Can Humans Initiate Saccadic Eye Movements to Targets They do not Consciously Notice?

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Human Neuroscience Master's Degree Program

Contents

1. Introduction

1.1 What are Saccadic movements?

Saccadic movements are crucial eye movements of both eyes that occur between two stimuli (Carpenter, 2000). These eye movements are best observed when an individual is reading but can occur in any modality that requires scanning or focusing on an object. They are the single most frequent movement of the human body, initiated 2-3 per second, which is more frequent than our own heartbeats (Carpenter, 2000). Saccadic eye movements are best classified into 2 categories, normal and express saccadic movements (Boehnke & Munoz, 2008). Express saccades are reflexive saccades that can be initiated approximately 100ms after stimulus presentation, while normal saccadic movements can be initiated around 200ms (Boehnke & Munoz, 2008) at the fastest possible that saccades can be initiated.

A saccade occurs when an intense burst of action potentials is generated by burst neurons (BNs) of the burst generator. This burst generator is made up of burst neurons (BN)s from within the pontine, medullary, and mesencephalic reticular formations (Soetedjo et al., 2002). During a saccade, the BNs fire in a burst of maximal frequency, which throws the eye into a new position (Carpenter, 2000). These BNs are subsequently under control of another group of cells called omnipausers (Carpenter, 2000). At rest, the omnipausers are firing continuously at maximum frequency, but during a saccade they are inhibited for exactly the duration of the movement, which determines the size of the saccade (Carpenter, 2000). Besides occurring extremely quickly, express saccades have an extremely short duration, lasting from 20-200ms (Carpenter, 2000). In addition to being short and fast, express saccades are also accurate. To make an accurate saccade, the BNs need to produce a specific number of action potentials proportionate to the needed saccade amplitude (Soetedjo et al., 2002). In experimental conditions express saccades occur especially after a fixation point is introduced, and then removed about 200ms before stimuli presentation. This phenomenon is known as the gap effect (Kingstone & Klein, 1993).

1.2 Neural generators of saccadic eye movements

The current belief is that express saccades are unconsciously controlled and do not require conscious perception of the stimulus to which the express saccade is directed towards. There are at least 3 possible theories for how saccades are formed, including regions such as the Superior Colliculi, Frontal eye Fields, Lateral Geniculate nuclei, and the extra-striate cortex.

The superior colliculi (SC) are sensorimotor structures at the top of the brain stem, made up of layers (Carpenter, 2000). The superficial layers of the SC form a sort of retinal map, with large receptive fields that cause stimuli to generate a sort of hill of neural activity (Carpenter, 2000, Munoz et al., 1991). The deeper layers of the SC form a motor map consisting of tectoreticular neurons (TRN) (Munoz et al., 1991). Prior to a saccade formation, TRN activity increases dramatically in a corresponding part of the Superior Colliculus (SC) (Munoz et al., 1991). The SC are also organized topographically, by saccade size; posterior neurons are ideal for large saccades, while anterior neurons are better for smaller saccades (Soetedjo et al., 2002). This activity of TRNs when presented on a graph forms a sort of diffuse hill that corresponds with the saccade target associated with a fixed location on the retinotopic map (Munoz et al., 1991). This hill formation has been observed shifting over time from the start and end of a saccade in cats (Munoz et al., 1991). These TRNs project monosynaptically and bisynaptically to the previously mentioned BNs (Soetedjo et al., 2002). The SCs are under constant inhibition by inhibitory fibers descending from the area of the midbrain known as the substantia nigra pars reticulata (SNPR) (Carpenter, 2000).

The SNPR is in consequentially influenced by several areas of the cerebral cortex, specifically the frontal eye field (FEF) in relations to saccade formation (Carpenter, 2000). The FEF units have a variety of tasks; some are sensory and respond to specific visual stimuli, while others are active in saccades, building linearly in the 100-200ms before a saccade (Carpenter, 2000). The FEF input comes from various sections of the cortex, most importantly areas activated by the recognition of specific visual targets (Carpenter, 2000). When these cortical areas have selected a target, the inhibition is momentarily lifted at the local level, and then the SC creates the cascade down to the BNs (Carpenter, 2000). Additionally, support for the FEF theory comes from experiments with macaque monkeys, where if an electrical charge is applied to the FEF, saccades are elicited (Bruce et al., 1985). Unfortunately, because most of the data has been observed in macaques, it's impossible to determine if the subjects are consciously or unconsciously controlling the saccades. However, as noted by the author Charles Bruce, the deeper the anaesthesia, the higher the threshold for the saccades (Bruce et al., 1985).

The primary visual center (V1) itself is organized in a parallel and hierarchal fashion. In the hierarchal system, there are 2 main pathways: a dorsal, magno-dominated pathway transmits to the parietal cortex and is associated with space, movement, and action, while the ventral, parvo-dominated pathway flows into temporal areas and is mostly concerned with object identification and perception (Lamme & Roelfsema, 2000). The parallel connections are best typed as feedforward, horizontal, and feedback. Feedforward connection pass input from lower levels cells to higher level cells, horizontal connections occur at the same level, and feedback happens from higher cells to lower ones (Lamme & Roelfsema, 2000). The Feedforward sweep is the process where the hierarchal levels of the V1 are quickly activated through feedforward connection cascades (Lamme & Roelfsema, 2000). These feedforward connections pass information from lower to higher visual cortical areas, and at the horizontal, local areas and feedback connection; the neurons activated are determined by the pattern of the feedforward connections (Lamme & Roelfsema, 2000). The feedforward sweep is mostly involved in unconscious vision, while recurrent processing is needed for visual awareness (Lamme & Roelfsema, 2000).

1.3 Blindsight and its importance to research question

Normal vision requires the classic neural pathway from retina to lateral geniculate nucleus (LGN) to cortex (Savina & Guitton, 2018). Blindsight is the condition in which a person has residual vision after trauma to the primary visual centers without being consciously aware of it (Sarkar & Tripathy, 2021). Blindsight can be observed in the cortically blind and the retinally blind (Pöppel et al., 1973). Cortical blindness is the loss of vision by lesions to the occipital lobe, specifically the striate cortex, and can range from a small blind spot (known as a scotoma) to an entire visual field (referred to as hemianopia) (Sarkar & Tripathy, 2021). Retinal blindness is caused by damage to retina and has no input to the brain. It should be noted that cortically blind patients have no advantage over the retinally blind, therefore the cause of the blindness should not interfere with blindsight studies (Pöppel et al., 1973). However, it has been recorded that cortically blind patients can report conscious perception, especially with moving stimuli (Railo & Hurme, 2021).

