UNIVERSITY OF GRONINGEN

Pupil Size Manipulation in Covert Attention to Red and Blue Contrasts: Study and Application in a Human Computer Interface

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Author:
Roberto DE CECILIO DE CARLOS
(s3071596)

Internal Supervisor:
Dr. Jelmer BORST
External Supervisor:
Dr. Sebatiaan MATHÔT

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Abstract

The size of the pupil can be modulated by manipulating brightness in covertly attended stimuli. This has allowed the development of Human Machine Interfaces that can take commands by recording changes in pupil size thanks to this manipulation. However this research has been limited to brightness as the factor to alter, as luminance is the main variable in pupil dilation. However, there are many other properties of light that should be considered. Here we decided to test colour, as the response of melanopsin in ipRGCs response varies with the amplitude of light and it has been suggested to be at least partially in control of the pupillary light response. Similarly, melanopsin from ipRGCs has been associated with covert attention. Here we present two experiments in order to observe if colour affects covert attention and can be measured with changes in pupil dilation. The first one used a Posner cuing task, while the second compared performance in a pupil size based Human Machine Interface between two versions, one using colour and the other one not. Our results, while not being fully conclusive on covert attention to colour being a measurable factor in pupil, did show a clear improvement in performance. Hence colour can be used to improve Brain Computer Interfaces that use covert attention as an input and is very likely to modulate the pupillary light response.

Keywords: Pupillary light response, covert attention, Human Computer Interfaces, ipRGCs, colour perception.

1 Introduction

Human Machine Interfaces have seen a strong development in the last 20 years with improvement in neuroimaging and computation. Among other potential functions, the most relevant is the recovery of lost motor and sensorial functions, with these currently being the main drive for their research. A recent new kind of interface uses pupil size changes as a source of input. It takes information from an eye tracker registering changes in the pupil size and these are converted to commands for the interface, as we can use these changes in pupil size to obtain information on what the user is attending to. These are especially useful for participants who have limitations in eye gazing, so we can use the changes in pupil to deduce what the user is attending to. However, with the limited eye gazing, it is necessary to obtain information on what is being attended on the edge of their field of view, which is called covert attention. Research in this area shows that the pupil will react to brightness changes in covertly attended stimuli, and this is what has been used to develop pupil size changes based Human Computer Interfaces. However it remains unclear if using another property of light, namely colour, would improve the performance of these interfaces. It is yet unknown if colour can have an effect in covert attention, but there is strong evidence theorising it, which we will discuss below. Here we present two experiments, one aimed to identify if colour affects covert attention and is measurable with changes in pupil size, and another one which would compare performance in a pupil size change based Human Computer Interface by adding covertly attended coloured stimuli. But before that we need to first go through some necessary concepts and theoretical background.

1.1 Covert attention

Every time we see something, we are performing a series of filtering and other cognitive activities that select the information that can be relevant for us, or not. Right now you are doing it, as you are (at least, we hope) reading these lines and ignoring other stimuli that would fall inside your field of view. This process is known as visual attention (McMains & Kastner, 2009). Visual attention can be divided in two types: The first, overt attention, involves eye movement. If there is no eye movement then it is called covert attention instead (Itti & Koch, 2001). As covert attention, by definition, implies the lacks of eye gazing, obtaining evidence of what stimulus is being covertly attended is harder than if it was overtly attended. For instance, with the means of electroencephalography (EEG) we can successfully tell if an object is being covertly attended or not (Sauseng et al., 2005). Similarly and more importantly for our subject, it is possible to tell if an object is being covertly attended by changes in pupil size (Mathôt, Van Der Linden, Grainger, & Vitu, 2013). However, the question that remains is how can we sure if an object is, indeed, being covertly attended? After all, these methods must have had a way to confirm their results.

Here is where we introduce the Posner cuing paradigm (Posner, 1980). This consists of presenting the participant the following task on a screen: A fixation cross is centered on the screen, which is where participants will have to keep their sight on, and on each side there is a location for the potential stimulus. After a small offset, there will be a cue that will indicate where the target stimulus is most likely to appear. This can be done with an arrow centered at the fixation cross pointing at one of the sides or by highlighting around the area we want to signal. After presenting the cue for a short period of time, there is another interval before the actual stimulus presentation. This stimulus will be presented in most cases at the location it has been signaled. However, in a minority of the cases, the stimulus is presented at the opposite location from it was hinted. This stimulus is presented for a period of time, and then afterwards the participant will have to complete the task that it was asked for before, which required knowledge of the stimulus presented. Since the stimulus must have been presented on the periphery of the participant's field of view, it must have only been attended covertly. Performing Posner cuing tasks is thus how it has been possible to identify measurements of covert attention.

1.2 The pupillary light response

We have mentioned before that changes in pupil size can be measured to identify covert attention. This is thank to a mechanism behind size changes in the pupil, the pupillary light response. This is one of the two reflexes of the pupil (the other one being the accommodation reflex, induced by the change of focus in objects at different distances), and is the involuntary adaptation of the pupil to the amount of light reaching the eye. The pupil will dilate if the amount of light reaching it is small, while it will contract if the level of luminescence is high. There are several other factors involved in different degrees of magnitude, but the most relevant ones can be seen in a general formula that was described by Watson and Yellott (2012):

$$D(L,a,y,y_0,e) = D_{SD}(F,1) + (y - y_0)[0.02132 - 0.009562 D_{SD}(F,1)] \tag{1}$$

This formula calculates the diameter (D) by taking in consideration the luminescence (L) in the environment, the field area of entrance in the pupil (a), the subject's age (y), their reference age (y_0) and the number of eyes (e), as the pupil will dilate differently if one or two eyes are being used. F is the effective corneal flux density, and it is calculated as $F = LaM(e)$, with $M(e)$ being 0.1 for a single eye (e) being used and 1 for both eyes being used. D_{SD} is the Stanley and Davies formula (1995) , which is represented below and takes as well the luminescence (L) and field area (a) parameters.

$$D_{SD}(L,a) = 7.75 - 5.75\left(\frac{(La/846)^{0.41}}{(La/846)^{0.41} + 2}\right) \tag{2}$$

So as we can observe in the model at Equation 1, all the factors that are taken are physical and biological factors from the environment and the subject themselves. As we mentioned, there are many other factors involved as well, but the effect of these ones are much smaller (Watson & Yellott, 2012). This is why the common understanding was that the pupillary light reflex was completely unconscious and involuntary. But we have now learnt that a factor that affects the size of the pupil are different signs of cognitive activity.

