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Institut für Psychologie

## **Bachelorarbeit**

zum Erwerb des akademischen Grades Bachelor of Science

Investigating the influences of hand movements on saccadic inhibition in an interception task

vorgelegt von

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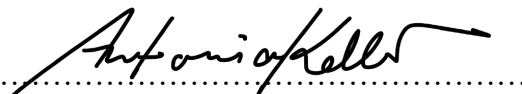
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## **Abstract**

This thesis focuses on investigating the phenomenon of saccadic inhibition to understand how motor demands of certain task conditions and the task relevance of visual changes influence visual processing. Participants performed an interception task on a screen involving either only eye movements or concomitant eye and hand movements. Visual changes were either task relevant jumps of the target that was to be tracked and sometimes intercepted with the hand or task irrelevant bright flashes that appeared on screen. This study was performed in a controlled lab setting using a portable eye tracker, aiming for high ecological validity as participants were free to move their head and were not instructed to make specific eye movements. The results revealed that saccadic inhibition occurs in response to both task relevant and irrelevant stimuli, with the magnitude of inhibition and subsequent recovery period varying depending on task complexity and relevance of the stimulus. This research advances the current understanding of the interplay between task complexity, saccadic inhibition and motor coordination and especially aims to highlight the potential of further research into the related phenomenon of recovery from inhibition.

## 1 Theoretical Background

Catching a ball thrown our way, reaching for a suitcase on a conveyor belt, or grabbing a pen that has fallen off a desk – all these seemingly ordinary tasks require intricate coordination between our eyes and hands. For individuals with operational oculomotor and limb motor systems who rely on their visual system as a primary source of sensory information, these everyday actions exemplify the interplay between these two essential motor systems. Each day, we are confronted with situations that call for precise collaboration between our eyes and hands.

### 1.1 Vision and the role of saccadic eye movements

The visual system has a variety of eye movements at its disposal to help us perceive and navigate our surroundings. To be able to give us the accurate sensory information we need to successfully complete movement tasks, our eyes need to keep the object of interest in focus. This is because the area of highest resolution on the retina makes up only the central 2° of visual angle. Beyond this small area at the centre of the retina, where the density of photoreceptors is highest, visual acuity declines drastically to the parafoveal region and even more in the periphery (Gegenfurtner, 2016; Liversedge & Findlay, 2000). It is thus crucial to fixate objects that we mean to touch, catch, or otherwise interact with. There are high-velocity ballistic eye movements that enable us to quickly orient our eyes to new objects of interest in our visual environment, to bring them to the centre of our vision, called saccades. They can reach velocities of up to 700 degrees per second (Burke & Barnes, 2006; Carpenter, 1988; Krauzlis, 2005) and are one of the most frequent human actions, happening about two to three times per second (Bargary et al., 2017; Land et al., 1999).

During movement tasks, such as reaching for a cup of coffee, saccades bring our eyes, or more specifically our fovea, to fixate important features of the task (Foulsham, 2015). In such goal-directed tasks as pointing or catching (Fookien & Spering, 2020), the eyes have been shown to start moving prior to the hand and usually arrive at the target before the hand, too, as the duration of saccadic eye movements is very brief (Bekkering et al., 1994; Neggers & Bekkering, 2000), typically lasting about 20-30 ms, increasing as amplitude increases (Carpenter, 1988; Land et al., 1999). When pointing or intercepting a target, the eyes provide important visual information by making these quick movements to align the fovea with the object of interest. Additionally, they supply extraretinal information our limb motor system can utilize, such as efference copy signals from the motor commands sent to the ocular muscles and proprioceptive feedback from the stretch receptors of these muscles (Fookien et al., 2021). Conversely, the

oculomotor system receives efference signals from the limbs (de Brouwer et al., 2021). This demonstrates the close connection between the oculomotor and limb motor systems.

The planning of saccades takes very little time. They can be made to a peripherally presented stimulus in about 160 ms (Gegenfurtner, 2016; Kirchner & Thorpe, 2006), with latencies of typical saccades around 200 - 250 ms and even faster, so-called express saccades, around 100 ms (Bekkering et al., 1994). The planning takes place continuously in saccade generation related areas of the brain with several saccadic movements able to be processed simultaneously (Katnani & Gandhi, 2013; McPeck et al., 2000). These areas include the frontal eye fields, supplementary eye fields and lateral intraparietal area of the cerebral cortex (Moschovakis et al., 1996). All of these regions have projections to the superior colliculi, the central element of saccade generation, which also receive fast direct input from the retina (Munoz et al., 2000). Neurons in these structures constantly fire and build up their activity until a threshold is reached and a saccade is executed (Hanes & Schall, 1996).

## 1.2 Saccadic inhibition as a reaction to sudden events

But what if the reaching or catching of an object of interest isn't so straightforward? What if something appears unexpectedly in the corner of our eyes while we prepare our planned movement? Sudden and unexpected changes in our environment are a common occurrence in everyday life. We might hear a car door slammed shut while walking down the street or see a bright flashing light while driving at night. Our body has a multitude of ways to respond to these kinds of surprising stimuli of various sensory modalities, like stopping in our tracks and orienting ourselves towards them (Lynn, 1966).

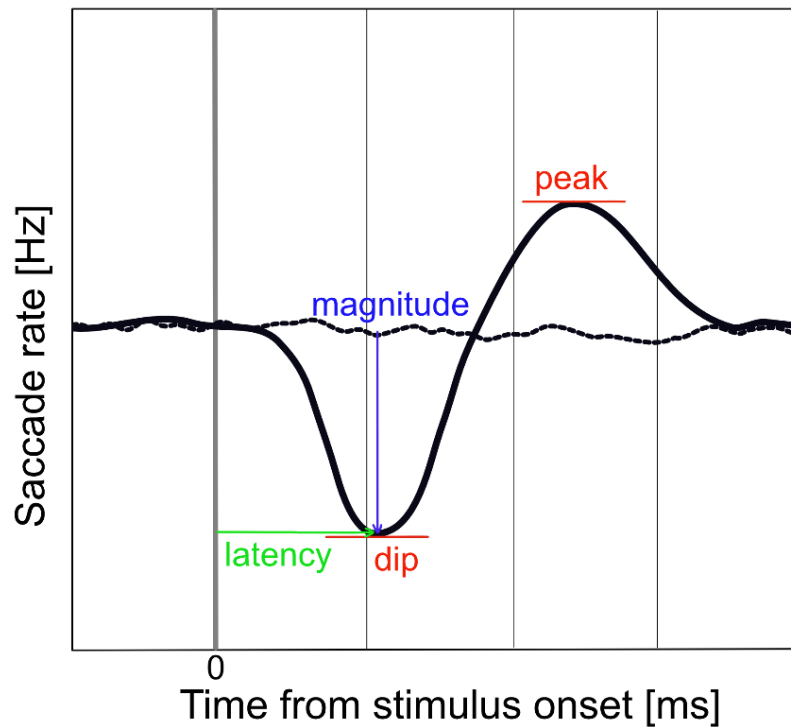
It is a common finding that our motor systems slow down or stop after unexpected perceptual events (Wessel & Aron, 2013). This has also been shown to affect cognitive functions, causing ongoing cognitive representation to be interrupted to allow attention to shift to the novel stimulus (Wessel & Aron, 2017).

Another common and well-studied phenomenon is the stopping of the production of saccades in response to sudden changes in our visual environment (Reingold & Stampe, 2000). When we are confronted with a change in our surroundings while performing an action, it might become necessary to make changes to our planned behaviour or adjust our previous plans according to the new information we just received. In the case of sudden visual stimuli in the periphery of the visual field, a reduction in the frequency of saccades directly following the stimulus has been observed consistently over a wide variety of visual tasks, like reading, scene viewing or other classic saccade paradigms and different types of saccades.

In their research, Reingold and Stampe describe this occurrence, known as saccadic inhibition, as a low-level reflex-like oculomotor effect with a possible neurophysiological locus in the superior colliculi (Reingold & Stampe, 2000, 2002, 2004). This has been suggested because of the very short latencies that have been observed, as saccadic inhibition occurs as early as 50 – 70 ms after stimulus onset (Buonocore & McIntosh, 2012; Reingold & Stampe, 2000). During these first few milliseconds after a visual change the rate of saccades remains constant and then drops to a maximum of inhibition, or minimum of saccade rate, usually around 85 – 100 ms (Buonocore & McIntosh, 2012; Edelman & Xu, 2009). This dip in saccade rate is then followed by a rise above the baseline, a ‘peak’ which represents the recovery from inhibition. After the peak, the rate of saccades returns to the initial level (Reingold & Stampe, 2004). This pattern has been observed under numerous conditions and across participants for a variety of stimuli. It has been shown for voluntary and stimulus-elicited saccades (Reingold & Stampe, 2002) and for microsaccades (Rolfs et al., 2008), for visual and auditory input (Pannasch et al., 2001), for the displacement of visual stimuli and for flickers (Reingold & Stampe, 2004) and for distractors of different sizes, location (Buonocore & McIntosh, 2012), or degree of saliency (Kadosh & Bonneh, 2022; White & Rolfs, 2016).

In their research, Salinas and Stanford (2018) build on the concept of the production of saccades as a rise-to-threshold process, the continuous rising of activity in subpopulations of neurons encoding certain movement vectors. When new information appears, these processes need to be interrupted or paused, allowing more time to deliberate on the new information and deciding whether to abort the previous movement plan and executing a new, concurrently produced plan or to continue with the old one. They propose that this results in a compromise concerning reaction times, shortening reaction times to new critical stimuli while delaying responses to previous targets, should the new information turn out to be unimportant. As this pausing phenomenon happens regardless of predictability of the sudden stimulus, it has been referred to as a reflex-like hardwired effect (Salinas & Stanford, 2018). An exemplary plot of the saccadic inhibition effect with all measures of inhibitions, as described by Reingold & Stampe (Reingold & Stampe, 2002), relevant for this study can be seen in figure 1.





**Figure 1.** Saccadic inhibition. The dashed black line shows the baseline saccade rate. The black line shows the saccade rate with the saccadic inhibition effect after stimulus onset. The dip is the minimum saccade rate or maximum of inhibition. The peak is the recovery from inhibition. The magnitude represents the proportion of saccades inhibited when inhibition is maximal ('dip'). The latency is the time from stimulus onset until inhibition reaches its maximum ('dip').

### 1.3 Bottom-up and top-down influences

It is well known that the stimuli that cause saccadic inhibition do not need to be task relevant to be able to cause this dip in saccade rates (Reingold & Stampe, 2000). However, the strength of the inhibition can be modulated by several bottom-up and top-down factors. Highly salient stimuli are known to attract saccadic eye movements, an effect known as oculomotor capture (Corbetta & Shulman, 2002; Salinas & Stanford, 2018). The saliency of the stimuli depends on their characteristics, like size or luminance contrast and certain neural mechanisms respond to this bottom-up information (Gottlieb et al., 1998; Salinas & Stanford, 2018).

Eye movement patterns in general have been shown to be modulated by top-down processes. In 1967, Yarbus showed that task instructions have a significant influence on eye movement patterns (DeAngelus & Pelz, 2009; Yarbus, 1967), with task relevant scenes being fixated more frequently and for longer durations. When performing tasks, we often have a course of action in mind or have been instructed about what we need to do. While the surprising stimulus that causes saccadic inhibition itself does not have to be relevant to the ongoing task, its embedding into the task context can have an effect.

In their study about saccadic inhibition in reading, Reingold and Stampe (2004) concluded that higher level cognitive or attentional processes modulate the saccadic inhibition effect. They found that a flicker in the direction of the next saccade (congruent condition) increased the magnitude of inhibition compared to a flicker in the opposite direction (incongruent condition), especially in the task of actual reading compared to the mindless reading of z-strings.

It is a well-established finding that covert shifts of attention happen prior to the execution of the next saccade (Morrison, 1984; Ohl et al., 2017; Rolfs et al., 2011; Rolfs et al., 2008). Based on Morrison's finding, the attentional guidance model describes a close bond between attention and saccadic eye movements, with perceptual enhancement occurring in the direction of the next saccade (Reingold & Stampe, 2004). In another study on top-down influences on saccadic inhibition, Glaholt and Reingold (2018) utilized a scene-viewing task with some scenes being deemed relevant to a memory task beforehand and others irrelevant. With greater magnitude and longer duration, saccadic inhibition, triggered by a flicker around the border of a fixated scene, turned out stronger and longer lasting when participants were fixating a scene that was categorized as relevant before the beginning of the task, while no difference in the onset of inhibition was found. They pose that attentional shifts toward relevant scenes enhance the saliency of the scenes, integrating the relevance of both bottom-up and top-down processes during scene-viewing (Glaholt & Reingold, 2018).