A possible explanation for blindsight, is that besides the LGN, other subcortical structures, such as the SC and pulvinar (PV), also project to various extrastriate areas (Lamme & Roelfsema, 2000). After a lesion in V1, visual information is still routed to parietal cortex through other projections, but cells in the parvo-ventral stream appear inactive; this suggests that visual awareness is mediated by the ventral stream, while the dorsal stream regulates unconscious activity (Lamme & Roelfsema, 2000). Unfortunately, there are some weaknesses of this explanation, since it can't explain how blindsight subjects can make qualitative assumptions about scotoma stimuli, such as color or shape, which are assumed to be processed by the by the ventral pathway (Lamme & Roelfsema, 2000). Finally, there is evidence of activity in ventral pathway regions evoked from unperceived stimuli in human blindsight patients (Lamme & Roelfsema, 2000).

The patients in the following studies were thoroughly tested in the cause and depth of their various sight issues (Pöppel et al., 1973, Zihl, 1980, Rafal et al., 1991, Savina & Guitton, 2018). The subjects in 3 of the studies were categorized as unaware by the experimenters (Pöppel et al., 1973, Rafel et al., 1991, Savina & Guitton 2018). However, in the Zihl 1980 experiment, 2 out of 3 participants were sometimes able to localize stimuli or saccadic response as under or overcompensating (Zihl, 1980). Indeed, a major debate is if blindsight is partially conscious but degraded sight, or an unconscious process (Railo & Hurme, 2021). The binary scale of “seen” or “not seen” while the simplest way to determine consciousness, doesn’t consider that conscious perception occurs over a gradient (Railo & Hurme, 2021). It has been suggested that repots of unconscious activity might be degraded conscious vison, demonstrated best when a graded scale is used (Railo & Hurme, 2021). For this reason, we used a graded scale in our experiment.

Blindsight is often divided into type-1 and type-2 forms: Type-1 blindsight is unconscious blindsight cases, in which the patients are assumed unable to consciously collect information about stimuli in the scotoma related to the stimulus presented to the scotoma (Railo & Hurme, 2021). Type-2 blindsight refers to cases where the patients can collect some conscious information regarding stimuli in the scotoma, although the information is assumed to be non-visual (Railo & Hurme, 2021). Given this information, Zihl’s 1980 study contains type-2 blindsight, while the Pöppel et al and Savina & Guitton study both contain Type-1 blindsight. The Rafal et al., 1991 experiment did not fall into either category due to stimuli and set up used but noted that while the participants did not demonstrate conventional blindsight via the forced choice test, they acknowledged with training and correct stimuli it might have been possible (Rafal et al., 1991).

Blindsight can also be subdivided by processing, in which are 3 possible types of blindsight: action blindsight, attention blindsight, and agnosopsia (Savina &Guitton, 2018). Most of the following studies fall into the testing of action blindsight, the motor responses to unseen stimuli (Savina & Guitton, 2018). There are at least 3 possible pathways in blindsight: The geniculostriate pathway, the retinotectal pathway, and geniculoextrastriate pathway. All 3 pathways are visualized in Figure 1 for better clarity.

The geniculostriate pathway involves the LGN activates a region of the primary visual cortex known as MHT+ (Ajina & Bridge, 2018). It should be noted that the geniculostriate pathway is only fully developed in mammals (Rafal et al., 1991), making non-mammalian studies more difficult to extrapolate information. Support for the geniculostriate pathway includes the results of the Rafal et al., studies, where hemianopia patients were unable to detect inhibitory signals designed to delay saccade formation if they had an intact pathway, implying that the extrastriate cortex takes priority over the retinotectal pathway (Rafal et al., 1991). Zihl later conducted another study in 1994 that examined oculomotor scanning behavior in hemianopia patients and devised a treatment strategy for the most severe cases (Zihl, 1995). With training via sight tracking and increased exposure times, approximately 80% of the patients were had search times equivalent to those of healthy patients, as well as fewer fixations and repetition of searches when compared with results prior to intervention (Zihl, 1995). The treatment resistant patients all had brain damage that involved either the posterior thalamus and/or the occipitoparietal cortex, as well as the optic radiation and the striate cortex (Zihl, 1995).

The retinotectal pathway involves signals directly from the retina into the superior colliculi (SC) where it is processed and then passed on to the area known as the pulvinar, and then the extra striate cortex (Ajina & Bridge, 2018). Support for the retinotectal pathway comes from Josef Zihl, who examined subjects with damage to the geniculostriate visual pathways (Zihl, 1980). Prior to this was believed that complete destruction of the postchiasmatic geniculostriate visual pathways caused great or complete loss of sight in the associated areas of the visual fields (Zihl, 1980). Based on prior studies in monkeys with a removed striatal cortex, it was assumed that it could be possible to train behavioral responses in humans with a residual visual function as well (Zihl, 1980). When the responses were replicated in human subjects, Zihl hypothesized that the activity was probably mediated by the extra-striate retinotectal pathway (Zihl, 1980). In a 1990 study of patients suffering from hemianopia by Rafal et al., humans demonstrated the ability to increase saccade latency and prevent saccade formation in the seeing field of vision, when a distracting stimulus was presented to the nasal hemifield in the blind field of vision (Rafal et al., 1990). While a possible explanation for these signals is mediation by the retinotectal pathway at least in oculomotor responses, which are widespread myogenic potentials caused by visual stimuli (Farlex, 2012), Rafal was unable to recreate this phenomenon in humans with intact geniculostriate pathways and was unable to recreate the phenomenon in other hemifields in hemianopia patients (Rafal et al., 1990). Zihl later discovered that the reason for this capability was because of disordered spatial organization in not just the affected hemifield, but the intact hemifield as well; this disorientation also affected spatial integration of visual information (Zihl, 1995). Finally, in 2000, Savina & Guitton were able to further confirm retinotectal activity in hemi-decicordate patients (patients missing half their brain structures) (Savina & Guitton, 2000).

The third possible explanation is plasticity in the white matter of the LGN projects to the extrastriate visual cortex (Ajina & Bridge, 2018). Most of this testing has been done in primates, namely macaques, and there still is no definitive pathway at this time (Ajina & Bridge, 2018).

