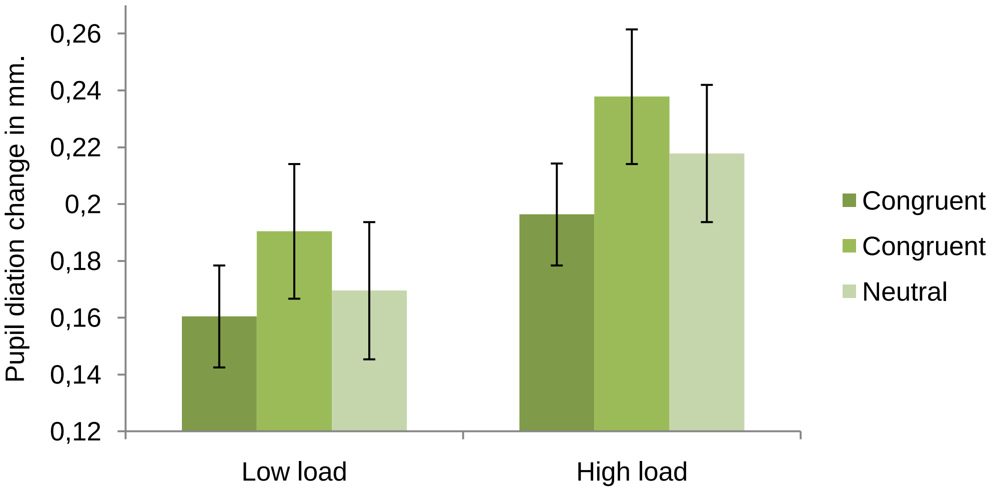


Figure 10. Pupil dilation by Load. Standard error is shown as vertical bars.

There were no significant effects involving Size. The data were therefore submitted to separate repeated measures ANOVAs at each Size level with Load and Congruency as within-subject factors. For the small display there was a main effect of Congruency, $F(2, 56) = 3.74$, $p = 0.03$, $\eta^2_p = 0.12$, due to a larger increase in pupil Size from baseline in incongruent (0.222 mm) trials, than in congruent (0.189 mm) and neutral (0.205 mm) trials. There were no other significant effects. For large displays there was main effect of Load, $F(1, 28) = 11.26$, $p = 0.002$, $\eta^2_p = 0.29$, and a main effect of Congruency, $F(2, 56) = 3.93$, $p = 0.025$, $\eta^2_p = 0.12$, but no interaction between these two factors. The main effect of Congruency was due to a larger increase in pupil Size from baseline in incongruent (0.217 mm) trials, than in congruent (0.190 mm) and neutral (0.204 mm) trials.

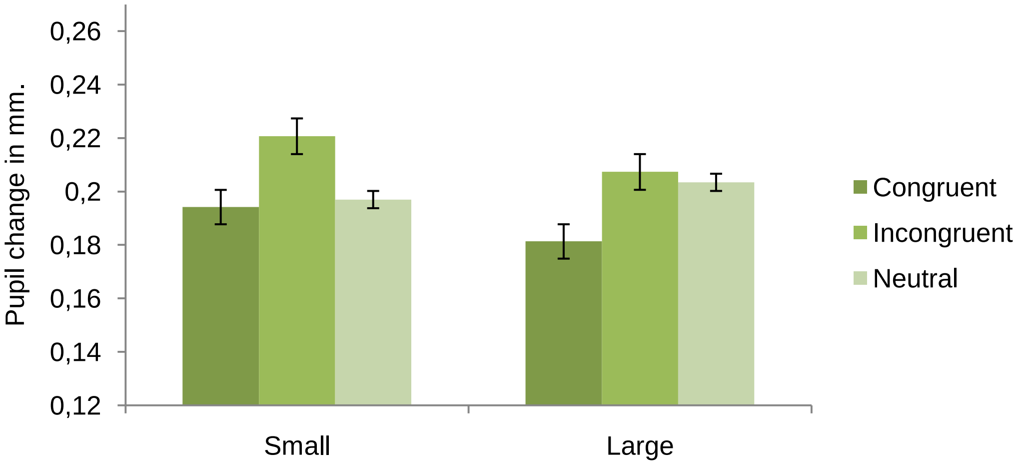


Figure 11. Pupil dilation by Size. Standard error is shown as vertical bars.

Discussion

Summary of findings

The high load tasks caused increased reaction times, reduced accuracy, and greater pupil dilations than low load tasks, as expected. The enlarged attentional area did cause increased reaction times, but there was no associated increase in errors or pupil dilations. Incongruent central distractors caused increased reaction times and increased pupil sizes, but no more errors. Surprisingly, while the behavioural measures of distractor processing was reduced in the high load condition, pupil reactions to distractors remained as in the high load condition as in the low load condition.

