Visual Comfort of the Head Mounted Display in the F35

- Master Thesis -

By: Sofie Hoving

Student number: 3978141

E-mail: sofiehoving@gmail.com

Master: Applied Cognitive Psychology (TCP)

Guided by: Lex Toet (lex.toet@tno.nl) &

Frank Kooi (frank.kooi@tno.nl)

Company: TNO Soesterberg

ECT's: 27,5

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Master Supervisor: *Dr. I. Hooge (I.Hooge@uu.nl)*

Master Second Supervisor: *Dr. J. S. Benjamins (J.S.Benjamins@uu.nl)*

Abstract

The F35 is the first jet to fly with a Head Mounted Display (HMD) instead of a Head Up Display (HUD). The HMD is built into the helmet of the pilot. Previous research has shown that eye complaints are a potential limitation while using a HMD. Therefore, research towards visual comfort is of great importance for HMD usage. We examine the influence of symbol eccentricity (15, 30 or 45 deg), spacing (small, medium or large) and polarity (same or opposite) on task performance and visual comfort. Participants' eye strain and health complaints were obtained before, during and after the experiment, by using questionnaires. Task performance (reaction time (RT) and percentage correct responses) was measured throughout the experiment. Results show a main effect for the RT of both the eccentricity and spacing condition and participants reported a significant increase of health complaints. The degree of eye strain, however, did not show a significant effect, i.e. neither increased nor decreased as the experiment progressed. In conclusion, the eccentricity that optimizes the RT, degree of eye strain and health complaints (i.e. an eccentricity with a maximum of 30 deg) should be taken into account when using the HMD's.

Introduction

Over the last few decades, interface technology has developed very quickly. Take the smartphone as an example; a device which is frequently used by the population on a daily basis. The Motorola DynaTAC 8000X , the first mobile phone which could be used for making phone calls only, was brought on the market in 1983. Nowadays, just fifteen years after the first IBM Simon smartphone was released, the mobile phones we carry around with us have fast 4G network and look like small computers with a high-resolution camera and display. The population does not just use them to make phone calls or send messages, but also for amusement through game applications (apps) and posting personal experiences on social media. In the summer of 2016 a new game attracted the attention of many smartphone users: Pokémon Go, an augmented reality game (NRC, 2016). New about this game was that people could use their smartphone as a Head Mounted Display (HMD): a device which is normally worn on the head and displays augmented reality (AR) or virtual reality (VR). Currently, many other games use HMD's as well to give the user a special experience (e.g. Cybersnake, VR Worlds, Wayward Sky, RoboRaid, etc.). The information of an HMD can be presented in two ways: 1) AR; projected over the natural world making it seem like the presented information is in front of you (see-through transparent; e.g. the HoloLens or Google Glass), or 2) VR; completely closed-off, so only the presented information is visible and the user will be completely absorbed in the environment (a virtual reality glasses; e.g. the Oculus Rift; personal communication Kooi, 2018).

VR has been examined for decades by the army for training of real-life activities (Lowood, 2015; Zyda, 2005). For example, if a soldier has a fear of heights and this can be simulated well by using a HMD, the soldier can train with heights to get rid of his or her fear. A theoretical advantage of using a HMD during a training is that the practice (nearly) equal's "real systems/places". This at lower costs and with greater safety (Lowood, 2015). In addition, the HMD has also been used, with positive outcomes, to treat soldiers who has experienced a traumatic event and suffers from posttraumatic stress disorder (PTSD; Pair *et al.*, 2006, Rizzo *et al.*, 2006).

Similar to see through HMD's, the defense also uses Head Up Displays (HUDs). In F16 fighter planes, a HUD is used to present spatial information to the pilot (Rockwell Collins, 2007). The HUD projects the information via a transparent lens (combiner), which is determined in the Field Of View (FOV) of the user. The displayed information nor the symbology (a symbol with a certain message), moves as the head is rotated (personal communication Kooi, 2018).