Albeit small, the effect of cognitive activity is still detectable from changes in pupil size. This was actually first reported a hundred years ago (Löwenstein, 1920), but no systematic studies came until the 1960s. It was then when it was reported that the pupillary light reflex can be modulated with arithmetic tasks (Hess, 1965) and with short-memorisation tasks (Kahneman & Beatty, 1966). This sparked research on the field that lead to a general understanding that pupil dilation can be a reliable reflection of cognitive activity (Verney, Granholm, & Marshall, 2004). Relevantly for our research, attention is among the cognitive processes that can be measured by changes in pupil size (Kahneman, 1973). This was observed when participants' pupil would dilate when just attending images, even if no instructions where given (Libby Jr, Lacey, & Lacey, 1973). The largest dilation was reported on those images that were described as ”interesting” and ”attention getting”. However the literature so far reported on the fact that attention can be identified from changes in pupil size, but not a proper measurement. However, there have been mathematical models that have described how ”attentional inputs” modulate changes in the pupil under the assumption of a constant luminescence (Hoeks & Levelt, 1993).

However, the relationship between attention and changes in pupil size were made without a clear distinction between covert and overt attention. This distinction is relevant since the effect of attention in pupil dilation, while small, is actually quite strong. This is supported by the fact that the pupil will actually not change in size based on the brightness in the environment but the perceived one (Laeng & Endestad, 2012). This was later shown in studies that showed that the pupil would contract as well when presented images that are perceived as bright, such as the sun, compared to equiluminant images without it (Naber & Nakayama, 2013; Binda, Pereverzeva, & Murray, 2013b). It would be thereafter when this effect was also induced via covert attention (Binda, Pereverzeva, & Murray, 2013a). Covertly attending to bright images will result in a contraction of the pupil, as this experiment showed, where participants would keep their sight in a fixation cross located in the center of the screen, while two circles, one dark and one bright appeared on the sides. Then participants would have to count how many times the dots would appear. When they covertly attended the dark disk, their pupils would dilate more than when they attended the bright disk. These findings were further established by Mathôt et al. (2013), which by the means of a Posner cuing task they also found a divergence in pupil size dilation depending on which stimulus was being attended. The pupil would contract when there was attention to one stimuli, but this contraction was significantly larger when covertly attending a bright stimulus compared to covert attention to a dark stimulus. Therefore it is here established that it has been possible to manipulate directly the size of the pupil by changing the properties of a covertly attended stimulus by having it set to dark or bright depending on what kind of change to the pupil was desired to be induced.

1.3 Application in Human Machine Interfaces

One of the applications of manipulating the pupillary light reflex would be with Human Machine Interfaces (HMIs). Also known as Human Computer Interfaces (HCIs) or Brain Computer Interfaces (BCIs), these are means to use a machine or computer directly from the brain instead of the classical interactive interfaces. This is a concept that has been researched more and more with the advent of modern neuroimaging and computing, beginning in the 1970s and has since gathered much more attention, especially for the last 20 years (Wolpaw et al., 2000; Naseer & Hong, 2015). These interfaces have been developed with multiple goals overall, but mainly they have been aimed for the recovery of lost body activity. The most developed is for the recovery of auditory perception, as cochlear implants have become widely spread, as even back in 2004 60000 people used them (Zeng, 2004). However there are considerable efforts in restoring motor functions (Pichiorri et al., 2015; Bundy et al., 2017). Other therapeutic application is in neurofeedback, which is the usage of brain signals for self regulation and teaching. Several interfaces have been developed for this purpose (Birbaumer, Murguialday, Weber, & Montoya, 2009; Martinez, Bakardjian, & Cichocki, 2007) and today several devices are commercially available for this purpose (Mershin & Karydis, 2016). Other applications of HMI that have been explored are gaming (Kaplan, Shishkin, Ganin, Basyul, & Zhigalov, 2013; Liao et al., 2012), remote control of a device (Khan & Hong, 2017; Wang, Li, & Huang, 2010), brain to brain communication (Grau et al., 2014) and even it has even been speculated to be a technology that will lead towards trans-humanism and immortality, with all it's ethical consequences (McGee & Maguire, 2007).