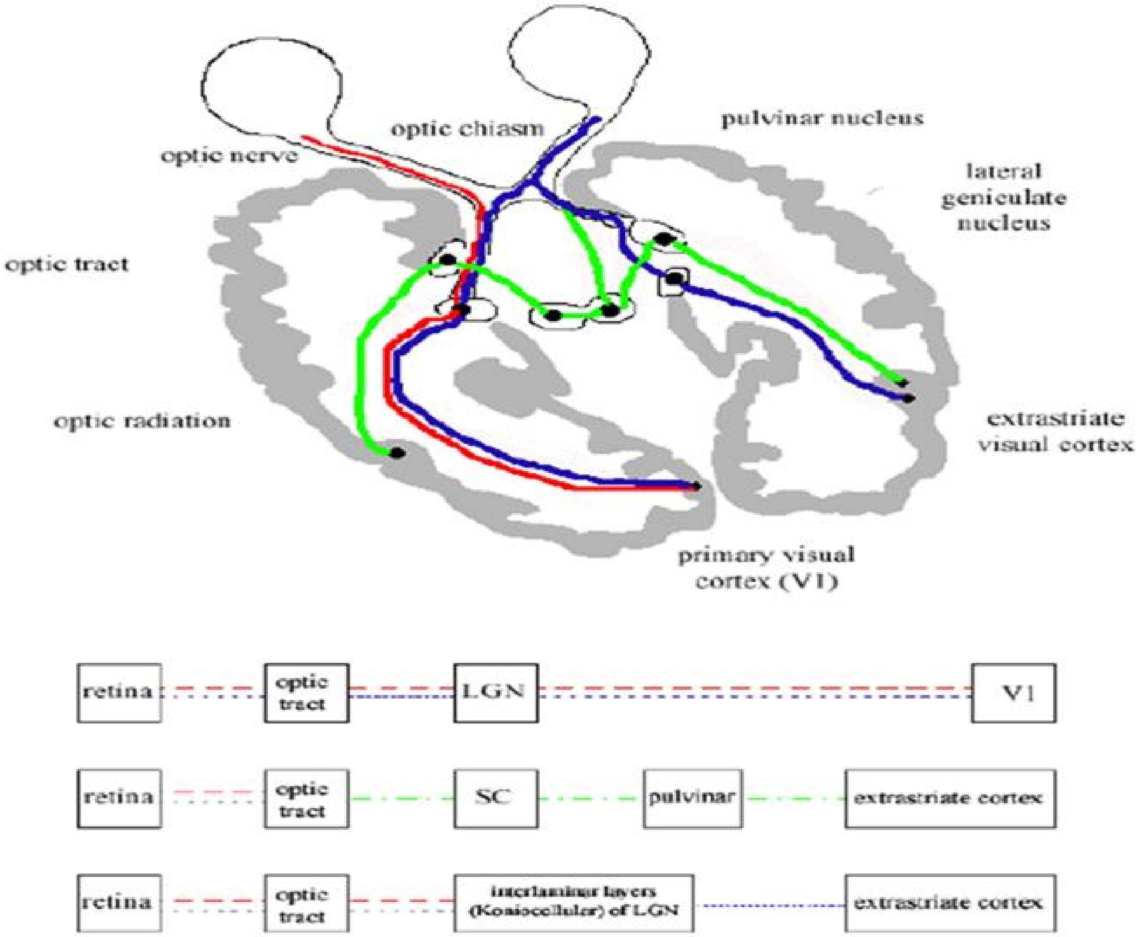

Figure 1. Visual representation of the 3 assumed alternate pathways responsible for blind sightedness. All visual pathways assume an undamaged retina and pathway at least up to the optic tract. (Ptito & Leh, 2007)

1.4 Challenges with Blindsight

Given the information above, it is possible under certain conditions for subjects to initiate saccades without being consciously aware. Unfortunately, there are some issues with using blindsight subjects, namely in the ways they have been studied. Alan Cowey's Blindsight saga reviews several studies in blindsight, and the flaws and strengths of the studies. He acknowledges that blindsight is useful in telling us about the nature of visual processing without the primary visual cortex but has many possible artefacts which are frequently overlooked or disregarded (Cowey, 2009). For example, the eyes can continue to follow movement in a phenomenon known as optokinetic nystagmus (OKN); however, residual OKN is controversial because it persists after unilateral brain damage, but not after total cortical damage (Cowey, 2009). The 2 most common criticism in blindsight studies is first that there is no clearly defined scale of awareness, and the second being that some of the reflexive saccades observed are merely artefacts from equipment (Cowey, 2009). A common theme throughout all the studies investigated, is that the V1 is essential for sight (Cowey, 2009). Cowey concludes that for continued studies into blindsight, awareness as a common scale of detection needs to be better defined and the tools and methods for determining blindsight also need to be better integrated and standardized (Cowey, 2009).

So, the question now the question remains, is it possible for healthy individuals to initiate saccades without being consciously aware of the target of the saccade? According to Crouzet et al., it is. In 2014, they conducted a case study where 4 healthy subjects (no blindsight or hemianopia) were introduced to a masked stimuli under 4 different visibility conditions, hypothesizing that if object-substitution masking (OSM) interfered with re-entrant processing, then it could be assumed that very fast, feed forward driven responses would not be affected by OSM (Crouzet et al., 2014). In their experiment, while all 3 masked conditions generally affected response and performance, the fastest saccade response times for OSM and backward masking experiments at similar times as unmasked response times; the general low-contrast condition (used to test if any visual impairment would cause the same affects) impaired both fast and slow saccades (Crouzet et al., 2014). The overall accuracy in all 3 masked conditions was identical, but still markedly decreased compared to the control condition (Crouzet et al., 2014). They concluded that masking effects are time dependant, and the fastest saccades are unaffected by masking (Crouzet et al., 2014).

Crouzet followed up the findings of the above OSM study 3 years later, with a substantially larger sample size and a perceptual awareness scale 1-4 where 1 was no awareness, and 4 was clear awareness (Crouzet et al., 2017). They noticed a decrease in awareness and accuracy while masked when compared to unmasked responses, as supported by the 2014 study (Crouzet et al., 2017). Notably, participants' judgements of subjective awareness indicated that stimulus processing during this early stage is not entirely devoid of conscious awareness (Crouzet et al., 2017)

As mentioned previously, it is possible to induce saccades unconsciously in neurologically impaired humans, and tentatively it is possible to initiate saccades in healthy humans. However, the 2 studies mentioned above that do deal with saccades in healthy humans have demonstrated other flaws. For example, besides in the 2014 study, the minimum duration of masking to have an effect had not been established at the time of writing (Crouzet et al., 2014); the duration of the target was also less than 10% of the average in most OSM experiments at 7ms vs. 80ms, which is extremely short especially considering the blanking was 200ms and the fixation screen was 800-1200ms long (Crouzet et al., 2014). This target window was increased only slightly in the 2017 follow-up to 10ms (Crouzet et al., 2017). The 2014 experiment also had no independent confirmation of awareness besides saccadic selection, and most of the accurate responses in the 2017 follow-up indicated that the participants were strongly aware of the stimulus (Crouzet et al., 2014, Crouzet et al., 2017). It should be noted at both the 2014 study and the 2017 study, saccades below a certain point (70ms and 100ms respectively) were removed from analysis, removing all express saccades (Crouzet et al., 2014, Crouzet et al., 2017). Finally, the stimuli and masks used in both the 2014 and 2017 experiments were quite small, which as noted previously do not trigger express saccades.