#### 1.4 Mutual influences of hand and eye movements

Combined eye and hand movements are typically made towards the object of interest in goal-directed movements. Usually, eye movements precede hand movements in these sort of tasks (Bekkering et al., 1995) and pointing movements towards a target are well known to be more accurate, when the target is gazed at simultaneously (Neggers & Bekkering, 2000). Neggers and Bekkering (2000) hypothesized that not only do eye movements precede hand movements, but they are also stabilized during pointing movements to keep the gaze anchored on the target, with saccades being inhibited, to provide stable fixation of the target area. Additionally, they showed that the preparation of saccades to a new target, too, is inhibited during pointing movements (Neggers & Bekkering, 2000). This stabilization would be advantageous, as visual perception is suppressed during the very rapid saccadic eye movements, where the high speed of the eye causes the retinal image to be blurred (Gegenfurtner, 2016). The same observation was made in an interception task by Mrotek and Soechting (2007). They had participants intercept a target moving along an unpredictable trajectory and expected predictive saccades to be made towards the target to provide vision of the target for the hand.

Contrary to their expectations, they found that pursuit was maintained until the target was intercepted and that saccades were indeed inhibited after the initiation of hand movements (Mrotek & Soechting, 2007). The interactive enhancement of eye and hand movements upon each other has also been found in a task where the performance of eye movements was assessed when tracking of a target was done by the eyes alone and by the eyes and hands combined (Koken & Erkelens, 1992). The authors showed an influence of hand movements on eye movements for predictable target movements, resulting in smoother tracking with fewer and smaller saccades. However, no such influence was shown when tracking more unpredictable pseudo-random target movements.

### 1.5 Hand movements and saccadic inhibition

In research, eye and hand movements have typically been studied separately. However, it is very common for our oculomotor and limb motor systems to function concurrently in everyday situations. Kuper and Rolfs (Kuper & Rolfs, 2024) showed that motor output as well as saccades are inhibited by sudden visual changes.

This thesis aims to explore the indirect modulation of saccadic inhibition through changed eye movement patterns in the presence of concomitant hand movements. It would be interesting to determine if there is an impact on the characteristics of saccadic inhibition in an interactive task involving hand movements compared to merely tracking a target with the eyes. Existing literature suggests that attention may be modulated when the hand is engaged in the task, as the eyes are known to guide the hands (Bekkering et al., 1995; de Brouwer et al., 2021; Mrotek & Soechting, 2007; Neggers & Bekkering, 2000). This shift in attention could alter the saliency of the stimuli used in this study, affecting gaze focus. Consequently, the focus of the viewer's gaze and the perceived strength of a stimulus may influence the degree of saccadic inhibition triggered. Building on the findings of Glaholt and Reingold (2018), which demonstrated stronger and longer-lasting saccadic inhibition for relevant scenes and enhanced saliency of a flicker stimulus when attention is directed towards it, this study aims to investigate whether the involvement of hand movements in an interception task, through inducing a similar allocation of attention, potentially results in stronger saccadic inhibition.

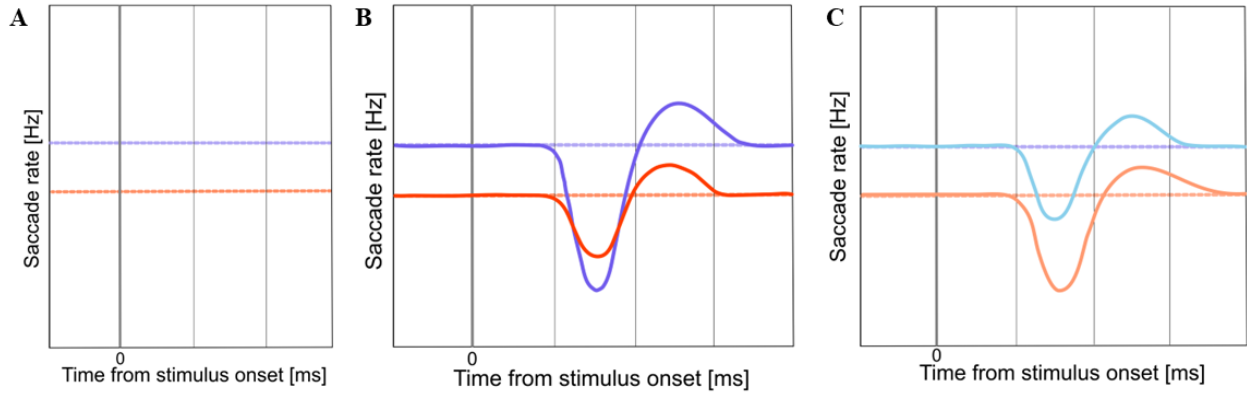
### 1.6 Hypotheses

The purpose of this study is to investigate the saccadic inhibition effect in two different task conditions, the first being an eye movement only task and the second a concomitant eye and hand movement task. The inhibition effect was also investigated in relation to two different kinds of changes in the visual environment, a task relevant jump of the target and a task

irrelevant bright flash that was briefly shown during trials. The saccadic inhibition effect is expected to be triggered both by the task relevant and the task irrelevant stimulus (hypothesis 1) (Kuper & Rolfs, 2024).

Further, based on the research on the phenomenon that gaze tends to lead the hand in concomitant eye and hand movement tasks and that the use of hands has a stabilising effect on the gaze (Koken & Erkelens, 1992; Mrotek & Soechting, 2007; Neggers & Bekkering, 2000), the baseline saccade rate in eye movement only trials should be similar to or higher than the baseline saccade rate in concurrent eye and hand movement trials (hypothesis 2).

Lastly, concerning the influence of the task condition and stimulus type, the magnitude of saccadic inhibition (the ‘dip’) (hypothesis 3) will be examined. The magnitude of inhibition triggered by a task irrelevant stimulus is expected to be greater in eye and hand movement trials compared to gaze only trials. This is hypothesised as the focus of gaze in eye and hand movement trials is expected to be on the areas where a task-irrelevant flash will be shown, as this is the area within which participants are supposed to make an interceptive hand movement. The task irrelevant stimulus might therefore be perceived stronger, resulting in a greater magnitude of inhibition (Glaholt & Reingold, 2018). The magnitude of inhibition triggered by a task relevant stimulus on the other hand is expected to be greater in eyes only trials as gaze is not anticipated to be focused on particular parts of the screen. Instead, gaze would be on the target itself since there is no need to make an interceptive movement in this condition. This is assumed to result in better perception of the task-relevant jump of the target and thus greater magnitude of inhibition. The ‘peak’, representing recovery from inhibition, is expected to be found for all conditions and stimulus types following the ‘dip’ of saccadic inhibition and will be analysed exploratively as an additional intriguing aspect of this study, as this phenomenon remains relatively unexplored. See visualisations of the hypothesised relationships in figure 2.



**Figure 2.** Visualisations of hypotheses 2 and 3. **A** shows the visualisation of the second hypothesis (higher or similar baseline saccade rates in the gaze condition). **B** and **C** show the third hypothesis (greater saccadic inhibition magnitude for irrelevant stimulus in move condition (**B**) and greater saccadic inhibition magnitude for relevant stimulus in gaze condition (**C**). Dashed blue line = baseline gaze condition, dashed orange line = baseline move condition, light blue line = inhibition triggered by irrelevant stimulus in gaze condition, light orange line = inhibition triggered by irrelevant stimulus in move condition, dark blue line = inhibition triggered by relevant stimulus in gaze condition, dark orange line = inhibition triggered by relevant stimulus in move condition.

## 2 Methods

### 2.1 Observers

Twenty-four subjects were recruited for the experiment. Four subjects were excluded because of technical problems and no-shows, replacements were recruited to obtain twenty participants overall. All participants had normal or corrected-to-normal vision and used their right hand for the experiment. They were aged 21 – 41 years (mean = 26.2 years), 8 were self-identified female. All gave written informed consent before testing and were naïve with respect to the aim of this study. The study consisted of two sessions with at least one night between sessions. All participants were compensated with £10 per hour. To incentivise accurate performance participants were informed they could receive a reward of £15 if their performance accuracy was among the top three. This performance bonus was based on accurate hand movements which are not part of the analysis presented here. The study was conducted at the University of Bristol between March and April 2024, and it was approved by the ethics committee of the School of Psychology at the University of Bristol.

### 2.2 Materials

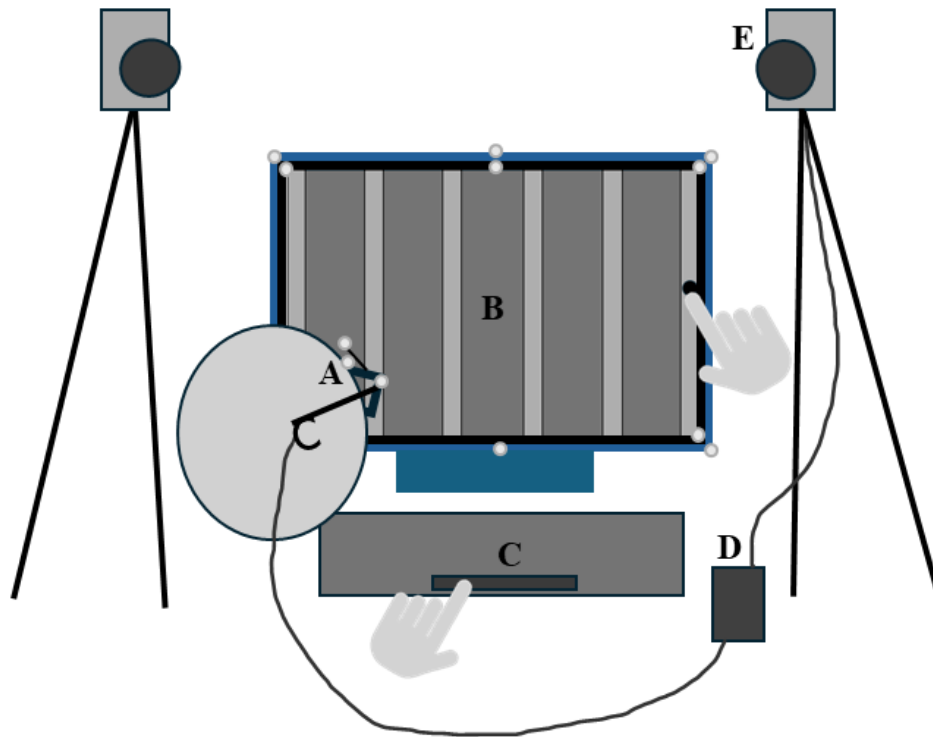
Participants sat in a darkened room in front of the experimental computer. Their head movements were not restricted by a chin rest so that they could move their head around freely during the experiment. On average, the monitor was 51 cm away from the participant.

Eye and hand movements were recorded using passive, optical motion capture with a 12-camera Qualisys (AB, Göteborg, Sweden) System (Oqus 300 cameras), sampling the marker positions at 300 Hz. A Windows 11 computer running the Qualisys Track Manager software (QTM, version 2023.3) controlled onset and offset of recordings and the interface with other equipment used in this study. Calibration of the system was performed daily before data collection.

Participants' gaze was tracked using a head-mounted eye tracker (Tobii Pro Glasses 3, Tobii AB, Sanderyd, Sweden) operating at 50 Hz with data streamed to the Qualisys system via WiFi. Time synchronisation between the Qualisys system and the Tobii glasses was achieved by connecting the Tobii recording unit to one of the Qualisys cameras using a trigger cable. Special markers attached to the eye tracker frame allowed for the tracking of the Tobii glasses.

The experimental stimuli were controlled by a Linux PC (Mint 18 Sarah) running MATLAB R2017 (Mathworks, Natick, MA, USA) with the Psychophysics toolbox 3 (Brainard & Vision, 1997; Kleiner et al., 2007). The experimental PC also sent timing triggers to the Qualisys Motion Capture system through a TCP connection. All experimental stimuli were presented on a ViewPixx 3D Lite monitor with 1920 x 1080 pixels resolution, operating at 120 Hz.

A scheme of the experimental set up is shown in figure 3.