Brain Computer Interfaces can be classified in two different categories: Invasive and non-invasive. The former are those that require some surgery in order to set up the input for the interface. These can be either with the form of a brain implant that introduces microwires containing electrodes into the cortical tissue (O'Doherty et al., 2011; Musk & Neuralink, 2019) or with electrocorticography (ECoG), a technique consisting of the implantation of electrodes on the surface of the brain cortex (Leuthardt, Schalk, Wolpaw, Ojemann, & Moran, 2004; Schalk & Leuthardt, 2011). These interfaces provide the advantage of the direct input from the brain, allowing a more accurate signal, as well as from deeper parts of the brain. However, the fact that it requires brain surgery to be implemented is a limitation on its own. Besides, as a consequence, these interfaces are tested and oriented towards subjects under a condition that is treated with brain surgery. This is why a different approach exists, which is our second category: noninvasive interfaces. These are those that use use neuroimaging techniques that do not require surgery for their setup. The most common is the use of electroencephalography (EEG). These interfaces are based on this technique, which requires the placing of electrodes on the scalp. There are several paradigms in EEG, which also apply for the aforementioned methods. The most common one is the oddball component paradigm, where an unexpected or strange stimulus is presented to the participant, which is then reflected in a related potential in the signal (Treder, Schmidt, & Blankertz, 2011; Farwell & Donchin, 1988). The most commonly used of these event related potentials (ERP) is the P300 component, which is a large peak appearing at about 300-500ms from the odd stimulus. Other approaches in EEG are the use of visually evoked potentials (VEP), especially steady state visually evoked potentials (SSVEP). These are periodic neural response located in the subject's central visual field that are induced by a repetitive visual stimulus, commonly flashes or patterns (Vialatte, Maurice, Dauwels, & Cichocki, 2010) and generally represented by component peaks at frequencies between 3 and 80Hz (Kimura, Tanaka, Higashi, & Morikawa, 2013). These two paradigms are often hybridized into an interface that uses both paradigms in order to overcome one's limitation with the other one's advantages (Xu et al., 2013; Yin et al., 2013). The last paradigm we are mentioning is the Graz BCI, named after the Austrian city it was developed. This interface looks at differences in patterns between event related desynchronisations (ERD) for the contralateral and event related synchronisations (ERS) for the ipsilateral hemispheres, which is why these interfaces are also known as ERS/ERD interfaces (Pfurtscheller et al., 2000; Pfurtscheller & Neuper, 2006). EEG signals, especially alpha and beta rhythms, are stable enough in an individual to allow this type of interface to observe for any event induced variation. EEG has shown to be a reliable technology in order to develop HCIs, but that does not mean there are other other noninvasive neuroimaging techniques that have not been used for developing an interface. Magnetoencephalography (MEG) maps the magnetic fields from the electrical signals on the brain, which allows a higher spatial resolution compared EEG, and it has been successfully used for developing BCIs, both as an individual input (Mellinger et al., 2007) as well as hybrid interface (that is an interface that will take input from more than one technology) with EEG (Kauhanen et al., 2006). Alternatively, fMRI (functional Magnetic Resonance Imaging) provides a very different paradigm, as it measures the blood oxygen-level dependent (BOLD) signal, granting access to a different source of information with high spacial resolution even in deeper parts of the brain non-invasively. This has allowed for the development of multiple interfaces (Weiskopf et al., 2004; J.-H. Lee, Ryu, Jolesz, Cho, & Yoo, 2009). Some attempts for a hybrid interface with EEG have been done (Hinterberger et al., 2004) since the BOLD signal highly correlates with EGG (Logothetis, 2003). However, due to the massive requirements in terms of space and energy needed for fMRI equipment, functional near-infrared spectrometry (fNIRS) is used more often. This technique also uses the BOLD signal at its core, looking at contrasts in concentration changes between oxygenated and deoxygenated haemoglobin, but it is comparatively easier and cheaper to use than fMRI, besides being portable (Naseer & Hong, 2015). This has allowed the development of both interfaces with fNIRS as their single input (Power, Kushki, & Chau, 2012; Shin & Jeong, 2014) as well as hybrid interfaces combining FNIRS with EEG (Khan & Hong, 2017; Fazli et al., 2012).

In the recent years there have been increasing efforts to develop a HMI based on pupil size changes as an alternative to neuroimaging interfaces. Given that most BCIs use visual stimuli in order to induce some manipulation of the signal's baseline, it is logical to explore changes in visual attention to complement existing interfaces. In recent years there has been developments in EEG based interfaces that used eye-tracking (E. C. Lee, Woo, Kim, Whang, & Park, 2010; Zander, Gaertner, Kothe, & Vilimek, 2010) as well as pupil size changes (Rozado, Duenser, & Howell, 2015). This has eventually led to the idea of developing interfaces where pupil size changes could be the sole source of input. After all, pupil size changes are a much simpler source of information and can provide attentional information at high temporal resolution (Wierda, van Rijn, Taatgen, & Martens, 2012), which is necessary for a functional real time interface. The first pupil size manipulation interface arrived with Stoll et al. (2013) Their interface involved participants replying to a binary question (ie: the answer is ”yes” or ”no”) for which the participant would know the answer. Five seconds after the question was asked, the computer would read one of the options (”yes” in half of the cases, ”no” in the other one) while presenting a simple arithmetic task that the participant must complete. After enough time to perform the task, the computer would read the alternative option and present another simple arithmetic task. The contrast in the changes in the pupil between both answers would be then decoded in order to obtain the answer to the question. Thus, this paradigm allowed the possibility of transmitting information to a computer with just changes in pupil size.

On a different research line, the idea of taking advantage of attention in order to improve the performance of a BCI has been around for some time already. Using visual spatial attention to control a BCI is interesting since it allows interaction without any kind of motor control. This includes using covert attention as one of the factors involved in the control of the interface, which has been successfully been done in EEG based interfaces using a SSVEP paradigm (Kelly, Lalor, Finucane, McDarby, & Reilly, 2005) as well as a ERP paradigm (Treder et al., 2011). These interfaces demonstrated that covert attention can be used to at least complement an interface for an improved performance, as covert attention on its own provides a reduced performance compared to overt attention. However, covert attention interfaces can be the only possibility for someone who has a limitation in their eye movement. Moreover these interfaces using EEG are reportedly less fast, reliable and have more difficulties in detecting ocular activity compared to an eye tracker, thus opening the opportunity to study covert attention with an eye tracker based interface.