1.5 The significance of this study

My study differs from the other given ones by trying to elicit saccades in healthy and nonimpaired subjects, while also verifying awareness with a visibility rating task besides saccadic selection task. To prevent conscious perception of stimuli, we used a visual metacontrast mask to suppress the visibility of an otherwise clearly visible target. A metacontrast mask is a mask that has no overlap in shape and rather exactly matches the edges of the stimuli, making the stimulus and the mask indistinguishable when presented at the same time (Metacontrast masking, n.d.). For example, if the stimulus is a square shape, the mask will be an annulus shape matching exactly around the edges of the stimuli. In a metacontrast study, the onset of the target and the mask is referred to as a Stimulus Onset Asynchrony (SOA), and is systematically varied in length (Francis, 2000). The reason I used a metacontrast mask is because it enables a delay between target and mask, unlike a typical noise or pattern mask. If the stimulus and mask are presented at the same time, the target is clearly visible; if the mask is delayed by several hundred milliseconds, the stimulus presents and disappears before the mask (Francis, 2000). When presented in a shorter span of time, as an intermediate SOA, the target is perceptually absent (Francis, 2000).

This effect is counterintuitive, as it suggests that the longer the delay between mask and target, the more effective the mask is (Francis, 2000). This is because metacontrast masking spares stimuli's transient responses and does not delay manual responses to stimuli (Railo & Koivisto, 2012). Another explanation is that the mask disrupts the recurrent interaction between high and low visual areas; this occurs when information about stimuli from high areas clashes with mask responses after being fed back to low areas (Lamme & Roelfsema, 2000). This also supports mask effectivity with longer SOAs (Lamme & Roelfsema, 2000).

As mentioned previously, the feedforward sweep is mostly involved in unconscious vision, while recurrent processing, at least under certain conditions, is needed for visual awareness (Lamme & Roelfsema, 2000). Most of our vision is perceived consciously, but a stimulus that bypasses awareness is transmitted as a motor output and occurs in both normal and blindsight subjects (Lamme & Roelfsema, 2000). Metacontrast masking suppresses feedback activity, so therefore our mask should interfere with the subject's ability to consciously perceive stimuli (Railo & Koivisto, 2012)

In the 2012 Railo and Koivisto experiment involving Transcranial magnetic stimulation (TMS) and visual masking inhibitory affects. TMS is the use of a magnetic pulse to suppress a cortical region of a healthy subject for short periods of time (Lamme & Roelfsema, 2000). TMS pulses that are applied to cortical areas (i.e., V1 or extrastriate areas), can impair awareness of a momentary stimulus, possibly by interfering with the feedforward sweep (Lamme & Roelfsema, 2000).Railo and Hurme's experiment supports this, as when conscious visual perception was eliminated, unconscious location detection was still possible for TMS inhibited conditions and metacontrast masking conditions (Railo & Koivisto, 2012). If express saccades are in fact unconsciously activated, the SOA between mask and target should give them enough time to be activated without interference from the metacontrast mask.

1.6 Challenges with Express Saccadic Movements

Unfortunately, it is difficult to create large, high-contrast stimuli without conscious perception, as express saccades are not triggered by small stimuli. The main issue is to show a strong and large stimulus but make sure a subject is unaware of the stimulus. We used a visual metacontrast mask to suppress the visibility of an otherwise clearly visible target.

The decline in saccades is also highly sensitive to even minor cerebral impairment, with even 24 hours' worth of sleep deprivation causing a decrease in velocity of saccades, as well as a decrease in accuracy and latency (Merz et al., 2013). The effect of mild depressants, such as sedatives and alcohol, have conversely shown to have a marked increase in latency, besides a decrease in velocity of saccades (Merz et al., 2013). The saccadic movements also have an issue that when time intervals between stimuli is longer than 300ms, the reaction times to previously stimulated locations are longer than new locations; this effect is known as inhibition of return (IOR) (Michalczyk & Bielas, 2019). The reaction times are also slower to target and cue areas that occupy the same area, compared to if the target and cue are in different areas (Michalczyk & Bielas, 2019). While many studies have implicated superior colliculus in controlling eye movements, the SC is also important in generating gap effects and IORs (Michalczyk & Bielas, 2019). Since both gap effect and IOR depend on eye programming according to the SC theory, there will obviously be some interactions. This is important to our work, as we utilize the gap effect to increase our chances of seeing saccades but need to attenuate the response to avoid IOR.

1.7 Hypotheses of present study

My hypothesis is that the express saccades are unconsciously triggered, even in the presence of a visual mask. As such, I should see no difference in express saccadic frequency, or slightly decreased number of express saccades, even when the participants did not report consciously seeing a stimulus. However, if the express saccade frequency is lower, I can infer that express saccades are not solely controlled by subcortical areas but are perhaps modulated by neural processes related to conscious vision. Conversely, if express saccades are not independent of conscious vision, therefore we should see a decline in express saccade rate as a function of invisibility.

2. Materials and Methods

2.1 Participants

2.1.1 Pilot testing

The pilot testing was performed between dates May 9th-17th 2019, using 5 participants from the Human Neuroscience master's degree program (All female, 2 with glasses, ages 25-35). The window of delay between stimuli and mask for the pilot was 60ms, but some participants reported being able to see the stimulus even with the masking. Using feedback based on responses from the pilot, I reduced the delay time to 50ms, and formulated an instructional sheet with an example of the block for experiment participants.

2.1.2 Experimental Program

A call for participants in the experiment was posted in https://psykoehlot.utu.fi/, the Psychology department website for the University of Turku, during Summer and Fall Semesters 2019. Initially the recruitment was in English, but later changed to Finnish to expand the audience reached. Fifteen university students (age 19-32 years; 2 Males, 3 with glasses) made up the experiment pool. The participants received a 1hour participation credit in compensation. Due to the exposure of experimental aims and participation in the pilot program, the Human Neuroscience Master's Degree Program year 2018 was excluded from the experiment. All other higher education students were encouraged to apply.

2.2 Materials of Experiment

The experiment design involved using an EyeLink Portable Duo eye tracker and a metacontrast mask. I used the EyeLink Portable Duo as it has a frequency of up to 2000Hz while stabilized, and is compatible with third party data analysis MATLAB, while still being accurate and precise (EyeLink Portable Duo, n.d.). Additionally, the EyeLink Portable duo has a tripod mount that makes it easier to track gaze during the experiment and could be adjusted for each subject's individual height while stabilized. We used the EyeLink in conjunction with a head stabilizer to keep participants into the same position and insure they weren't moving their heads instead of their eyes. The stabilizer was kept in the same position for all experiments, we adjusted the height of the table as needed for participant size and comfort. The experimental stimuli and mask were all presented on the same CRT monitor at 120Hz with a screen resolution of 1024 x 768. This monitor was kept in the middle of the same table used for all experiments.

2.3 Experimental design:

The experiment started with a brief presentation of a fixation point (+) in the middle of the monitor, after which the fixation point is turned off. This fixation point creates a gap effect, which significantly reduces the reaction time to produce express saccades from an average of 180-200ms to 80-100ms (Sparks et al., 2000). To improve detection of stimuli, we have included an empty slide between stimuli and fixation to induce the blanking effect; a phenomenon where detection of target displacement is improved by inserting a short blank period (50-300ms) during the saccade and before the target reappears at a new position (Takano et al., 2020). If inserted post-saccade, the displacement should be perceived (Takano et al., 2020). For our experiment, we have included an empty slide between the fixation point and the stimulus (see Figure 2).