General discussion

The lack of order effect on pupil size shows that the sliding baseline correction worked as intended. The fleeting baselines did not shift significantly from task to task and the results were therefore not differentially affected by large baseline shifts. This is noteworthy because the impact of load changes gets artificially inflated when the pupil size is small (Beatty & Lucero-Wagoner, 2000). Also, considering the rather large age range of the sample, it was of great importance to the study to effectively deal with individual differences in pupil size. The procedure that corrected for baseline differences controlled the effect of age related decrease in pupil responsiveness (senile miosis). This was evidenced by the lack of age effects for the baselines.

The load manipulation used in this study, using homogenous versus heterogeneous distractors at potential target locations, had the expected effects on both behavioural and physiological measures. Similar to the results of Lavie (2005) study, reaction times increased and accuracy declined, which indicates that the altered scripts employed in the present study had the same behavioural effects as the original scripts. In addition, the physiological measure, the pupillary response, indicated that the high load condition required more effort than the low load condition. Increased pupil sizes as a reaction to increased perceptual load is in perfect accordance with other studies of load and pupil reactions (e.g. Bailey & Iqbal, 2008, Kahneman & Beatty, 1966). Thus, Wolfe's (1998) concept of inefficient searches seems to be measurable both behaviourally and physiologically.

The size of the display, on the other hand, had mixed influence on the various measures analysed in this study. The increased reaction time induced by a larger display fits Castiello and Umilta's (1990) finding that there is a decrease in processing efficiency when the size of the attentional focus increases. The pupillary response, in contrast, did not indicate that there is any noteworthy difference in the effort required. This could have several possible explanations. It could be due to the lack of power in the statistical analyses, which in turn, is partly because of high rates of discarded data. The behavioural data had high power; both because it is based on a larger number of valid data sets and because they contain less noise. The physiological data used in this study was calculated on the basis of an incomplete data set. Another explanation for the lack of dilation effect of size increase is that the method used did not actually manipulate perceptual load. Experiments have demonstrated that attention can be directed to noncongtiguous locations (Castiello & Umilta, 1992; Kramer & Hahn, 1995). If the attentional aperture simply moulds into the required shape, in this case a large doughnut-shaped circle, the total attended surface is in effect no larger than for the small condition. If that be the case, the attended area is not larger, just differently distributed. Because the empty space within the circle of potential targets does not contain relevant information, it does not have to be attended to.

The congruency effects show, as predicted, that Eriksen’s (1995) response competition concept had a strong effect both behavioural and physiological measures. This finding supports the assumption that that pupil size is sensitive to not only between-task differences in perceptual load, but also to subtle within-task fluctuations in effort as stipulated by Kahneman as early as 1973. It also indicates that the kind of load involved in suppressing incongruent distractors is measurable not only behaviourally, but also with pupillometry. Consequently, this study demonstrates two different manipulations to which the pupil is sensitive, perceptual load and the requirements of response competition. Both manipulations appear to increase the required level of effort although they include slightly different concepts. The finding that two of the variables that did influence behavioural measures in this study (Load and Congruency), but not the third (Size), demonstrates that behavioural and physiological measures have different outcomes and that the relation between the two is not automatically parallel.

Finally, the expected reduction in distractor processing for the high load tasks was not reflected in the pupillary data. For the behavioural data, the expected interaction between load and congruency was present, and was similar to that of earlier studies (e.g. Lavie, 2005). The discrepancy between the pupillary and the behavioural data could be interpreted in several ways. The pupils could be more sensitive to subtle variations in required effort than behavioural data is. It might be that the pupils reacts with such sensitivity that they detect fluctuations that other types of data miss out on. It has been argued that pupillometry is a reliable measure for very slight changes in cognitive load. In fact, Kramer (1991) argued that pupillometry could be an even more reliable measure of processing demand than both event-related potentials (ERP) and electroencephalograms (EEG).

Apart from its apparent superior sensitivity to slight differences in load, pupil responses may reveal something different than behavioural data does and, consequently, require a different interpretation. The pupils seem to react to a kind of effort that is not necessarily detectable in behavioural data. When the participants in this study were performing a task involving high perceptual load, they seemingly failed to process distractors. But the pupils still reacted quickly and reliably to demands placed by response competition. This occurred while his attentional system is presumably already too overloaded to pay attention to anything irrelevant. This implies that pupil data do indeed provide information that is different from that of behavioural data, whether that is called demand, load, or effort. Studies of overload (Peavler, 1974) and preparations of response (Moresi et al., 2008) could indicate that effort (exerted by the individual performing the task), and not the task's built-in load or demand, is a more befitting term of what the pupil actually reveals. The results from this study can contribute to understanding the nature of what the pupil of the eye actually reveals.

Conclusion

Based on the results discussed above, it is concluded that two of the manipulations used in this study had a significant influence on the pupil, whereas one did not. Pupils reacted to rapid and slight fluctuations in effort, but their movements did not consistently parallel reaction times and accuracy. This indicates that the information revealed by the pupils must be treated slightly differently than behavioural data. Pupillometric data can, when interpreted with caution, provide a useful, reliable, and cost-effective way of investigating effort requirements both between tasks and within a task.

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