Therefore by combining the two concepts studied in the previous paragraphs, interfaces based on pupil size changes and interfaces using covert attention, we would then hypothesise an interface that by manipulating the brightness of a stimulus being covertly attended and reading the changes in the pupil with an eye tracker, it would be possible to decode the information for a BCI to use it. This is what the Mind Writing Pupil (Mathôt, Melmi, Van Der Linden, & Van der Stigchel, 2016) achieved. This interface is a speller, that is, an interface used to spell words letter by letter. This interface presented a disk of eight different circles arranged around a fixation cross, half of them bright and half of them dark, each containing a letter or a group of letters. The brightness of these circles would invert after an interval. This will induce a pattern of changes in the diameter of the pupil. For instance, if the participant wants a letter that is in one one of the circles that start as bright, then their pupil will begin more contracted. When the circle flips to dark, the pupil will slightly dilate, and then it will contract again when the circle flips back to bright. This pattern can be identified by the BCI, which will begin to discard those circles that do not follow the pattern that the subject's pupil is following until eventually a single circle with a single letter is left. Thus it is possible to develop a BCI that can use manipulations of the pupil size with covertly attended stimuli as its input.

1.4 The role of ipRGCs and colour in covert attention

We have so far established that changes in the pupil size can be used to identify covertly attended bright and dark stimuli, and we can even manipulate that to develop a brain-computer interface. However the only variable we have been manipulating so far is the perceived brightness by the subject. This is reasonable, after all the perceived luminance is the largest factor in pupil dilation. Nevertheless, there is more information in light than the amount that there is in the environment, as light itself carries more information. After all, the light that we can perceive is just the visible part of the electromagnetic spectrum. Photons travel in wave patterns of different lengths, and this is what defines the spectrum itself. We can only see light for which we have the receptors for. These cover a very specific wavelength range of approximately 400 to 700nm (National Aeronautics and Space Administration, Science Mission Directorate., 2010). This range covers the spectrum that goes from red to violet light, and every colour we see is either a colour associated to a specific wavelength or a colour generated from the combination of multiple lights of different wavelengths.

Colour perception was traditionally attributed to rods and three different kinds of cones, which contain a different pigments, each with their own sensitivity peak at a specific wavelength (Dartnall, Bowmaker, & Mollon, 1983). However, there is a third type of photoreceptor in primates. These are known as intrinsically photosensitive retinal ganglion cells (ipRGCs) (Markwell, Feigl, & Zele, 2010) and while their main role is to transmit the information received by cones and rods, they also have some photoreceptive properties, as they contain the photopigment melanopsin (Dacey et al., 2005). Melanopsin produces a long but lasting reaction to coloured light, especially blue tones, in the pupil, as it peaks at around 483nm (Gamlin et al., 2007). The role of melanopsin and ipRGCs in the pupillary reflex is still not fully understood, as the response to luminance from the pupil is probably the result of the combined input of rods, cones and ipRGCs. Furthermore, Watson and Yellott (2012) described in their mathematical model of the pupillary light reflex that the summation of luminance over space that their model provides is not reflected by typical retinal ganglion cells, whereas ipRGCS have much larger receptor fields that are more consistent with the pupillary reflex. This expresses the relative relevance of ipRGCs in the pupillary light reflex, and considering that the melanopsin in ipRGCs response varies on the frequency of the light reaching it, it is then reasonable to suggest what role would coloured light would have in the pupillary reflex.

Moreover, melanopsin mediated photoreception, which is exclusive of ipRGCs, has been associated with strong BOLD responses at several subcortical areas (Hung et al., 2017). This response was the strongest in Frontal Eye Fields (FEFs). FEFs themselves have been associated with covert attention, as experiments in macaques show how activity at the FEFs reflected shifts in covert attention in tasks (Buschman & Miller, 2009). Tasks that needed to be solved by covertly searching for an item showed oscillations in activity at FEFs. This is consistent with experiments with subthreshold stimulation of FEFs can cause "attention-like" effects (Armstrong & Moore, 2007). In addition, melanopsin is itself associated with vigilance and alertness, especially since alertness is shifted towards blue tones rather than the general white spectrum (Lockley et al., 2006), making it consistent to be related with attention. The link between melanopsin and covert attention still remains open. However if we combine it with the fact that ipRGCs can be highly influential in the perception of luminance in the pupillary light reflex with the findings on melanopsin inducing activation at the FEFs, which are associated with covert attention; and as well that blue shifted light, to which melanopsin responds the most, is also associated with alertness, it is then logical to suggest the possibility of covertly attended coloured stimuli, especially in blue shifted tones, can have a small but measurable effect in pupil size diameter.

Thus, we hereby present two experiments in order to observe the potential role of colour in pupil size manipulation via covert attention. Experiment 1 consisted on a combination of the Binda et al. (2013a) and the (Mathôt et al., 2013) experiments, using a Posner cuing task with red and blue stimuli while performing a task that requires covert attention to be solved. Experiment 2 used the aforementioned Mind Writing pupil, comparing performance between the original using brightness and a variation using red and blue tones equiluminant to the dark and bright tones from the first one. These experiments sought to find the answers to our main question: Can covert attention to colour induce a manipulation in pupil size? If that is the case, we would be closer to understanding the role of ipRGCs in the pupillary reflex. Since their response is dependent in the colour of the light perceived, then their importance would be evident. Furthermore, knowing that colour modulates covert attention would strengthen the links between FEFs and attention and vigilance. Moreover, an improved performance in the Mind Writing Pupil interface would help in the development of future pupil size change based BCI, providing an improved participant in subjects using these interfaces. Any HMI using covert attention as one of its factors could be potentially benefited, as it would encourage better designs by a smarter use of colour.

2 Experiment 1

2.1 Methods

2.1.1 Participants

32 participants from the University of Groningen first year students subject pool were allocated to our experiment.