The stimulus was presented to one of the 4 quadrants briefly, then the metacontrast mask was presented over all 4 quadrants to cover the whole field of vision (Fig. 1). This stimulus was exactly 150 pixels on each side, to give the total area of 22,500 pixels per stimulus and the total area of all 4 quadrants at 90,000 pixels. Comparably, a single metacontrast mask is 250 pixels on all sides, but with the center removed the total area is 40,000 pixels with the total mask area as 160,000 pixels. The stimulus position was also randomized to prevent priming to any one area. Some trials had no stimulus, in which case the subjects were asked to fixate towards the center of the screen to avoid creating a false saccade. On some trials, the mask was absent as well to establish a baseline condition to compare the saccade rate to. These blank trials and stimulus free trials were interspersed randomly with stimuli trials (both with masks and without masks) throughout the block to prevent priming. Figure 2 presents the prototype of a typical block.

To prevent IOR, we have limited our window to 50ms delay, and included a gap between stimuli and masking to decrease the overall reaction times and avoid overlap with potential saccadic IORs. There was a delay of 50ms between presentation of stimuli and masking (presented for 10ms each). This is so increased exposure to the stimuli will allow the brain more time to process the image, and therefore a higher chance of express saccades occurring. By limiting the window to 50ms, we prevent the chance of IORs, and the gap between stimuli and masking decreasing the overall reaction times hypothetically decreases the chance of overlap with potential saccadic IORs. Since saccadic eye movements latencies are longer than target presentation, the subjects would not report seeing the target.

Our design used 10 blocks with 50 trials per block for a total of 500 trials per subject. Each block took approximately 2 minutes to present with the average testing period, with time included for trial instruction, adjustment of head stabilizer, calibration, and validation of eye movements between each block, a shortened practice block of 20 trials prior to the 10 experiment blocks and breaks as needed by the subject. The experimental period on average lasted about 45-50 minutes per subject. After 60 minutes, if the subject had not completed all 10 blocks, the experiment was terminated, and data collected for the trials completed. This was to prevent subjects from becoming too tired, which leads to erratic eye movements and overall, negatively impacting the data.

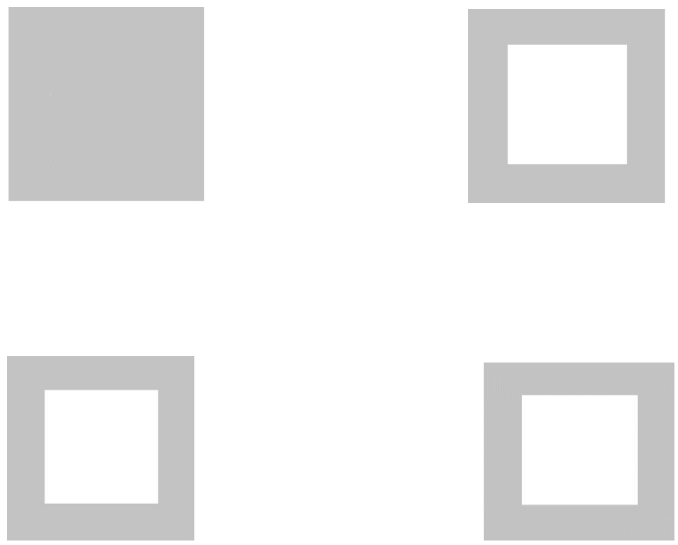

Figure 2. Example of stimuli in a metacontrast mask. The empty space in the center is perfectly shaped to contain the edge of the stimuli in the upper left quadrant.

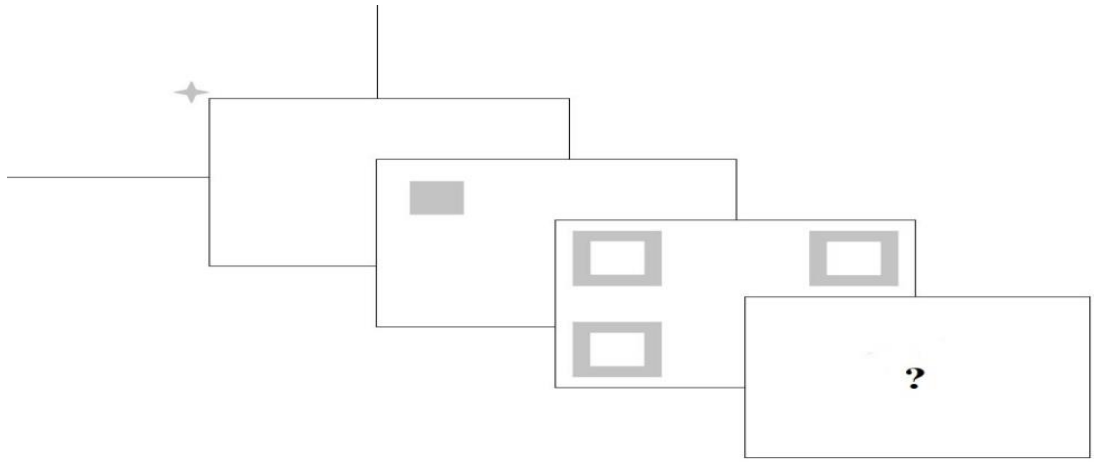

Figure 3. Prototype of a typical trial in the order of fixation, blank, stimulus, mask, and the feedback question. In the event there is no stimulus or no mask, 1 or more of these slides will be skipped and go directly to the feedback slide.

2.4 Experimental tasks

Each subject had 2 tasks. The first was a finding task, where the subject was simply instructed to look towards the target stimuli as quickly as possible. Ideally, this would create express saccades. The second task was a visibility rating scale immediately after stimuli presented, signalled when a question mark symbol was presented. The rating scale was a scale of 0-3, where 0 was not seen at all, 1 as possibly, 2 was mostly sure, and 3 was definite. The rating task was not timed, and the next task would not proceed without a rating. If there was no stimulus seen, subjects were instructed to look towards fixation point in the middle and rate the task as 0. The most important distinction was between 0 and 1, as this indicated basic awareness of the subject.

2.5 Experimental Variants

2.5.1 Control condition 1: Clearly visible stimuli

The purpose of the first control condition is to establish baseline eye movements and average amounts of express saccades and normal saccades with an average stimulus without masking. This is so it can compare with experimental procedure to see if there is any increase or decrease in express saccades or normal saccades. The control number of express saccades and normal saccades will be subtracted from the overall experimental values, since this is what the subject would see normally without any kind of masking.

2.5.2 Control Condition 2: Masking without stimuli

The main purpose of this control is to see if it is possible for the masking process itself to trigger express saccades or normal saccades. This control amount will be subtracted from the experimental amount to establish a truer baseline with the control 1a amount as both are the non-experimental subjects, but a subject of the overall condition.