**Figure 3.** The experimental set up. **A** The Tobii Pro Glasses 3 with tracking markers. **B** ViewPixx 3D Lite monitor with tracking markers. **C** The keyboard, participants used the spacebar with their left hand to start a trial. **D** Tobii recording unit, connected to one of the Qualisys cameras by trigger cable. **E** 12-camera Qualisys system surrounding the participant and monitor.

### 2.3 Relevant terms

*Move condition:* This is the term assigned to the concurrent eye and hand movement condition where participants followed the target with their eyes and tried to catch it with their index finger within each catch zone.

*Gaze condition:* This is the term assigned to the gaze-only condition. Participants were instructed to rest their hands and only follow the target with their eyes.

*Task relevant stimulus:* This is the jump, a large positional change of the target along the y axis during its movement along the screen.

*Task irrelevant stimulus:* This is the flash, a brief and bright change of luminance within the catch zone.

*Catch Zone:* These are the lighter coloured areas on screen, in which participants are supposed to intercept the moving target. There are six catch zones in total.

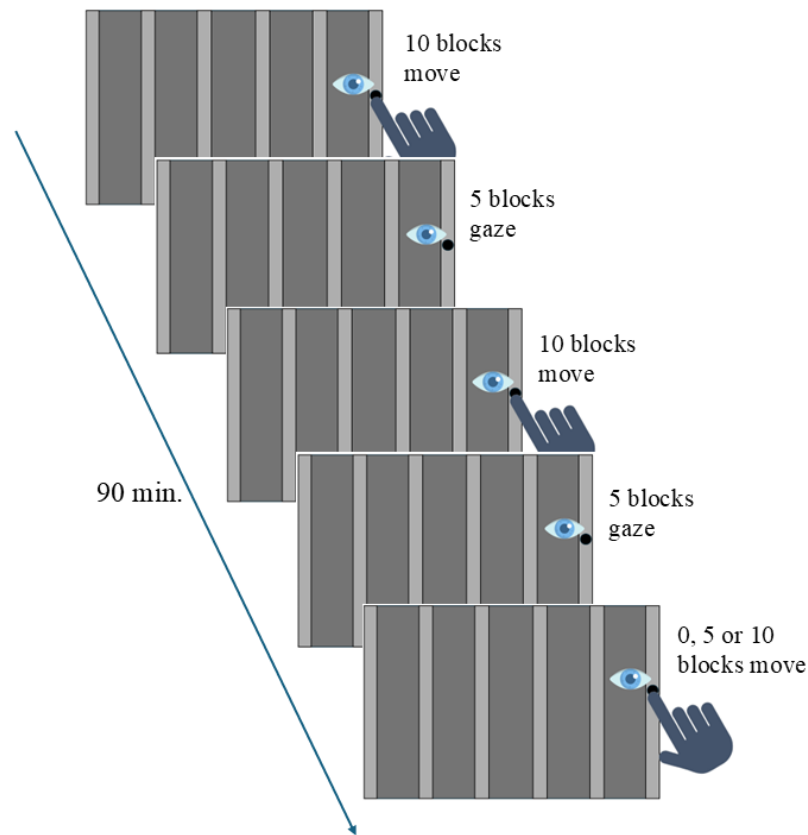
*Observation Zone:* These are the areas in between the catch zones. There are five observation zones in total.

### 2.4 Experimental paradigm

Participants completed 50 move and 20 gaze blocks of 15 trials each. *Move* blocks consisted of concomitant gaze and hand movement trials while the *gaze* blocks were gaze-only trials. 50 blocks of hand movements and 20 blocks of gaze movements were distributed across two sessions alternating between 10 move and 5 gaze blocks. Every session started with move blocks. The last series of move blocks was sometimes shortened from 10 to 5 blocks when time ran out in the first session and there would either be 5 or no more move blocks at the end of the second session accordingly. The interspersed gaze blocks allowed the participants to rest their arms, as the interceptive movements tended to become tiring after some time. Every session took about 90 minutes. Figure 4 shows the block sequence of a session.

Participants started each *move* trial by placing their right index finger on the target (a black dot, 36 pixels in diameter, 1.1 dva (degrees of visual angle) at a mean viewing distance of 51 cm, range = 0.97 – 1.36 dva, 0% luminance) on the farthest right side of the screen. The screen was designed to contain six so-called ‘catch zones’, evenly spaced lighter coloured zones along the screen (72 pixels wide, twice the size of the target, about 2 cm, at 25% luminance) on a dark grey background (20% luminance). The target moved from the right side of the screen to the left, passing through each of the catch zones and taking 4000 ms from start to finish. It moved

along a random walk trajectory derived from pink noise, making its path unpredictable to the participants while encouraging an extrapolation of the targets' path into the future.



**Figure 4.** Block structure. Every Sessions started with 10 move blocks. The amount of move blocks at the end of each session could vary depending on time constraints. Move blocks were interspersed with gaze blocks. Every session took about 1.5 hours.

In the *move* condition, participants were instructed to place their index finger on the target and to press the space bar when they wanted to begin the trial. The target would then start moving and the participants' task was to intercept it by tapping on it whenever it passed through a catch zone. Participants were further instructed to let their index finger rest within each catch zone before moving it again to intercept the target in the next zone and to tap the target quite lightly ('Imagine the target to be a blueberry you want to tap on but not squish.').

In the *gaze* condition trials participants were instructed to rest their arms and hands and to only follow the target with their eyes. They were told to imagine performing the same task as before, but without moving their hand. This was done to minimise the differences in instruction between task conditions ('Mentalise moving your hand and anticipating where the target will cross the catch zone.'). Participants would also begin each gaze trial by pressing the space bar.

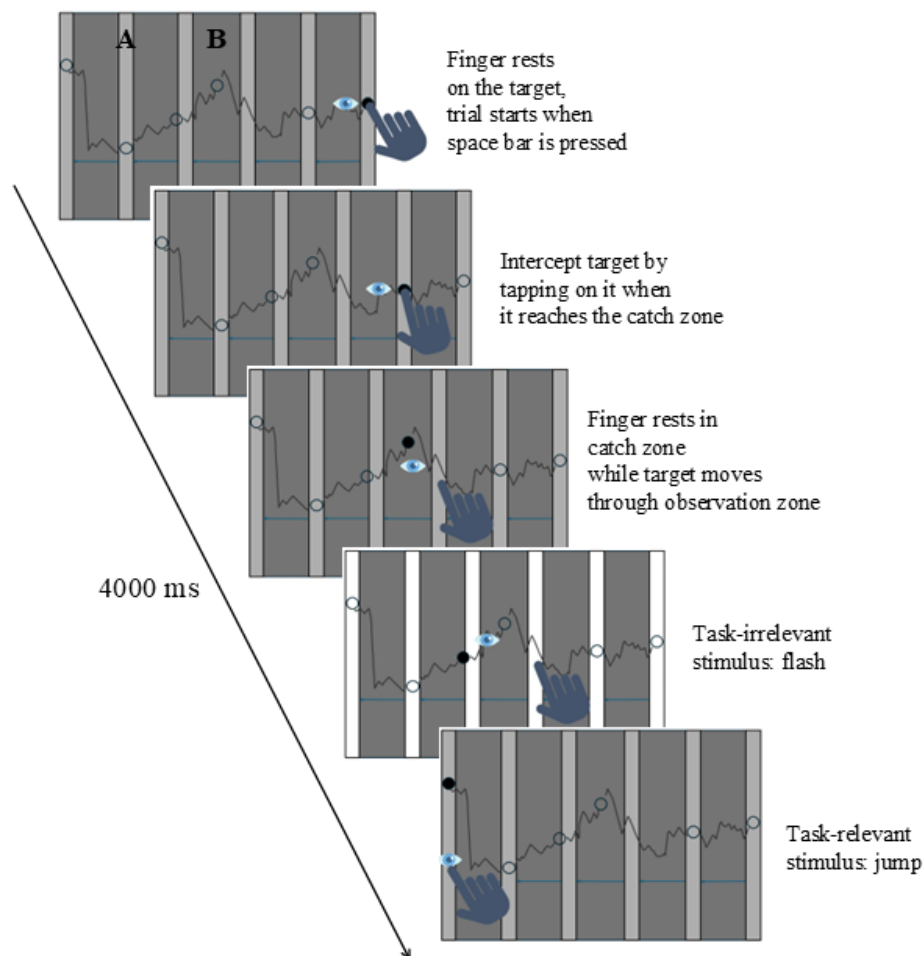
Two changes were programmed to appear in every trial to trigger saccadic inhibition. A very brief bright flash (zones light up to 100% luminance for a duration of 100ms) appearing in each catch zone was the task irrelevant stimulus, as this change in the visual environment did not



interfere with participants' objective to intercept the target. The task relevant stimulus was a jump of the target, implemented by a large positional change along the y axis (target jumped 180 pixels, five times the size of the target). This change was task relevant as it had an impact on the participants' ability to intercept the target at the correct position in the catch zone. The flash and jump would appear randomly during each trial. Within an observation zone there was a 1/3 probability of a jump, flash or nothing being shown. In the first observation zone nothing would ever be shown. On average, 1.2 flashes and 1.2 jumps were shown during a trial. There was never a case where both changes were shown within the same observation zone.

This paradigm was created by Clara Kuper for the project Linking Manual Inhibition and Perceptual Decision Making - How Integration Time Windows Behave Across Salient Changes ([https://osf.io/dkp5t/?view\\_only=40db1897740c47328cb005eccb4b4247](https://osf.io/dkp5t/?view_only=40db1897740c47328cb005eccb4b4247)). The study for this thesis took place within the framework of the overarching project, with the gaze blocks added specifically for this study.

The paradigm and trial sequence are shown in figure 5.

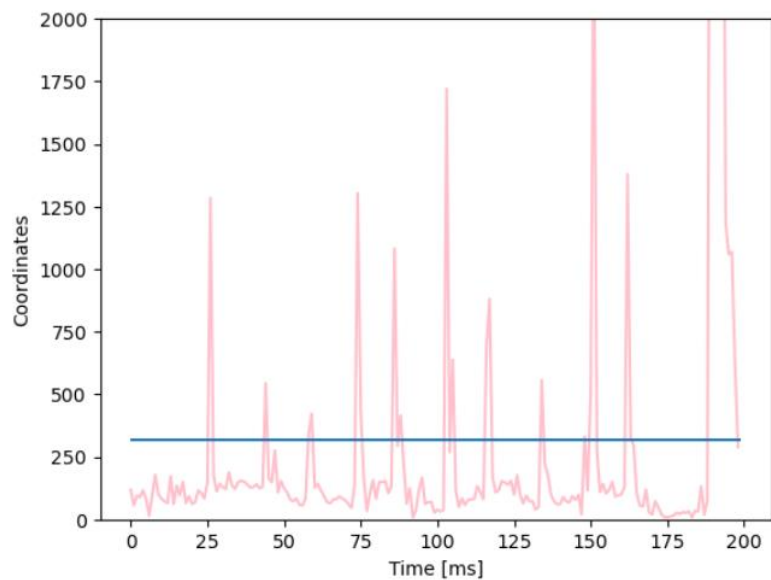


**Figure 5.** Trial sequence and paradigm. **A** shows a catch zone, this is where the target is supposed to be intercepted. **B** shows an observation zone, this is where the participant only observes the target as it moves toward the next catch zone while their index finger rests in the previous catch zone.

## 2.5 Analysis

To map participants' gaze positions onto the screen, the screen was defined as a rigid body within QTM (Qualysis Track Manager), and the screens' rotation matrix in global coordinates was applied to the gaze vector. The intersection of the gaze vector of each eye with the screen was calculated (the point where the z-component of the three-dimensional vector becomes 0). The gaze position was then determined as the average of these two intersection points. In a small subset of trials, only one of the two gaze vectors was available. In those cases, this vector was used to define the location of the gaze on the screen.