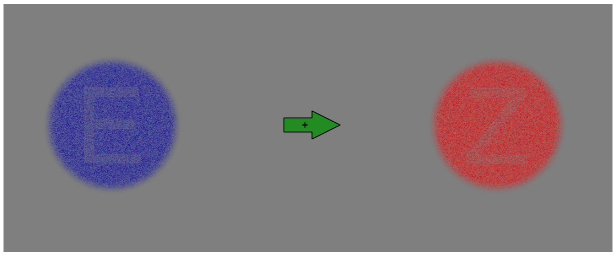

Figure 1: Main screen for Experiment 1. These letters flashed simultaneously inside the red and blue stimuli in intervals of 250ms for 28 times. The green arrow pointed at one of the sides with the highest likelihood to have the target stimuli. However the target stimuli would in some cases appear on the opposite stimuli. For instance, the target could be in this case letter ”E” but the cue would be pointing at the opposite direction.

2.1.2 Materials

The experiment was developed and run in OpenSesame 3.2.6 (Mathôt, Schreij, & Theeuwes, 2012). This was run in a desktop computer Hewlett-Packard HP ProDesk 600 G1 SFF with 8GB of RAM and a 3400MHz processor running windows 10. The display was a IIYAMA ProLite G2773HS monitor.

The eye tracker used was an Eyelink 1000 from SR Research Ltd. Participants also had a stand where they could rest and fix their head while taking their experiment, as the eye tracker needs as little head movements as possible.

Information on where the experiment files are available can be found at the Resources section.

2.1.3 Design

A within subjects design was developed for this experiment. The independent variables were colour of the stimulus and the level of brightness, resulting in four possible types of stimuli: Dark blue, dark red, bright blue and bright red. These were assigned randomly, but there was always one stimulus of each colour on the screen. These manipulations were meant to be observed with changes in pupil trace. Participants were able to practise for as many trials they wished to complete. Once they felt comfortable, they would proceed with the experiment, which consisted of 180 trials per participant.

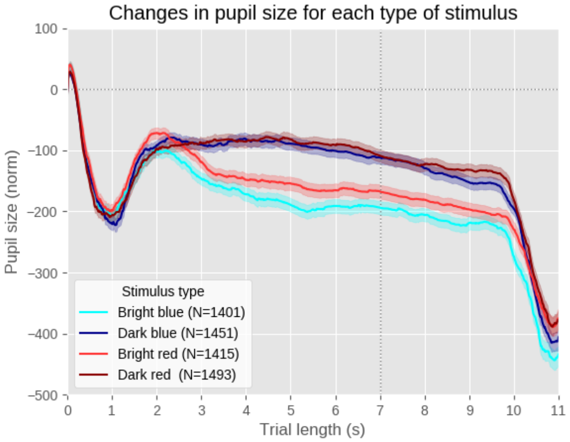

Figure 2: Mean pupil size across trial for each of our different stimuli when they included the target letter. The faded area around the line is the standard error. The dotted line at 7s show the point where the stimuli were no longer being presented. Note the clear difference between light and dark tones, but also the slight divergence of the trace of bright blue tones.

2.1.4 Procedure

Participants sat in front of the computer, resting their head on the stand and with the eye tracker ahead pointing at their right eye. Before the actual test two calibration tasks were performed: The first calibration task was simply the eye tracker calibration that comes with the Eyelink itself. This simply required participants to follow a dot on the screen with their sight on 10 locations on the screen. This task was done until the eye tracker correctly validated the values from the calibration, which would require either a single or multiple attempts. Following that there was a second calibration task, with the aim of finding the equiluminent colours for the participant. This consisted of presenting a large red circle in the screen, to after stay completely dark for 2.5 seconds. Then, the same would be done with a blue circle instead. There were 20 presentations for each colour. Participants only had to keep their sight in the center of the screen for all of this task and to assist them with that there was a small fixation cross at the center of the screen for the whole duration. In the meantime, the eye tracker would take measurements of the changes in pupil size in order to calculate the values for an equiluminant colour.

Once these calibrations were done, the participants would actually start the experiment, performing as many practice trials as they wished. This experiment was based on the ones performed by Binda et al. (2013a) and Mathôt et al. (2013) but with the manipulation of colour that we described on the design section: At the start of every trial, the screen would show a target letter to the participant to remember for the trial. After they pressed any key on the keyboard, they would see the main screen of the experiment. At the center there was a fixation cross, surrounded by a green arrow pointing to either the left or the right. At each side there was a circle, one red and the other one blue. Depending on the trial the blue one was on the left and the red one on the right or the other way round. Also, depending on the trial, each circle could, independently, have either a bright or a dark tone. Thus, in total there were four different kinds of circles. All the stimuli on screen were over a neutral, grey background. Inside each circle there was a letter from a selection of 10 possible: A, D, E, G, H, M, S, W, X, Z. Each circle showed a different letter every 250ms, for a total of 28 times to give a total trial length of 7 seconds. However, the target letter that was memorised at the start of the trial would only appear inside one of the two circles, for two to five times randomly decided before each trial. In 80% of the cases the arrow would be pointing at the circle that has the target letter but in the remaining 20% of the cases it would be pointing at the other circle, thus following the conditions of a Posner cuing paradigm (Posner, 1980). Participants were asked, while keeping their sight on the fixation cross, to count how many times the target letter had appeared. Once the trial was completed, they were prompted to respond using the computer's keyboard by pressing the key for any number from 1 to 9. In the practice runs participants would get feedback if their answer was correct or not. If they were not, they would get told of the correct answer. Moreover they would also be told if they had moved their sight away from the fixation cross. No feedback at all was given in the experimental trials, aside for an average accuracy score at the end of the experiment. One last manipulation included in the experiment was adjusting the contrast of the stimuli based on the response: If a participant responded correctly, the contrast for the stimuli they had responded correctly on that trial (for instance, bright red and dark blue) would be decreased for the next time they would appear in a trial. The same occurred in the opposite direction: If the participant got the answer wrong, the contrast for those specific stimuli would be increased the next time there was a trial involving them.