2.5.3 Control Condition 3: Masking with stimuli visible

The main purpose of this condition is to see if being able to consciously determine stimuli with a mask makes any difference between express saccade or normal saccade frequency than masking without any visibility. If there is higher frequency with stimuli visible than without, I can conclude that express saccades are controlled or at least modulated by some conscious perception within the brain

2.5.4 Experimental design: Masking without stimuli visible

This is the main condition that the highest frequency of express saccades is expected. If there is a higher frequency with stimuli visible than without, I can conclude that express saccades are controlled or at least modulated by some conscious perception within the brain.

2.6 Data Analysis

Results of rating data was analyzed via MATLAB in VMWare Horizon, in the format of a text file for each subject. The rating was presented with the stimulus block used (if present), the location of the stimulus, and if the mask was presented after stimulus or not. The data from the file is plotted in the form of the graph, with a comparison drawn between the test block and the experimental blocks (Fig. 3 and 4). The rating task is then compared with the eye tracking data to see if despite rating a stimulus as unseen, the eye did or did not move towards the area of the stimulus.

EyeLink data was also analyzed with MATLAB statistics. All data across the subjects and pilot pools was compiled by Henry Olkoniemi of University of Turku. Data was filtered for fixations that did not start within 100px of center screen, as we concluded that the saccade would start at the fixation point and move towards the stimulus at the given quadrant. The region of interest (ROI) was 350px of the edges of the screen, where the edges of the target were met by the mask. EyeLink Data was provided in the format of an Excel file that was analyzed via MATLAB, and directly from the result files of the subjects. The resulting saccadic data was then filtered for saccades that occurred prior to stimulus presentation (fig. 5), and then again for saccades that occurred outside the ROI (fig. 6). The last filtration occurred for first fixations per subject per trial.

Finally, we compared and contrasted reaction times between masked and unmasked saccades. We did statistical analysis in the form of a paired t-test. A t-test analyzes how large a specific difference in means is relative to the amount of variance. The t-statistic is the size of the difference in units of variance, where even a small difference in variance will produce a large t-value, given low overall variance and a large enough sample size. The larger the sample size, the smaller the probability of a null hypothesis being rejected assuming the difference is constant across means. This difference is unlikely with larger samples. A paired t-test in our results defines this variance as how great a difference in means between participants.

3. Results

A total of 15 subjects have been tested and their data collected. The results of the rating task were analyzed and plotted for all 15 subjects in Figure 3.

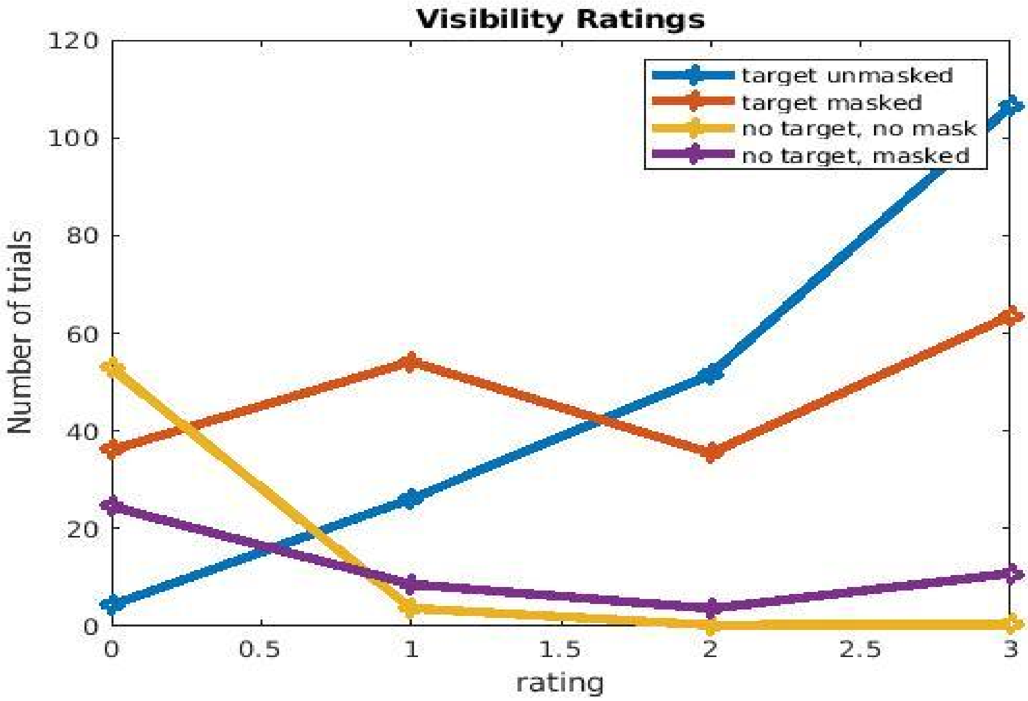

Figure 4. Average rating for all subjects and pilots over the 4 trial conditions (N = 20). All subjects were required to answer before proceeding to next block.

As expected, the participants rated stimulus data higher than stimulus free data. The masked trials had an increase in ratings of 1 compared to 0, where 1 is "possibly seen" and 0 is "not seen" for both presentations with and without stimuli. The next step after measuring the response time was to verify that the saccades started after the stimulus (if seen) was presented. We did this by filtering for saccade starts that occurred after the time of stimulus presentation. We then presented the data as the scatter plot in Figure 4 to reflect a saccade presentation when a saccade was detected, compared to when the stimulus was presented. While there is a wide range of saccade development, even with filtration for saccades that only occurred after the stimulus presented, most of the saccades occur about 300ms after presentation, classifying them mostly as normal saccades instead of express saccades.

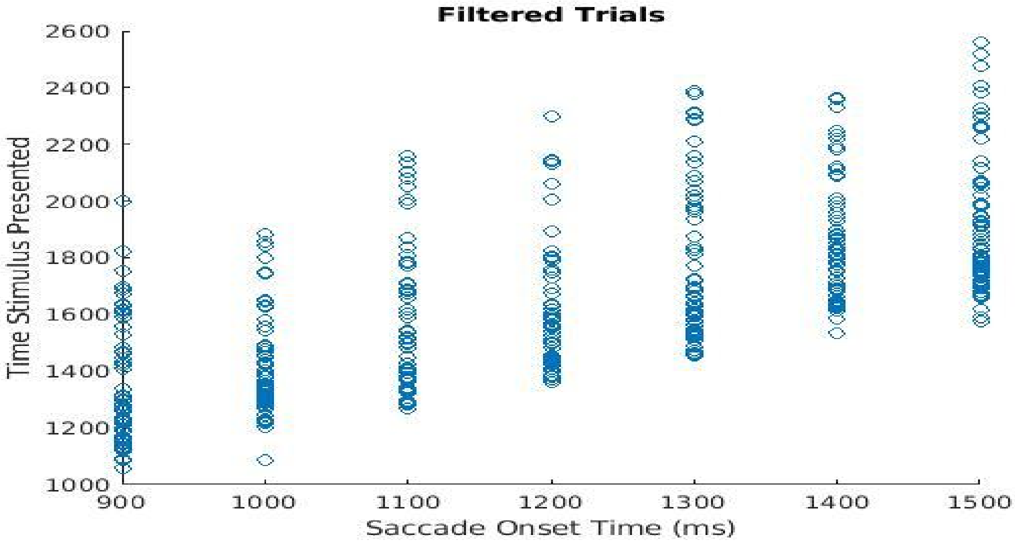

Figure 5. Scatterplot of stimulus presentation and saccade start time of subjects (N=466). The saccades fall into 7 distinct bands, as there was stimulus presentation at 7 possible intervals.