To classify participants' eye movement events, the REMoDNaV (Robust Eye Movement Detection for Natural Viewing) (Dar et al., 2021) event classification algorithm was applied to the pre-processed eye movement data. This algorithm was developed with the goal of providing a reliable way of classifying events from viewing dynamic stimuli at variable levels of noise. It includes the identification of saccades using a critical value as the velocity threshold, as well as detecting pursuit and fixation events through the application of a low-pass Butterworth filter. The scaling factor that converts pixel coordinates to degrees of visual angle ('px2deg') was determined by first calculating the median viewing distance for each participant across all blocks. This median distance was then used, along with the screen size and resolution, to compute the appropriate conversion factor and the sampling rate was set to 50 Hz. Another parameter of the algorithm, the size of the Savitzky-Golay filter for noise reduction ('savgol-length'), was adjusted from a default value of 0.019s to 0.06s to account for the sampling rate of 50 Hz. Additionally, the minimum duration of a saccadic event candidate was adjusted from 0.01s

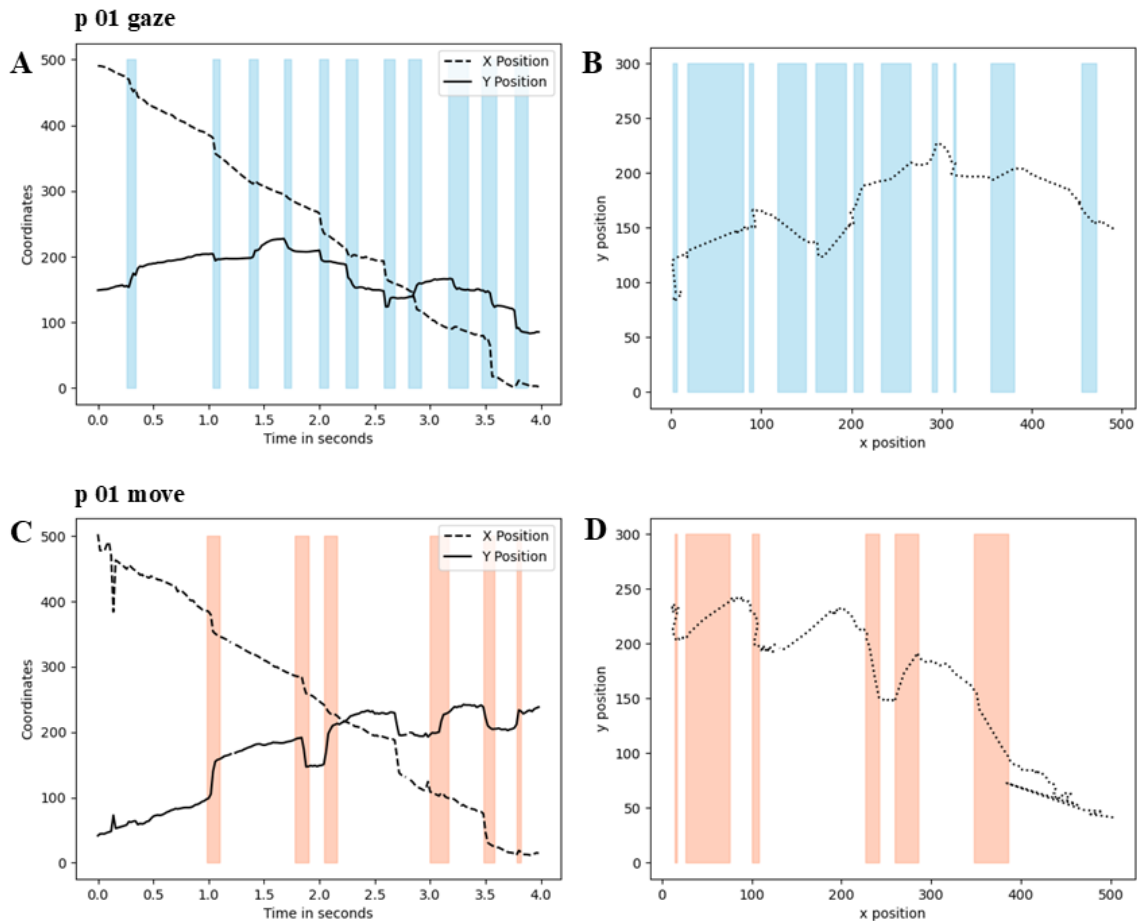


**Figure 6.** Velocity of eye movements. The blue line shows the threshold when the noise factor was set to 3.

to 0.02s and the noise factor ('noise-factor') was adjusted to 3. The appropriate noise factor was determined by plotting velocity graphs for each trial, computing the median noise levels and multiplying it with variable noise factors. The resulting threshold was then visually

inspected to determine which noise factor included the most prominent velocity peaks. An example of a plotted trial with the noise factor set to 3 can be seen in figure 6.

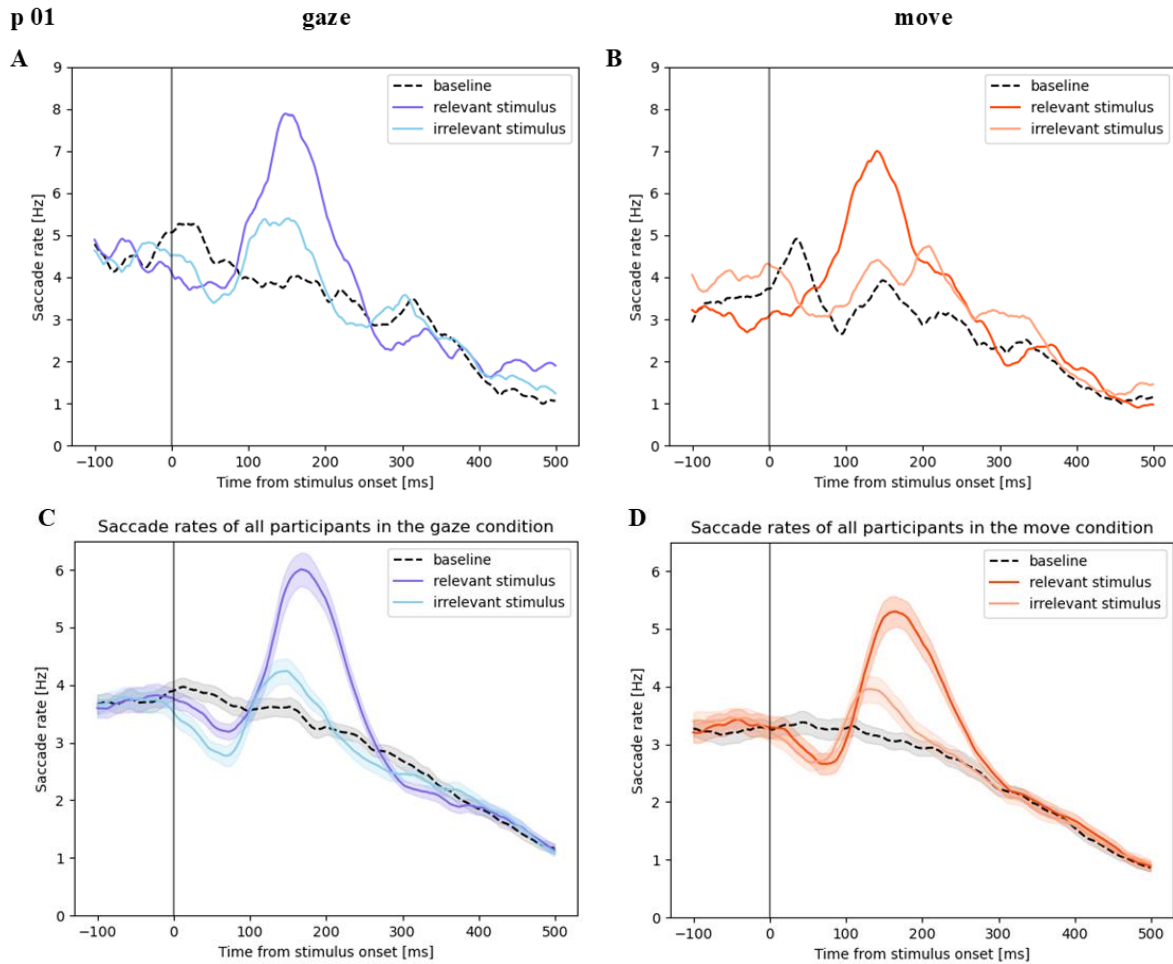
To get an idea of the saccade event patterns, the gaze path and positions on screen were plotted for the gaze and move condition respectively and the start and end of gaze positions of saccade events detected by the REMoDNaV algorithm were added to the visualisation. Plots of example trials can be seen in figure 7.



**Figure 7.** Gaze positions over time and gaze path on screen. **A** shows the x and y coordinates of the participants' gaze across time in the gaze condition. The x position visualises the path of gaze along the x axis of the screen, showing how the gaze moves along the screen following the stimulus from right to left. The y position visualises the path of gaze along the y axis, showing how the gaze follows the stimulus as it changes position along the y axis. **B** shows the combined path of gaze along the x and y axis in the gaze condition, visualising the actual path of the stimulus from the right of the screen to the left. **C** shows the x and y positions of the participants' gaze across time in the move condition. **D** shows the combined path of gaze along the x and y axis in the move condition. Blue and orange boxes indicate the start and end of gaze positions for detected saccades.

An analysis of movement rates using a moving causal kernel (Rolfs et al., 2008) was performed to obtain the saccade rates for the baseline stimulus condition (no relevant or irrelevant stimulus was shown) and for the task relevant (jump shown, no flash shown) and irrelevant (flash shown, no jump shown) stimulus conditions. This analysis was performed for the gaze and move conditions respectively. It computed the rate of saccades within a causal

time window and yielded participants' movement rates (movement onsets per second) adjusted by the number of trials. Saccadic rates for each participant were plotted separately for both conditions and for each stimulus type and then averaged across all trials and participants for the gaze and move condition respectively including the standard error of the mean. Examples for one participants' individual saccade rates and the averaged rates of all participants can be seen in figure 8. The individual rates for all participants are presented in the appendix.



**Figure 8.** Individual and averaged saccade rates. **A** shows the saccade rates for all stimulus types in the gaze condition for participant 01. **B** shows the saccade rates for all stimulus types in the move condition for participant 01. **C** shows the averaged saccade rates for all stimulus types of all participants in the gaze condition. **D** shows the averaged saccade rates for all stimulus types of all participants in the move condition. The black vertical line represents the moment of stimulus onset at 0 ms. Shaded areas show the standard error of the mean.

On average, 293 trials were included in the analysis of the gaze condition (range = 277 – 300). For the move condition, a random sample of about 296 trials from the 750 available ones was selected for analysis ( $M = 296.45$ , range = 281 – 300).

To examine whether saccadic inhibition was triggered by both the task relevant and task irrelevant stimuli, as proposed in hypothesis 1, mean values of saccadic inhibition were first computed for the time frame of 85 to 100 ms. This period has been consistently identified in

research as the window for peak saccadic inhibition (Reingold & Stampe, 2000, 2002, 2004; Salinas & Stanford, 2018). Additionally, the minimum saccadic rate within the 0 to 100 ms time window was computed, ensuring that the dip of saccadic inhibition in the data was captured. This minimum was calculated for both task relevant and irrelevant stimuli, as well as for the baseline, to enable a meaningful comparison between them.

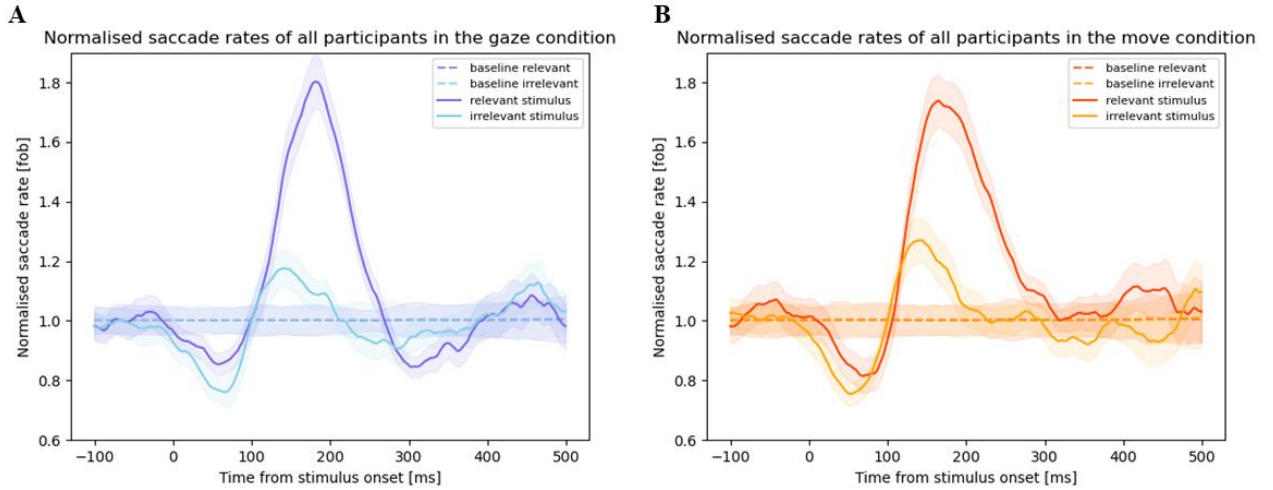
Next, mean saccade rates within the -100 to 0 ms time window were calculated to establish a reliable baseline comparison between the gaze and move conditions, as outlined in hypothesis 2.