2.2 Results

After collection, all data was parsed and processed in order to observe if there were differences in pupil size between colour and tone when performing the task. We plotted the pupil trace and compared the mean pupil size across time per trial for every stimulus when they had the target letter in it. In other words, when the target letter was inside the bright blue circle, when it was inside the dark blue circle, inside the dark red circle and inside the bright red circle.

As expected, there was a very clear differentiation between the dark and the bright stimuli (see Figure 2). Nevertheless, there may also be a difference between colours as well. While there was not much difference between the dark variants, there was still some clear distinction between the brighter colours.

To add more depth to this analysis, we ran a series of lineal models for the stimulus brightness, the stimulus colour and the interaction between both across a point in time(see Figure 3). The results from the analysis showed a very significant effect for brightness, coinciding with previous research. The effect of colour was more dubious however. It mainly hovers under the threshold, meaning no significance. However it still tended to hover between 1 and 2, which would perhaps indicate some effect, but there was not enough evidence for it. Interestingly, the interaction between tone and colour followed a similar pattern to colour yet in the opposite direction, yet still below significance level.

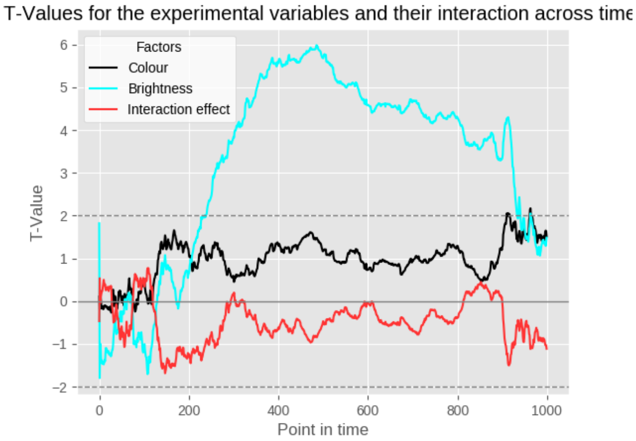

Figure 3: T Values across time for brightness, colour and the interaction between both. Values over 2 or under -2 are considered statistically significant. As we expected brightness was clearly significant. Colour hovered most of the time between 1 and 2 which may indicate the existence of an effect but there is not enough evidence for it.

3 Experiment 2

3.1 Methods

3.1.1 Participants

12 participants, either from the University of Groningen first year students subject pool or the University of Groningen paid participant pool, were allocated to our experiment.

3.1.2 Materials

The experiment was developed and run in OpenSesame 3.2.7. This was run in a desktop computer Hewlett-Packard HP ProDesk 600 G1 SFF with 8GB of RAM and a 3400MHz processor running windows 10. The display was a IIYAMA ProLite G2773HS monitor.

The eye tracker used was an Eyelink 1000 from SR Research Ltd. Participants also had a stand where they could rest and fix their head while taking their experiment, as the eye tracker needs as little head movements as possible. A Spyder 4 Elite colorimeter from Datacolor was used for the identification of equiluminent tones.

Information on where the experiment files are available can be found at the Resources section.

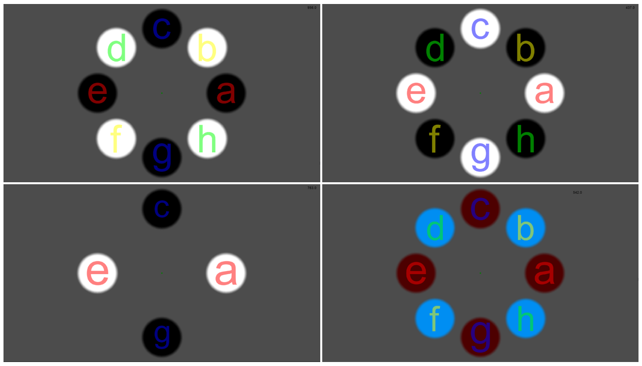

Figure 4: Screens for Experiment 2.Top right: Participants will see the disk for 8 possible letters to select. As we can see, 4 of the circles containing letters are bright and 4 are dark. Top left: After a second, the colours will be inverted, with dark stimuli turning bright and vice-versa. A second later it will return back to the screen of the Top Right, and they will be alternating between one of the other once the threshold is reached. Bottom Left: Once that threshold is reached, one group of letters will be discarded. In this example, lets say that the participant wanted to select letter ”E”. The interface kept switching alternating between Top Left and Top Right until enough evidence for the letters than began as dark, including ”E”, was collected, discarding the other group of letters. Then the process begins again, but only with four letters. This was repeated until only one letter is left. Bottom right: Coloured version of the experiment. As we can see, the dark tone was replaced by dark red, and the bright ones with light blue.

3.1.3 Design

A within subjects design was developed for this experiment with trials being either a control or an experimental condition randomly assigned. Participants were tested in terms of accuracy and response time for the presented task. Participants had the chance to perform as many practice trials as they wished before the experiment. There were a total of 80 trials per participant, divided in 8 blocks of 10 trials to give the participants resting time if they desired so.

3.1.4 Procedure

For the whole experiment, the participants would sit in front of the computer, resting their head in a stand while the Eyelink would keep track of their right eye. After the calibration of the eye tracker and some practice trials at the start, participants would begin the experiment.