Next, we filtered only for saccades that occurred within the target area of the stimulus and created the scatterplot shown in Figure 5.

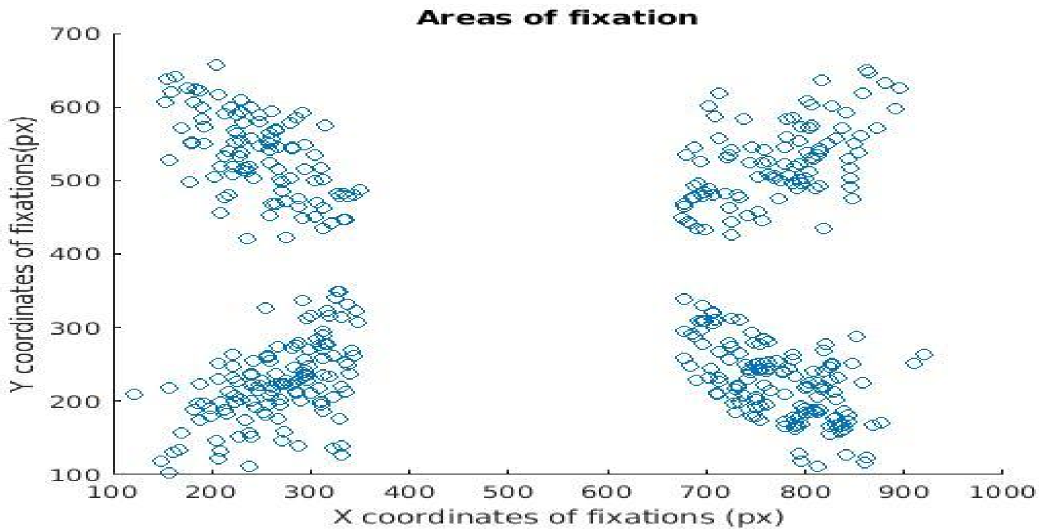

Figure 6. scatterplot of areas of fixation for subjects (N=459)

When this scatter plot is overlaid with stimulus areas, or within the metacontrast mask, most of the coordinates fall within the borders of the metacontrast mask.

We then calculated the reaction times (RTs) of the subject and pilot groups and compared them between trials that had a metacontrast mask, and trials that were unmasked. Approximately half of the RT averages were longer for masked trials than for unmasked. However, there were significantly more reaction times for masked vs. unmasked data, despite that the trials for masked and unmasked were split exactly in half. The result of this comparison is as seen in Figure 7 Three subjects between the pilot and subject pool did not produce saccades at all (Subjects 1-3), and 3 more participants did not produce saccades without masking (Pilot 3, and Subjects 13 and 14)

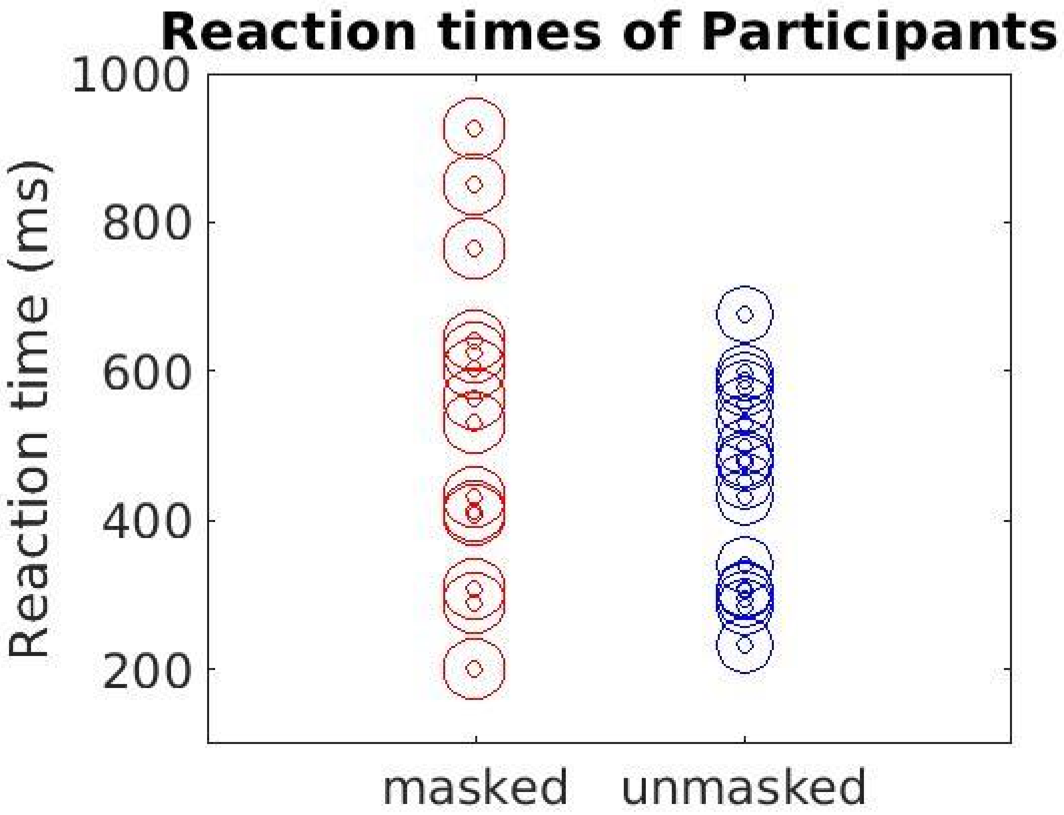

Figure 7. Scatterplot of average reaction times for subjects. The average reaction time of masked trials was 448.6256 seconds, and the average reaction time for unmasked trials was 539.8807 seconds.

Lastly, we conducted a t-test for all participants (pilot and study) for the percentage of 5% (α =0.05). The p-value was 0.0840 with a confidence interval of -13.1942 to 184.0314. Additional statistics from the t-test produced a t-stat of 1.8713 with 13 degrees of freedom, and a standard deviation of 170.7928. According to these statistics, the difference in reaction times between masked and unmasked conditions is not statistically significant, but the data does indicate a trend in shorter RTs while masked compared to without masking. However, some individuals had the exact opposite condition, with longer RTs while masked compared to unmasked. While there may be a trend, there's potential for individual variation as well.