Lastly, the saccade rates obtained by the causal rate analysis were normalised to exclude border effects and to attain a relative measure of inhibition. The computation excluded each participants' own data from the normalisation process. This ensured a more unbiased comparison as an independent baseline was created that would not be influenced by the participants' own data. This analysis and others followed analyses described in Kuper & Rolfs, 2024.

The minimum of saccadic inhibition (translating to the maximum of inhibition, the 'dip') was then computed for the normalised data, as well as the latency of this measure. Additionally, size and latency of the peak after saccadic inhibition (or recovery from inhibition) were computed.

This data was subsequently used to conduct repeated measures ANOVAs to determine whether the factors 'condition' (move/gaze) and 'stimulus type' (relevant/irrelevant), or their interaction, significantly influenced the magnitude of saccadic inhibition, as proposed in hypothesis 3. The same method was used to explore the characteristics of the recovery after inhibition. Plots of the normalised data can be found in figure 9.

All statistical analyses, including paired t-tests, repeated measures ANOVAs and post hoc pairwise comparisons, were conducted using the Pingouin statistical package in Python (Vallat, 2018). The code used for all data processing and statistical analyses performed for this study is publicly available at [https://github.com/antoniake/saccadicinhibition\\_bachelor\\_thesis](https://github.com/antoniake/saccadicinhibition_bachelor_thesis). This repository includes all scripts necessary to reproduce the results presented in this thesis. The preregistration of this study can be found at [https://osf.io/qhyft/?view\\_only=30458200710d497491d701e9fc2dcb66](https://osf.io/qhyft/?view_only=30458200710d497491d701e9fc2dcb66).

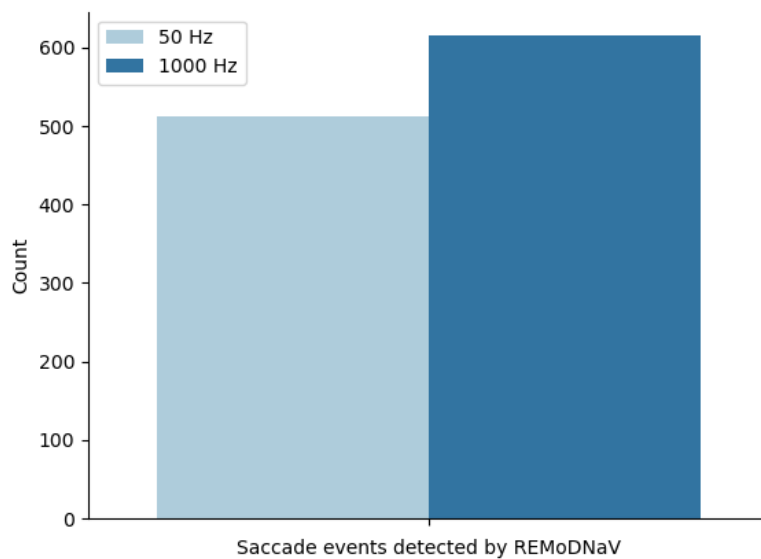


**Figure 9.** Normalised saccade rates of all participants for the move (A) and gaze (B) conditions for all stimulus types. Shaded areas show the standard error of the mean. Shaded areas show the standard error of the mean.

## 2.6 Technical feasibility evaluation of the sampling frequency

To assert whether it was viable to use the Tobii Pro 3 glasses with a sampling frequency of 50 Hz to analyse saccadic rate, a feasibility evaluation was performed. For this purpose, a version of the experiment was implemented on the EyeLink 1000 Plus Tower Mount at the Active Perception and Cognition Group at Humboldt University in Berlin, at a sampling rate of 1000 Hz. The REMoDNaV algorithm used in the analysis of eye movement patterns for this study was also used on the 1000 Hz data which was then down sampled to 50 Hz and run through the algorithm again. The results of this evaluation can be seen in figure 10.

With 83.25% of saccadic events detected in the 50 Hz data compared to the events detected at 1000 Hz, it was concluded that this detection rate was sufficient for the purposes of the study.



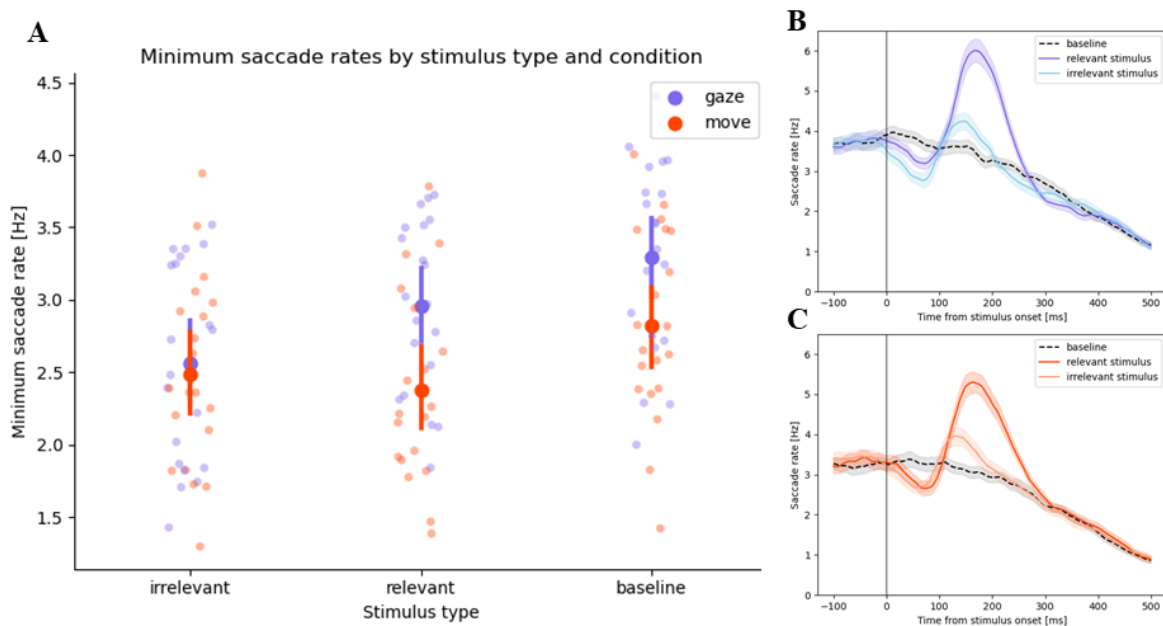
**Figure 10.** Visual comparison of saccadic events detected by REMoDNaV at 1000 Hz (dark blue) and after down sampling to 50 Hz (light blue). REMoDNaV classifies saccades of maximum magnitude as SACC and all other saccades as ISAC. For the purpose of this analysis, they have been merged and labeled ‘saccade events’.

### 3 Results

#### 3.1 The saccadic inhibition effect

To reveal the influence of task relevant and irrelevant stimuli on the saccade rate of participants, the mean minimum saccade rate for both types of stimuli were analysed in both conditions and compared to the baseline. Both stimuli resulted in lower saccade rates in both conditions.

The mean minimum saccade rate in the time window 0 to 100 ms for the gaze condition was  $M = 3.29$  Hz ( $SD = 0.67$ ) for the baseline,  $M = 2.56$  Hz ( $SD = 0.69$ ) for the irrelevant stimulus, and  $M = 2.96$  Hz ( $SD = 0.59$ ) for the relevant stimulus. For the move condition, the mean minimum saccade rate in the above-mentioned time window was  $M = 2.82$  Hz ( $SD = 0.66$ ) for the baseline,  $M = 2.49$  Hz ( $SD = 0.66$ ) for the irrelevant stimulus, and  $M = 2.38$  Hz ( $SD = 0.65$ ) for the relevant stimulus. Plots of these statistics and of the saccade rates can be found in figure 11.



**Figure 11.** A shows the minimum saccade rate in the time window of 0 to 100 ms across stimulus types. Individual data points represent participants' mean saccade rates, with blue points representing the gaze condition and orange points representing the move condition. Superimposed points with error bars indicate the mean and standard error of the mean. B and C show the averaged saccade rates in gaze and move conditions. Shaded areas show the standard error of the mean.

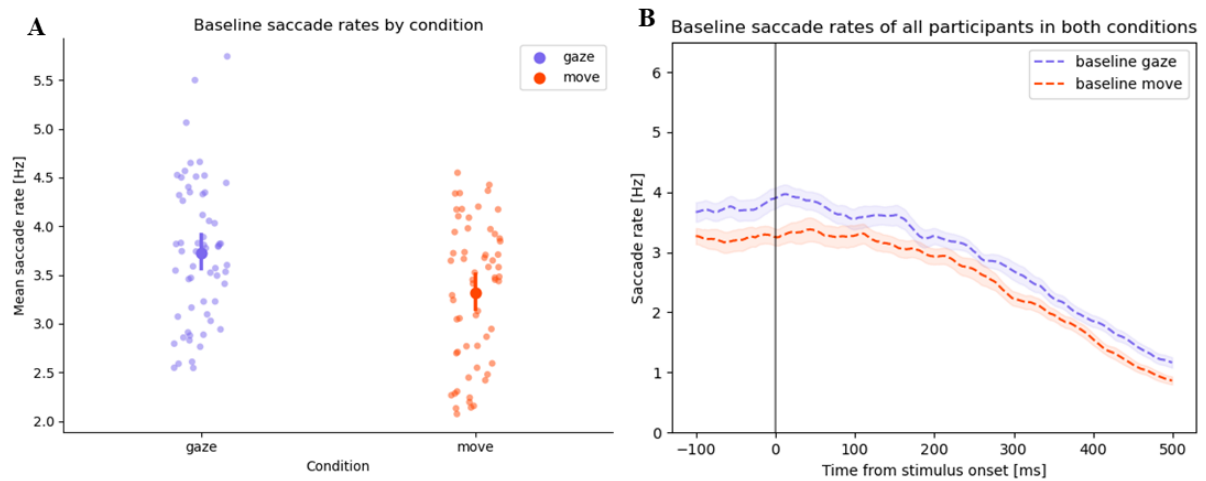
Paired t-tests were performed to determine whether the saccadic inhibition effect was triggered by task relevant and irrelevant stimuli in this experiment. This was done by comparing the minimum saccadic rate for each stimulus type in the time window of 0 to 100 ms against the baseline in the same time window in both the gaze and move conditions.

To ensure the validity of the paired t-tests, the assumption of normality was tested for each combination of condition and stimulus type using the Shapiro-Wilk test. Results indicated that the assumption of normality was satisfied for all combinations with all p-values exceeding .05.

Significant differences between relevant stimulus trials and baseline, as well as between irrelevant stimulus trials and baseline, were found in both the gaze (relevant:  $t(19) = -4.12, p < .001$ ; irrelevant:  $t(19) = -7.96, p < .001$ ) and move condition (relevant:  $t(19) = -3.53, p < .001$ ; irrelevant:  $t(19) = -3.11, p < .001$ ). These results indicate that both relevant and irrelevant stimuli led to significantly lower saccadic rates compared to baseline in both conditions, suggesting that saccadic inhibition was triggered by both types of stimuli. The effect sizes were medium to large, with Cohen's d values for the gaze condition of 0.53 and 1.07, and for the move condition of 0.68 and 0.51, for the relevant and irrelevant stimuli, respectively.

### 3.2 Baseline comparison

To assess the impact of gaze and move conditions on saccadic eye movement patterns, we analysed baseline saccade rates in both scenarios. Specifically, we compared baseline saccade rates to determine how they differed between tasks involving only eye movements and those requiring both eye and hand coordination, as outlined in hypothesis 2.



**Figure 12.** **A** shows the mean saccade rate in the baseline time window of -100 to 0 ms in gaze and move conditions. Individual data points represent participants' mean saccade rates, with blue points representing the gaze condition and orange points representing the move condition. Superimposed points with error bars indicate the mean and standard error of the mean. **B** shows the averaged baseline saccade rates of all participants plotted over time in gaze and move conditions with the vertical black line representing stimulus onset at 0 ms. Shaded areas show the standard error of the mean.