At the start of the trial, participants were tasked to select one random letter from A to H. After a key press, they then saw one of the two possible kinds of trials, which were decided on random before the start of that trial. Both were versions of Mind Writing Pupil (Mathôt et al., 2016), but the first one was a control that only uses brightness as a factor, whereas the second one had colour instead. But for both cases they had to select the tasked letter doing the following: Once they had began their trial, they had to keep their sight focused in a fixation dot placed at the center of the screen while thinking of the target letter. They saw, arranged around in a circumference, 8 different circles. Each contained a letter from A to H. The difference between the trials resided in these circles: for the control version they had either a dark or a bright background, distributed alternatively. In other words, if a circle had a bright background then the two closer circles had a dark background, giving a total of 4 circles with dark background and 4 circles with bright background, effectively dividing them in two groups. These circles smoothly transitioned to their opposite tone every second. For instance: A circle that at the start of the trial was dark turned to bright after a second, and then back to dark the second after, and so on for the rest of the trial. In the experimental condition the circles, instead of being dark or bright, were either dark red or bright blue respectively, and would alternate between colours. This means that a circle that began dark red turned to bright blue a second after, and then back to dark red, and so on. In the meantime, and for both conditions, the eye tracker was obtaining the participant's median pupil size for every time the colours inverted. This information was used by the computer to determine which pattern the pupil was following. By looking at the pattern of contraction and dilation that the pupil was doing, it was possible to determine which group of letters was attending covertly. In other words, if the pupil dilated, contracted and then dilated again, the computer interpreted that as if the user wanted to select a letter within one of the circles that began as dark, then went bright and then back to dark. Once the computer got evidence for one group of circles, it began to increase the font size of that option, while it decreased the size of the font of the other group of circles. This was done until the level of evidence reached a threshold value, keeping the more likely group whereas the other group was discarded. The remaining group was then arranged in a square, and divided again in two groups with opposite inversion patterns, and the same process would begin. After discarding letters again, the last two letters were placed on the top of the screen, each with opposite background colour brightness inversions. The same process went on again one last time until there is one final letter left, which should have been target letter. If the target letter was discarded in the middle of the trial, the screen showed a circle containing a question mark and ended the trial.

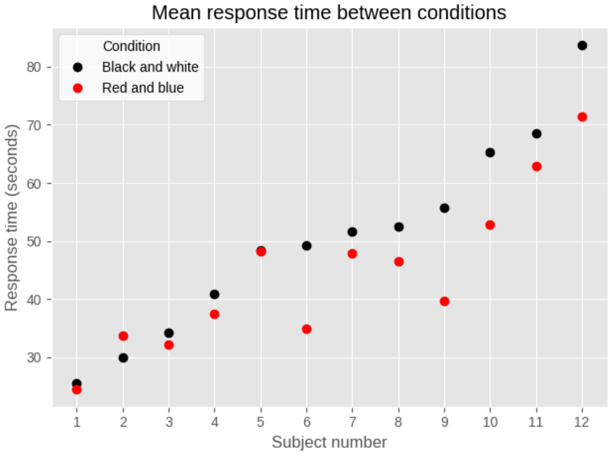

Figure 5: Response times for each participant, comparing control and coloured trials and sorted by their mean response time for the former. Aside for a single one, all participants were able to select a letter in coloured trials. The distinction is clear in most cases as well.

As we mentioned, there were two conditions, one using only brightness while the other one used dark red and bright blue. The tone of red was calibrated to be equiluminant to the dark background of the control condition and similarly was done for the tone of blue used to replace the bright tone. This calibration was done with the help of the Spyder 4 colorimeter. We found that, for the monitor we used, the shade of dark red defined under the RGB colour space as $(77,0,0)$ was equiluminent to the dark grey tone $(34,34,34)$ and the shade of light blue defined as $(0,142,242)$ was equiluminant to the light grey tone $(126,126,126)$. Therefore these were the colours we used for this experiment.

3.2 Results

Participants were measured in terms of how accurate their response was (ie: What proportion of the trials they got to select the target letter correctly) and the time they took to perform each trial. For the first one we compared the mean accuracy for each participant between the two conditions. Accuracy was measured as the proportion from 0 to 1 of correct trials against the total correct trials of each condition per participant. There was a significant difference in the mean accuracy between the coloured $(\mu = 0.5386, \sigma = 0.2927, = 12)$ and the non-coloured $(\mu = 0.4729, \sigma = 0.3039, n = 12)$ conditions; $t(22) = -2.783, p = 0.0054$. The participants were, on average, 32.77% more accurate in the coloured version of the experiment compared to the regular, colourless version. Response times, measured in seconds, were compared between the control and the experimental conditions per participant. There was a highly significant difference in response time between the coloured $(\mu = 44.0689, \sigma = 16.0523, n = 12)$ and the non-coloured $(\mu = 50.6320, \sigma = 12.9003, n = 12)$ conditions; $t(22) = -2.7833, p = 0.0184$. There was a faster response time for the red and blue version of the interface.

4 General discussion

Here we show that we were successful in improving the effectiveness of a covertly attended pupil dilation based HCI. We first aimed to identify if an effect could be measured in the pupil from changes in colour with Experiment 1 by using a design that was similar to related experiments in covert attention. We then used what we learnt from Experiment 1 to apply it into our design for Experiment 2 and compare between a control condition and an experimental condition if the latter showed some improvement in performance.

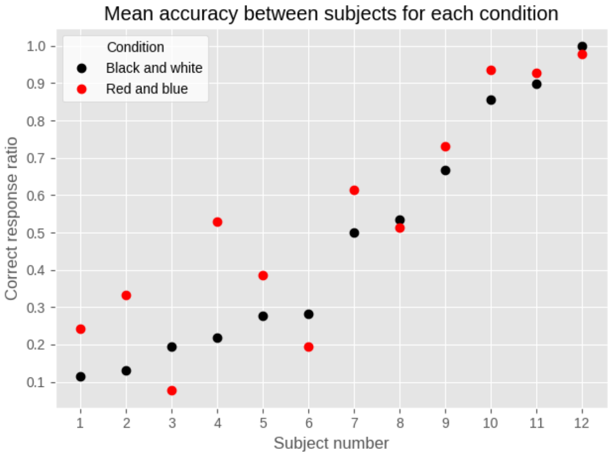

Figure 6: Mean accuracy for both conditions for each participant, sorted by their mean accuracy. While there were a handful of exceptions, the overall trend shows that accuracy was significantly better for coloured trials, with an average increment of 32.73% compared to control trials.