4. Discussion

Given the tendency for shorter RTs when masked, and the fact that 15% of participants did not produce saccades in the unmasked condition, we can tentatively assume that saccades do not require conscious perception. We may also tentatively assume that there is individual variance in this expression, as we had subjects with the exact opposite tendency, having longer RTs when masked and shorter RTs when unmasked. A possible explanation for our masking decreasing RTs comes from Crouzet et al.s' 2014 experiment, when they noted that their OSM and backwards masked conditions had similar reaction times to unmasked conditions (Crouzet et al., 2014). The explanation they gave was that the masking effects were time dependent, and the earliest saccades were not affected by masking as a result (Crouzet et al., 2014). These findings tentatively support Railo and Koivisto's work suggesting that metacontrast masking does not interfere with transient and feedforward responses, and that this activity may be sufficient for unconscious perception (Railo & Koivisto, 2010). It also supports their hypothesis that metacontrast masking does not increase RTs, as our average RTs in the masked condition were significantly reduced, nearly 100ms less, compared to the unmasked condition (Railo &Koivisto, 2010). Background for their work also indicated that feedforward activity may only be sufficient for unconscious perception, but would decrease perceptual contrast (Railo & Koivisto, 2010).

It does detract from the Crouzet et al. 2014 study that stated their fastest reactions did not have perceptual impairment from the masking conditions, however it should be noted that they did not have measure perception, they measured accuracy and reaction times, but not whether the subjects were consciously aware or not of the stimuli (Crouzet et al., 2014). It should also be noted that the fastest responses were classified as between 120-200ms, and do not fit the description of express saccades, but normal saccades (Crouzet et al., 2014).

It also detracts from the Crouzet et al. 2017 study, which claimed that fast saccades escaped OSM, and that the correct performances indicated subjective awareness; even the early feedforward processes can have some visual awareness, which was confirmed subjectively by a perceptual awareness scale by the subjects, and objectively associated with EEG activity that indicated a shift in spatial attention (Crouzet et al., 2017). It should be noted that fast saccades are defined as <350ms, and that the OSM on slower saccades (> 350ms) was affected by masking in decreased awareness and accuracy (Crouzet et al., 2017).

We also had above chance level formation of saccades in the masked condition, like the above chance detection while unaware of Railo & Koivisto's experiment (Railo & Koivisto, 2012).

To the knowledge of the writer, this is the only known study attempting to examine express saccades as conscious or unconscious events in healthy human subjects. Our experimental design was created using various techniques to lower the threshold of saccade latency and increase our overall chances of seeing express saccades. Specifically, we used the removal of the fixation point to induce the gap effect, an empty slide to induce the blanking effect, and metacontrast masking shortly after the stimuli to decrease perceptual awareness. This is the ideal design for creating saccades and given the simplicity of creation can easily be re-used in the future. We used a perceptual awareness scale to measure awareness in subjects, which was surprisingly underutilized in many of the studies read, despite the graded nature of site and noting that.

The main weakness with our experiment was that the number of participants was far fewer than expected, with the initial recommended numbers a minimum of 20 subjects, ideally 30 for a better distribution and experimental pool. A possible confounding factor was confusion between languages used, as the experiment and recruitment after September was in Finnish, but the verbal and visual instructions were in English. This caused some issues during the practice block, and occasionally the experiment had to be re-explained to be understood. If possible, we would include instructions in both Finnish and English for additional clarity in the next experiment. Another possible explanation of why we didn't see as many express saccades as hoped for, is that with the usage of the metacontrast mask, the perceptual load is increased due to divided attention between mask and target areas; these target locations were inferred from the mask areas, which are also known to alter the appearance of the masks (Railo & Koivisto, 2010). The participants rating visibility in each trial may also have delayed RTs because the participants had to wait for evidence from the slower parvocellular pathway, that have been suggested to regulate conscious visual processes (Railo & Koivisto, 2010). Another possibility with our study, is that the mask itself may have served as a sort of unconscious cue to participants to form saccades, regardless of if the target was there or not. It should also be noted that we did not restrict analysis to unconscious trials, as only 2 participants that made saccades had unconscious trials. This limits our ability to infer about unconscious RTs and our interpretation of the RT trends. Finally, we used a perceptual awareness scale that was subjective to each participant. We did this to increase our subject pool and decrease overall experiment time. If done again, it would be better to use a method of perceptual awareness that could be objectively verified as well, for example, EEG monitoring.

4.1 Other possible applications of Express saccadic movements.

One of the reasons we wanted to explore the nature of express saccades, was in the explanation of if people with varying degrees of blindness could see, whether as a degraded conscious response, or an unconscious response. While we investigated blindsight as there was a large body of research for this condition, it could have further applications for those that have other disabilities. Specifically, for those that need to communicate consciously and effectively. Assistive technology has greatly improved the lives of people with disabilities that limit limb movement or speech impairment (i.e., cerebral palsy, traumatic brain injury, amyotrophic lateral sclerosis), especially in recent times (Soltani & Mahnam, 2016). These disabilities besides leaving them dependent on others and limiting their communication skills have generally led them to have a poor quality of life. However, even with the most severe motor disabilities, most of these people can still control their eye movements, and systems for these methods, including video-based eye tracking are relatively non-invasive, inexpensive, and fast enough for real time applications (Soltani & Mahnam, 2016). Besides these advantages, classification of different eye gestures (i.e., blinking, looking in a specific direction at a specific time), creates a system of language previously unobtainable by disabled people and with easier interpretation of intention than other more conventional, but more invasive methods such as electroencephalography or electromagnetography (Soltani & Mahnam, 2016). With the advent of assistive technology, especially with human-computer interfaces, this has greatly improved their communications socially, educationally, and even vocationally (Soltani & Mahnam, 2016).

If express saccade movements could be tracked consistently and reliably to the millisecond with definitive confirmation, it could open the possibilities of communications to an even greater audience and give them a voice they didn't previously have.

Besides aiding disabled persons, specific and marked impairments of saccades have been reported in Alzheimer's Disease, and mild frontotemporal dementia (Merz et al., 2013). The current methods of establishing these neurodegenerative disorders have been subjective at best, with the cognitive tests administered only able to show progress, but doesn't control for mild cognitive impairment, sleep deprivation, or even issues with communication such as pre-existing trauma or illiteracy. Because of these issues, the only verifiable diagnosis of AD is post-mortem brain examination. A possible application of express saccadic movements if standardized could prove to be an objective, non-invasive, early detection method, or an extension of a diagnosis battery.

5. Conclusions

Given that there was a difference in reaction times between masked and unmasked data, and that reaction times on average tended to be shorter when masked, the results are consistent with the initial hypothesis that saccades do not require conscious perception. However, the statistic results from our data do not support our findings, and more data is required for conclusive results. We must also use a more objective method of measuring awareness, such as EEG, and control for the possibility of the metacontrast mask acting as a cue for saccade formation.

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