The mean saccade rate in the baseline time window of -100 to 0 ms for the gaze condition was  $M = 3.73$  Hz ( $SD = 0.73$ ) and  $M = 3.32$  Hz ( $SD = 0.72$ ) for the move condition. Plots of these statistics and of the baseline saccade rates can be found in figure 12.

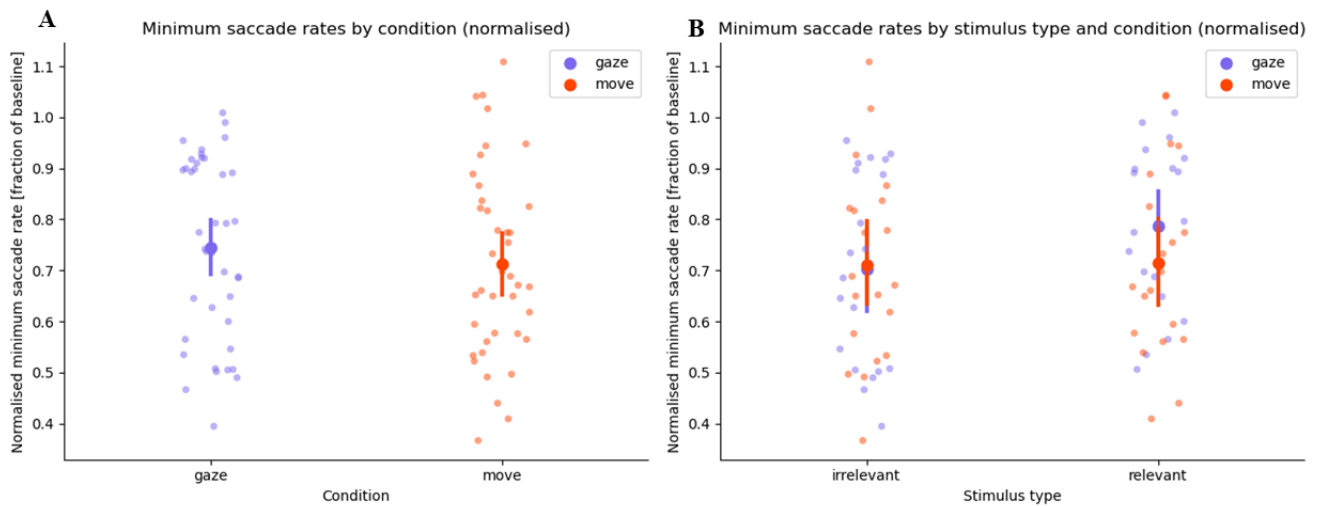


Another paired t-test was conducted to determine whether participants' baseline saccade rate in the gaze condition was higher than in the move condition. Mean saccade rates in the baseline time window of -100 to 0 ms were compared between conditions. The differences between the baseline saccade rates in the gaze and move conditions were significant,  $t(59) = -4.79, p < .001$ . The effect size was medium, with a Cohen's  $d$  value of 0.57.

### 3.3 Concomitant eye and hand movements

To further investigate the dynamics of saccadic inhibition under different task conditions, normalised saccade rate data was used to perform repeated measures ANOVAs. After normalisation, all saccade rates are expressed as a fraction of the baseline (f.o.b.). This analysis aimed to explore how the gaze and move conditions, along with task relevance of the stimulus, influenced the magnitude and timing of saccadic inhibition and of the recovery from inhibition.

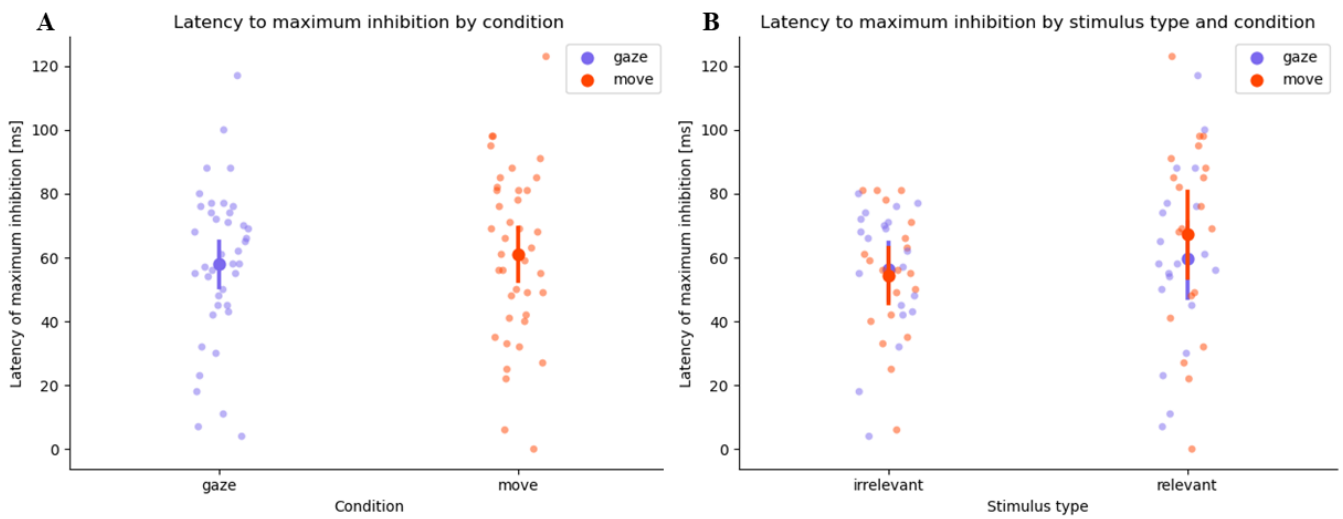
#### 3.3.1 Magnitude of saccadic inhibition



**Figure 13.** **A** shows the mean normalized minimum saccade rates in gaze and move conditions. **B** additionally shows the mean normalized minimum saccade rates for both stimulus types. Individual data points represent participants' normalised saccade rates, with blue points representing the gaze condition and orange points representing the move condition. Superimposed points with error bars indicate the mean and standard error of the mean.

The mean normalised minimum saccade rate in the time window of 0 to 200 ms for the gaze condition was  $M = 0.66$  fraction of baseline (f.o.b.) ( $SD = 0.16$ ) for the irrelevant stimulus and  $M = 0.78$  f.o.b. ( $SD = 0.18$ ) for the relevant stimulus. In the move condition, the mean normalised minimum saccade rate in the same time window was  $M = 0.71$  f.o.b. ( $SD = 0.18$ ) for the irrelevant stimulus and  $M = 0.72$  f.o.b. ( $SD = 0.21$ ) for the relevant stimulus. Plots of these statistics can be found in figure 13.

Rather than focusing on the movement rate at its minimum – the proportion of saccades that continue to occur – we can also examine the size of inhibition, which reflects the proportion of saccades that are suppressed. This can be done by measuring the difference between the rate and the baseline. Given that the normalised baseline is set to 1, the size of inhibition can be determined by subtracting the normalised rate from 1. The mean maximum of saccadic inhibition in the gaze condition was  $M = 0.34$  f.o.b. ( $SD = 0.16$ ) for the irrelevant stimulus and  $M = 0.22$  f.o.b. ( $SD = 0.18$ ) for the relevant stimulus. In the move condition, the mean maximum of saccadic inhibition was  $M = 0.30$  f.o.b. ( $SD = 0.18$ ) for the irrelevant stimulus and  $M = 0.28$  f.o.b. ( $SD = 0.21$ ) for the relevant stimulus. Plots of these statistics can be found in figure 14.



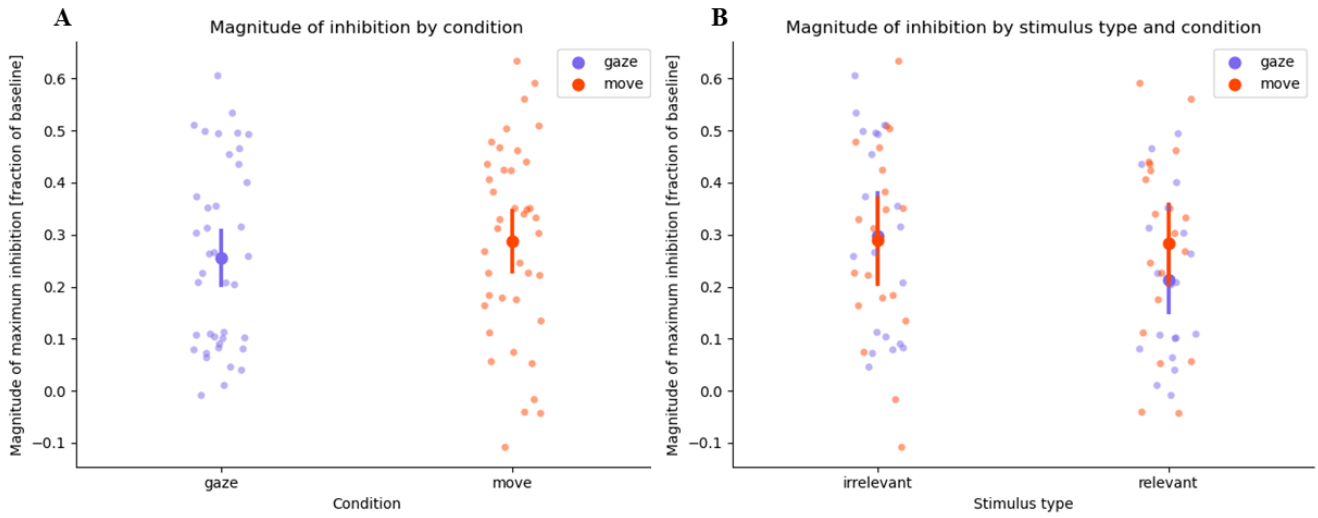
**Figure 14.** **A** shows the mean magnitude of saccadic inhibition in gaze and move conditions. **B** additionally shows the mean magnitude of saccadic inhibition for both stimulus types. Individual data points represent participants' inhibition magnitudes, with blue points representing the gaze condition and orange points representing the move condition. Superimposed points with error bars indicate the mean and standard error of the mean.

The mean latency of maximum inhibition, defined as the time from stimulus onset to the maximum of saccadic inhibition, in the gaze condition was  $M = 64.60$  ms ( $SD = 16.15$  ms) for the irrelevant stimulus and  $M = 53.80$  ms ( $SD = 33.38$  ms) for the relevant stimulus. In the move condition, the mean latency of maximum inhibition was  $M = 60.45$  ms ( $SD = 14.46$  ms) for the irrelevant stimulus and  $M = 66.35$  ms ( $SD = 29.32$  ms) for the relevant stimulus. Plots of these statistics can be found in figure 15.

A repeated measures ANOVA was performed to assess the effects of the within-subject factors 'condition' (gaze and move) and 'stimulus type' (relevant and irrelevant) on the dependent variable 'magnitude of maximum saccadic inhibition' as well as their interaction.

Prior to performing the repeated measures ANOVA, the assumptions of normality and sphericity were evaluated. The results of a Shapiro-Wilk test indicated that the normality

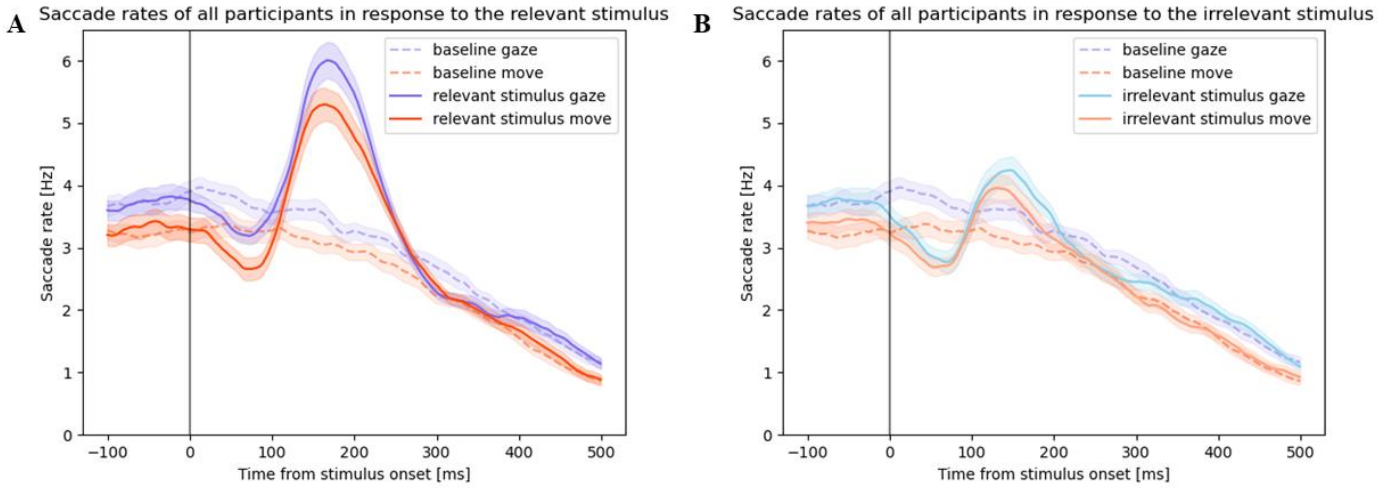
assumption was met, with all  $p$ -values exceeding .05. Mauchly's test of sphericity suggested that sphericity was not violated, with all  $p$ -values greater than .05.