Experiment 1 was, as discussed, a Posner cuing task where participants had to count how many times a letter appeared in one of two possible stimuli, one red and one dark. There was an arrow cuing the stimulus with higher likelihood to contain the target letter. The participant's pupil trace was recorded for each trial, which we can see in Figure 2. Overall the size of the pupil decreased compared from the start to the end of the trial. However it is possible to see that there was a distinction between the stimuli. When the target was in either dark red or dark blue stimuli target, the pupil size followed comparable patterns. In comparison, for the light red and light blue stimuli there was a different pattern. Both of them diverged, constricting more than their darker counterparts. Moreover, while quite similar, the patterns are rather similar, the pupil contracted more for the light blue stimuli. Thus we can see one clear effect for brightness, which was expected to happen. However the plot alone would not tell us if there is really an effect for colour. The pupil size changes seem to determine a small effect that is especially true for light blue light, which is what we predicted. However this does not seem to be fully supported by our statistical analysis. The results show that brightness was, as expected, a significant factor. However, for both the colour and the interaction effect between colour and brightness it often hovered close to significance levels, but it was not enough to surpass the 2 or -2 threshold levels, which would determine significance at a 95% significance level. Therefore from these results we cannot really conclude that there is indeed an effect in pupil size from covertly attended colour, but if such effect is to exist, the effect would be greater for light blue tones. This is in alignment with what we had already in the literature on how melanopsin in ipRGCs is more sensitive to blue light, so it is reasonable that if there is an effect it is going to be induced especially by blue tones.

Experiment 2 was, as discussed, a comparison between two versions of the Mind Writing Pupil, one using grey stimuli, a dark one and a grey one, and the other one using coloured stimuli, a red one and a blue one. We learnt for Experiment 1 that the ideal tones to use would be a dark red tone and a light blue tone for the experimental condition. As we saw, if there is an effect in the pupil from covertly attended changes in colour, they are going to be with blue tones. Therefore we selected a dark red tone that was equiluminant to a dark shade of grey and a light blue tone that was equiluminant to a bright shade of grey. This approach seemed to report positive results. These showed that there was a significant improvement in performance for the coloured option. Participants were consistently and clearly faster when selecting a letter using the coloured version of the experiment than with the black and white version. Only one participant opposed this pattern and another one had similar times. The rest had moderate to quite considerable improvements in timing. Accuracy did not seem to be a payoff to this speed as well. In fact, there was a significant improvement in accuracy for the coloured version, which was reflected in a majority of participants. The accuracy results are also not due to random chance, since if that was the case the overall average accuracy would hover around 12.5% (one out of eight possible options) when it was 47.3% with both conditions combined. Thus the improved performance in the interface was reflected in both timing and accuracy. Nevertheless there were still a handful of participants which showed no effect or the opposite. While still a minority, their role should not be ignored. This could potentially be caused by some individual differences, in the same way that there was quite some variety in overall response time and accuracy between participants.

We believe that Experiment 1 had a series of limitations that led to the lack of a clear, conclusive result when compared to the solid results from Experiment 2. One potential limitation was perhaps the equiluminescence task. We calibrated equiluminesence by adjusting a base shade of red that produced a pupil size as close as possible to the shade of blue that was presented with it. While the idea behind it is that similarly luminescent colours are going to cause a similar pupil contraction and it would remove some potential individual and equipment differences, we are thus assuming that colour is not going to have a direct effect in the size of the pupil, which is a small contradiction against our test. This is why we decided to go instead with a photometer to measure the luminesence of the colours, and it would be interesting to see what results Experiment 1 would return with this calibration instead. Another factor that could have lead to the differences in exposition time to the stimuli between both experiments. Despite melanopsin's effect being long and lasting, the better results were acquired in Experiment 2, which inverted patterns every second rather than Experiment 1 which should have showed a more clear distinction between colours as the exposition time was 7 seconds per trial. There is one last limitation to address in Experiment 2, which is that, given the large divergence in trial length, ranging from a few seconds to several minutes, it is not feasible to compare the pupil traces between trials, even within the same subject. Therefore this experiment, while it strongly showed that there was an improved performance with the HCI, cannot by itself confirm the effect of colour in covert attention.

Nevertheless, our results show that we succeeded in our goal to improve the performance of a pupil size based BCI significantly by using coloured stimuli rather than just manipulating brightness with shades of grey. This means that it is advised that future versions of the Mind Writing Pupil would use colour for their pupil size manipulation, and similarly it would be interesting to see what results would be obtained in other kind of Human Machine Interfaces, both those based in the pupil but using different paradigms, as well as more classical approaches like evoked potential interfaces that take covert attention in consideration. Regarding if colour does affect covert attention, we cannot yet conclude if that is the case but considering that the HCI did show an improvement in performance there is a strong lead suggesting that, on top of the evidence that melanopsin in ipRGCs is more sensitive to blue tones. Moreover the fact that Experiment 1 did still show some preference, albeit not significant enough, towards blue tones, is another reason to believe that there is indeed an effect of colour in covert attention. Therefore we suggest for future research to perform experimentation in this area, whether by running variations of our experiments covering their limitations or with a total change of paradigm. In the meantime, we can at least say that the improved performance in Experiment 2 can already be considered in newer HCI that consider covert attention.

In a quick summary, our two experiments, one running a Posner cuing task and the second one using a Human Computer Interface, tested how colour affected covert attention from changes in pupil size. While our results do not show a conclusive effect of colour in covert attention, we did manage to improve performance in a HCI by applying colour in it, suggesting that there is a strong possibility for it.

5 Resources

All files and data used for the experiment are available at OSF (`https://osf.io/cztre/?view_only=9421a1da29c94ef6820266898676dd0f`). Files for both experiments are also available at GitHub (`https://github.com/erredece/color-pupil-experiment`).

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