**Figure 15.** **A** shows the mean latency to the maximum of saccadic inhibition in gaze and move conditions. **B** additionally shows the mean latency to the maximum of saccadic inhibition for both stimulus types. Individual data points represent participants' inhibition latencies, with blue points representing the gaze condition and orange points representing the move condition. Superimposed points with error bars indicate the mean and standard error of the mean.

There was no significant main effect of condition on the maximum of saccadic inhibition,  $F(1,19) = 0.04$ ,  $p = .845$ ,  $\eta^2 = .0004$ , suggesting that the type of task (gaze or move) did not significantly affect the magnitude of maximum inhibition. However, there was a significant main effect of stimulus type,  $F(1,19) = 9.35$ ,  $p = .006$ ,  $\eta^2 = .035$ . The interaction between condition and stimulus type was significant ( $F(1,19) = 8.54$ ,  $p = .009$ ,  $\eta^2 = .027$ ). This interaction suggests that the effect of stimulus type on saccadic inhibition may vary depending on whether the task involves eye movements alone or a combination of eye and hand movements. Plots of the saccade rates for the relevant and irrelevant stimulus respectively can be seen in figure 16.

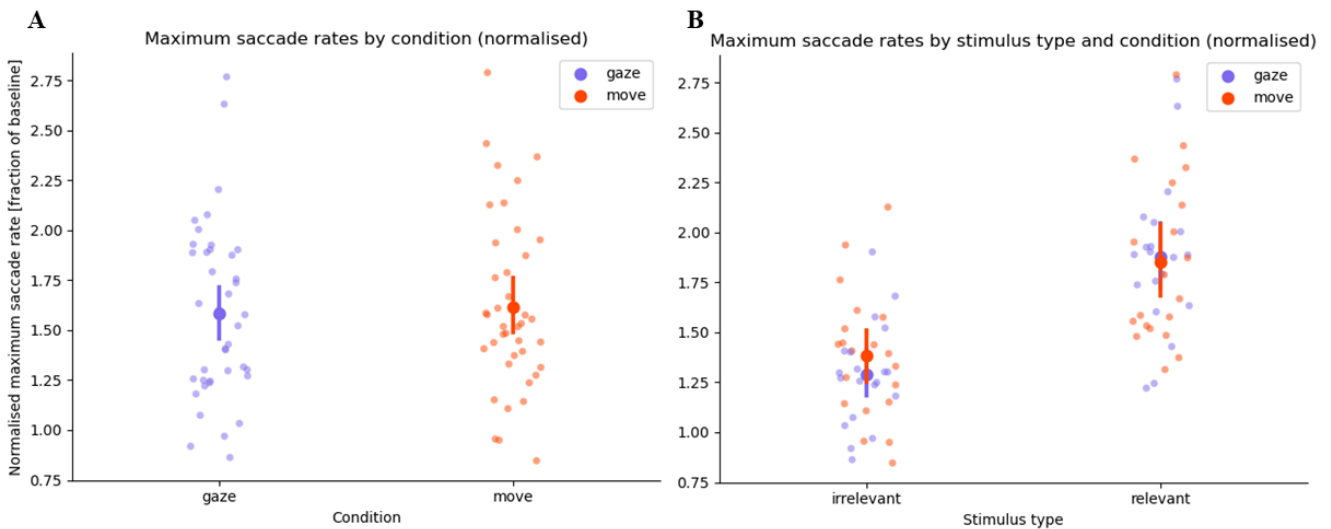
Post hoc pairwise comparisons using the Bonferroni correction were performed following the significant interaction between condition and stimulus type. The difference in the magnitude of maximum inhibition between the gaze and move conditions was not significant,  $t(19) = -1.00$ ,  $p = .328$ . There was a significant difference in the magnitude of maximum inhibition between the task relevant and irrelevant stimuli, with the irrelevant stimuli resulting in greater inhibition,  $t(19) = 2.32$ ,  $p = .032$ . In the gaze condition, task irrelevant stimuli led to significantly greater inhibition than task relevant stimuli,  $t(19) = 3.11$ ,  $p = 0.011$ . In the move condition, the difference between task relevant and irrelevant stimuli was not significant,  $t(19) = 0.22$ ,  $p = .826$ .



**Figure 16.** **A** shows the saccade rates of all participants in response to the relevant stimulus and for the baseline in gaze and move conditions. **B** shows the saccade rates of all participants in response to the irrelevant stimulus and for the baseline in gaze and move conditions. Shaded areas show the standard error of the mean.

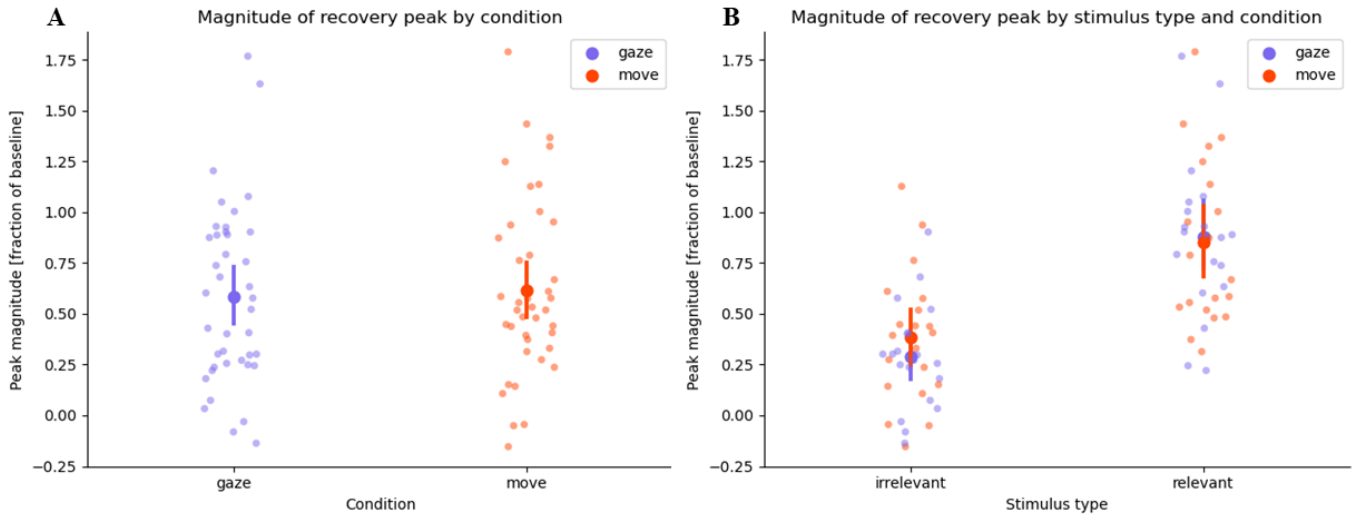
### 3.3.2 Recovery from inhibition

To analyse the recovery from saccadic inhibition, the time window of 100 to 300 ms was used. The mean normalised maximum saccade rate in this timeframe for the gaze condition was  $M = 1.29$  f.o.b. ( $SD = 0.26$ ) for the irrelevant stimulus and  $M = 1.88$  f.o.b. ( $SD = 0.38$ ) for the relevant stimulus. In the move condition, the mean normalised maximum saccade rate in the same time window was  $M = 1.38$  f.o.b. ( $SD = 0.32$ ) for the irrelevant stimulus and  $M = 1.85$  f.o.b. ( $SD = 0.41$ ) for the relevant stimulus. Plots of these statistics can be found in figure 17.



**Figure 17.** **A** shows the mean normalized maximum saccade rates in gaze and move conditions. **B** additionally shows the mean normalized maximum saccade rates for both stimulus types. Individual data points represent participants' normalised maximum saccade rates, with blue points representing the gaze condition and orange points representing the move condition. Superimposed points with error bars indicate the mean and standard error of the mean.

Analogous to the analysis of the magnitude of saccadic inhibition, the maximum movement rate can be expressed as the peak magnitude. The mean peak magnitude in the gaze condition was  $M = 0.29$  f.o.b. ( $SD = 0.26$ ) for the irrelevant stimulus and  $M = 0.88$  f.o.b. ( $SD = 0.38$ ) for the relevant stimulus. In the move condition, the mean peak magnitude was  $M = 0.38$  f.o.b. ( $SD = 0.32$ ) for the irrelevant stimulus and  $M = 0.85$  f.o.b. ( $SD = 0.41$ ) for the relevant stimulus. Plots of these statistics can be found in figure 18.

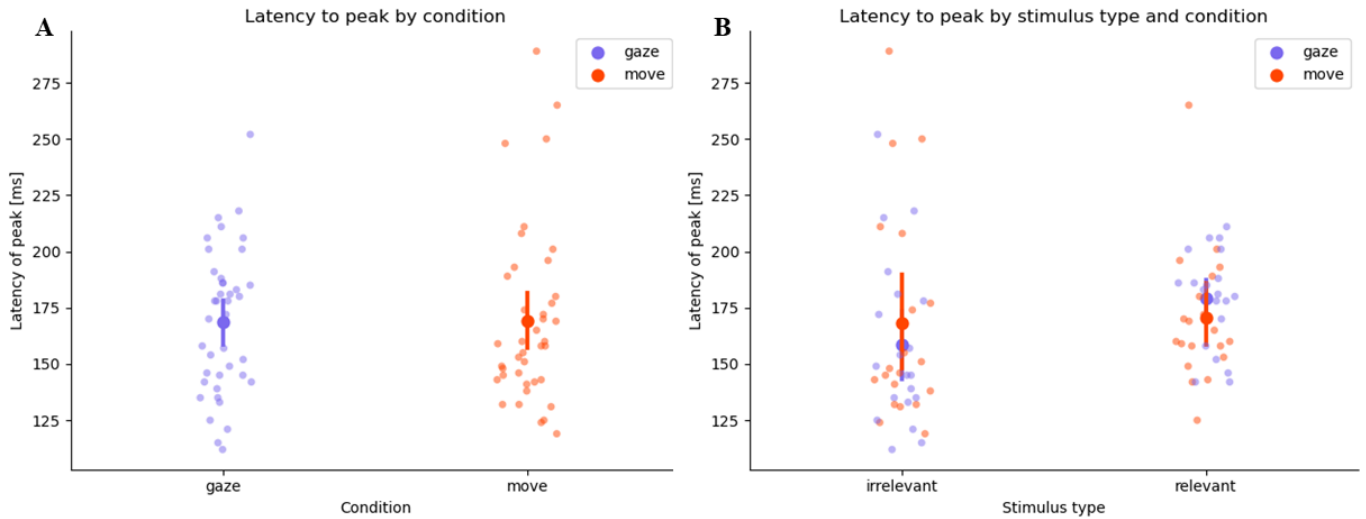


**Figure 18.** A shows the mean peak magnitude, representing recovery from inhibition, in gaze and move conditions. B additionally shows the mean peak magnitude for both stimulus types. Individual data points represent participants' peak magnitudes, with blue points representing the gaze condition and orange points representing the move condition. Superimposed points with error bars indicate the mean and standard error of the mean.

The mean latency of the maximum peak, defined as the time from stimulus onset to the point of maximum recovery after inhibition, in the gaze condition was  $M = 158.60$  ms ( $SD = 37.55$  ms) for the irrelevant stimulus and  $M = 179.00$  ms ( $SD = 21.48$  ms) for the relevant stimulus. In the move condition, the mean latency of the maximum peak was  $M = 168.10$  ms ( $SD = 47.99$ ) for the irrelevant stimulus and  $M = 170.35$  ms ( $SD = 29.52$  ms) for the relevant stimulus. Plots of these statistics can be found in figure 19.

A repeated measures ANOVA was performed to assess the effects of the within-subject factors 'condition' (gaze and move) and 'stimulus type' (relevant and irrelevant) on the dependent variable 'peak magnitude' as well as their interaction.

Prior to performing the repeated measures ANOVA, the assumptions of normality and sphericity were evaluated. The results of a Shapiro-Wilk test indicated that the normality assumption was met, with all p-values exceeding .05. Mauchly's test of sphericity suggested that sphericity was not violated, with all p-values greater than .05.



**Figure 19.** **A** shows the mean latency to the peak of recovery in gaze and move conditions. **B** additionally shows the mean latency to the peak of recovery for both stimulus types. Individual data points represent participants' peak latencies, with blue points representing the gaze condition and orange points representing the move condition. Superimposed points with error bars indicate the mean and standard error of the mean.

There was no significant main effect of condition on the peak magnitude,  $F(1,19) = 0.38$ ,  $p = 0.544$ ,  $\eta^2 = 0.002$ . There was, however, a significant main effect of stimulus type,  $F(1,19) = 121.34$ ,  $p < .01$ ,  $\eta^2 = 0.38$ , suggesting that the task relevance of the visual change had a significant effect on the magnitude of the peak. The interaction between condition and stimulus type was not significant,  $F(1,19) = 3.37$ ,  $p = 0.082$ ,  $\eta^2 = 0.008$ . Although this p-value is above the conventional threshold of .05, it suggests a trend that might be worth exploring further in future research. Plots of the saccade rates for the relevant and irrelevant stimulus and of the peak after inhibition can be seen in figure 16.

Post hoc pairwise comparisons using the Bonferroni correction were performed following the significant result of the repeated measures ANOVA. Stimulus type had a significant impact on peak magnitude,  $t(19) = -11.02$ ,  $p < .01$ , with the result suggesting that the task relevant stimulus resulted in higher peaks than the irrelevant one.

## 4 Discussion

The aim of this research was to investigate the phenomenon of saccadic inhibition under different task conditions, specifically comparing tasks that involved only eye movements with those that required both eye and hand movements, and exploring whether the presence of concomitant hand movements would have an influence on the characteristics of the inhibition effect. This was further investigated in relation to task relevance of environmental visual changes, depicted as a task relevant jump of the visual target and a task irrelevant bright flash in the visual field. The central question guiding this study was how eye and hand coordination would impact the processing of sudden visual changes, a topic with important implications for understanding the interplay between the oculomotor and limb motor systems in everyday tasks.

The main questions that were addressed in this thesis were whether saccadic inhibition is triggered by both task relevant and task irrelevant stimuli in different task conditions (hypothesis 1), how eye movement patterns, particularly saccade rates, would differ between the eye movement only and combined eye and hand movement tasks (hypothesis 2), and how the magnitude of saccadic inhibition varies based on task condition and stimulus relevance (hypothesis 3). Additionally, this study aimed to examine the less explored aspect of the saccadic inhibition phenomenon, the recovery period after saccadic inhibition, also known as the ‘peak’ (hypothesis 4). This was done to better understand what happens when the visual system recovers from inhibition in response to different kinds of stimuli and under differing task conditions.

The results of this study provide evidence that the saccadic inhibition effect occurs in response to both task relevant and irrelevant stimuli, as evidenced by the significant reduction in saccadic rates compared to the baseline for both types of stimuli (figure 10). This supports previous findings, that saccadic inhibition is a robust effect triggered by visual stimuli irrespective of their relevance to the task at hand (Glaholt & Reingold, 2018; Reingold & Stampe, 2000, 2002). The effect was also found to happen in both task conditions, one involving only following the target with the eyes and the other additionally involving intercepting the target with the hand.

The evidence provided here aligns with prior research that a combination of eye and hand movements tends to smooth out eye movement patterns, resulting in fewer saccades, as reflected in the lower saccade rate baseline in the move condition compared to the gaze condition (figure 11B) (Mrotek & Soechting, 2007; Neggers & Bekkering, 2000). This was also shown to be the case for a target moving along a random walk trajectory derived from pink

noise, which can be considered unpredictable while still encouraging participant to try and intercept the target. These results extend the findings of Koken & Erkelens (1992), who found the smoothing of eye movement patterns in a task involving the eyes and hands when tracking a predictably moving target but could not find the same for unpredictable pseudo-random target movements (Koken & Erkelens, 1992).

#### 4.1 Magnitude of saccadic inhibition

The task condition, whether the participants only used their eyes to track the target or also used their hands to make an interceptive movement, had no significant influence on the magnitude of saccadic inhibition. However, the relevance of the visual change significantly affected it, resulting in greater magnitude of saccadic inhibition for the irrelevant stimulus, the bright flash. Interestingly, the interaction between the task condition and relevance of the stimulus was also significant, suggesting that the effect of stimulus type on saccadic inhibition may vary depending on whether the task involves eye movements alone or a combination of eye and hand movements. While the magnitude of inhibition was significantly greater for the irrelevant stimulus in the gaze condition, no such significant difference between stimulus types was found for the move condition. This highlights a potential varied sensitivity of the oculomotor system under different motor demands. The task involving concomitant eye and hand movements appears to be more challenging and the complexity of this task condition might have led to the result of greater saccadic inhibition magnitude in response to the irrelevant stimulus in the gaze condition as opposed to the move condition since the involvement of the hands would present a higher cognitive demand due to the need of coordinated motor actions. This might leave less cognitive capacity for the oculomotor system to perceive and process the inhibition triggering stimulus in this task condition.

In short, there is no evidence for the hypothesis that differences in the allocation of attention in the two types of conditions influence the magnitude of saccadic inhibition for the different types of stimuli. It was expected to find greater inhibition for the irrelevant stimulus in the move condition, where participants would be incentivised to focus more on the catch zones, the area where the irrelevant stimulus appears, to be able to accurately intercept the target. Instead, the only significant difference was found for the gaze condition, where the irrelevant stimulus caused greater saccadic inhibition. However, the level of task complexity appears to influence inhibition, presenting an unexpected finding that warrants further exploration. It would be informative to include in the analysis the locus of fixation of the participants in relation to the



visual change to explore whether this would explain more about the variance of the magnitude of inhibition.

#### 4.2 Recovery from inhibition

The ‘peak’ of saccade rates observed after saccadic inhibition is a consistent effect, representing a rebound in saccade rates after inhibition. This rebound often exceeds the baseline saccade rate before returning to the original levels and has been shown to be more variable across participants compared to the ‘dip’ of saccadic inhibition (Reingold & Stampe, 2004). Reingold & Stampe (2004) showed an increase in peak area after larger displacements of a target, which also corresponded with a greater magnitude of inhibition. They also showed that a flicker produced larger inhibition magnitude as well as peak area. In this thesis, while the relevant stimulus (a jump of the target) did result in larger peak magnitudes, the saccadic inhibition was greater for the irrelevant stimulus (the bright flash).

The difference in peak magnitude following a relevant versus irrelevant stimulus was highly significant, with consistently greater peak magnitudes observed after the relevant stimulus in both conditions (figure 9). This effect demonstrates how movement plans, as reflected in peak magnitude, vary according to the demands imposed by specific stimuli, such as a positional change of the target, on the visual system. The interaction of condition and stimulus type was not significant by conventional standards. However, this result may still suggest a potential effect that could be relevant, particularly if explored with a larger sample size or improved eye-tracking sampling frequency, which might yield more definitive outcomes. This possible interaction may indicate that the effect of stimulus type on the recovery period after inhibition, much like its effect on inhibition magnitude, could vary depending on whether the task involves only eye movements or a combination of eye and hand movements.

The ‘peak’ represents all eye movements for which the motor plans did not yet exist when saccadic inhibition was triggered and all those for which the motor plans were delayed. These movements would have never been made, had inhibition not taken place. These findings emphasise the importance of the ‘pause’ created by the inhibition effect, preparing the visual system to react to unexpected visual changes in the environment and enabling us to perform adequate eye movements without wasting time on outdated information. The significantly more pronounced effect on the peak magnitude after a jump of the target compared to a much smaller peak after a task irrelevant flash reiterates that the peak encompasses all new motor actions that are computed to be able to catch up with the new location of the target.

These results also demonstrate the tight relationship between the saccadic inhibition effect and the period of recovery following inhibition and suggest that these two phenomena are part of a resourceful system to help us navigate our ever-changing surroundings. To learn more about the nature of movement plans contained within the peak would be an important addition to the knowledge that already exists about the inhibition of movements. Future research could explore how the magnitude of the peak changes with differing characteristics of stimuli or magnitudes of positional changes and where exactly the newly planned movements go, especially when considering varying oculomotor and limb motor demands on the system.

#### 4.3 Limitations

The set up of this experiment provided somewhat more ecologically valid conditions to run an eye tracking study than is typically the case in this area of research. The lack of a chin rest, while enabling participants to move more freely during the experiment, however, might have led to more variability in the eye movement data collected that would be due to head movements and not the variables of interest. This also led to inconsistent viewing distances between and within subjects, affecting the perceived size and position of stimuli. When participants are closer to the screen it would cause the flash to fill more area of their visual field, the target would appear bigger, and the jump of the target would have a relatively larger effect on the retina. This was accounted for in the calculations of the individual viewing distances in preparation of the eye movement pattern analysis but could be explored further, for instance by additionally looking at the inhibition effect as a function of viewing distance.

Concerning ecological validity, the use of stimuli of varying luminance only in an experiment that is conducted on a screen in a completely dark room does not represent real world conditions, especially when investigating the impact of changes in the visual environment. The complexity of visual processing in naturalistic settings should be more of a focus in today's vision research, especially since the introduction of portable eye trackers.

The eye tracker used in this study operates at 50 Hz. This does not provide sufficient sampling frequency to capture all saccadic eye movements made, given that typical saccades last for about 20 – 30 ms. Critical details of eye movement patterns might be missed due to this. However, a technical feasibility evaluation was conducted prior to data collection, resulting in a satisfactory comparison between the saccadic events detected by the algorithm in the 50 Hz and 1000 Hz data.

Additional variability in the data of the move condition could have been introduced by participants' fatigue from having to perform an eye hand coordination task, which imposes a

higher cognitive demand than the gaze only task. Furthermore, participants could have been distracted by their hand movements, influencing the magnitude of saccadic inhibition. Participants also reported that their arms would tire after some time, which is why the alternating order of move and gaze blocks was introduced.

The greatest constraint of the present study, especially for interpreting the timeframe of saccadic inhibition, comes from an unresolved issue with data transmission from the QTM (Qualysis Track Manager). The timing of saccadic inhibition appears to be shifted forward in the data used for the analyses at hand, resulting in latencies that conflict with the established literature by a few tens of milliseconds. This, however, does not conflict with the rest of the analyses that have been done.

Further analyses should be done to examine the direct interplay of gaze focus and saccadic inhibition. Future investigation could assess the magnitude of inhibition and the resulting recovery period when gaze is directly on the sudden change in the visual field.

#### 4.4 Conclusion and outlook

In the study, the phenomenon of saccadic inhibition was investigated under different task conditions and for varying task relevance of the inhibition triggering stimulus. From these findings it is evident that saccadic inhibition is a robust mechanism, triggered by both task relevant and irrelevant stimuli across different oculomotor and limb motor demands. The results demonstrate that the magnitude of saccadic inhibition and the following period of recovery from that inhibition are impacted significantly by task complexity and relevance of the stimulus to the task at hand. These findings highlight the importance of considering complexity and motor demands when studying saccadic inhibition.

It has been shown that the visual stability provided by the inhibition of saccades improves detection abilities (Denison et al., 2019) and that lower saccade rates are related to improved detection of very short visual asynchronies (Foerster et al., 2023). A deeper understanding of the inhibition effect – particularly how its magnitude and subsequent recovery from inhibition depend on task complexity – should be considered when developing training programmes involving quick reflexes or coordination of different motor systems. Additionally, this knowledge can aid in the creation of more immersive and intuitive human-machine interactions by considering the interplay between visual attention, task complexity and responses to sudden changes in the visual field. In the ever-evolving field of virtual reality and user interface design, integrating insights about how visual stimuli influence saccadic inhibition is crucial. This integration can help prevent unwanted saccadic inhibition or incorporate its purposeful

application to optimises reaction times and reactions to visual changes, thereby enhancing overall user experience.

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## Appendix