The F35 fighter planes are the first jets build, where the HUD has been replaced by a HMD (Rockwell Collins, 2007). Because a HMD is attached to the head, the presented information moves over the background each time a head movement is made, in contrast to the HUD where the projected information remains fixed. The human visual system ensures that a reflexive eye-movement, called optokinetic nystagmus, enables a person to process the projected information and symbology such that it remains stable and legible. The eyes will involuntarily track a continuously moving object by moving smoothly in one direction in pursuit of an object moving in that same direction, and then snapping back (Wolfe, Kluender & Levi, 2012). One advantage of the HMD is that the presented information always remains in the FOV. However, the movements and changes in the background structure and/or color (for example from a clear blue sky to the yellowish color of an unstructured desert), could cause that the presented information and symbology are not very readable. So, while the visual system ensures good readability of HUD symbology, this is not the case for a HMD, necessitating either perfect stabilization or larger symbology (personal communication Kooi, 2018).

In addition, when using an HMD, eye complaints may develop (Kooi, 1997; Kooi & Toet, 2004; Peli, 1995; Regan, 1995; Wann, Rushton & Mon-Williams, 1995). To reduce the eye strain, the information is displayed in the central FOV which ensures that the eyes remain mostly straight ahead ("eyes forward position"; Adler, Bahill & Stark, 1975). This allows the pilot to read the information at a glance without making large eye movements; the displayed information can be easily processed by the cognitive system (Wolfe, Kluender & Levi, 2012). However, not all information fits within the central FOV and some must therefore be presented in the peripheral field. When the information is presented too far out of the central FOV, this could not only be exhausting and annoying to look at due to the large eye movements that have to be made, but the extra time may even be dangerous in certain situations (e.g. think of an F35 pilot during a time critical mission). Thereby, it may be that the presented information will overlap each other within the FOV. Overlap will dramatically decrease the readability of the text and/or symbols that are presented and thus limits the fast processing by the pilot (Kooi, Toet, Tripathy and Levi, 1994; Strasburger, 2005). This could cause that the pilot is more likely to miss crucial information. Thus, it is of great importance to make sure the readability is optimal, the fatigue symptoms of the user (which accumulate over time) are minimal and the instantaneous visual comfort remains as high as possible.

Previous studies

In the past, several studies have shown that letters presented in the peripheral field are less legible when neighboring contours are present (Ehlers, 1936; Flom, Weymouth & Kahneman, 1963; Strasburger, Harvey & Rentschler, 1991; Toet & Levi, 1992; Kooi, Toet, Tripathy & Levi, 1994; Whitney & Levi, 2011). This phenomenon is called visual crowding (Levi, 2008; Whitney & Levi, 2011). Visual crowding is affected by cluttering: the distance of the flankers from the central target (Flom, Weymouth & Kahneman, 1963; Whitney & Levi, 2011). The more clutter is present (e.g. overlap of letters), the more it interferes with searching for a specific symbol (e.g. a target letter; Rosenholtz, Li & Nakano, 2007). However, results by Duncan and Humphreys (1989) show that an increase of difference between target and nontargets also increases the efficiency of visual search (i.e. the greater the difference, the more efficient the search: also known as target-nontarget similarity). For example, a black target T surrounded by black flanker T's is more difficult to detect than when the target T is white (see figure 3). Results found by Kooi, Toet, Tripathy and Levi (1994) extend the statement that difficulty in detecting targets in small spacing conditions (e.g. overlap) is reduced when the target and flanker letters have contrasting polarity (e.g. black and white).

Current study

The current study is inspired by the methods of previous studies by Kooi (1997; use of eye movement) and Kooi, Toet, Tripathy and Levi (1994; cluttering and polarity). As mentioned before, not only visual crowding (Flom, Weymouth & Kahneman, 1963; Rosenholtz, Li & Nakano, 2007; Kooi, Toet, Tripathy & Levi, 1994; Toet & Levi, 1992; Strasburger, Harvey & Rentschler, 1991, Whitney & Levi, 2011), target-nontarget similarity (Duncan & Humphreys, 1989) and polarity (Kooi, Toet, Tripathy & Levi, 1994), but also the place in the FOV affect the readability of the presented stimuli (Adler, Bahill & Stark, 1975; Levi & Carney, 2009; Strasburger, Harvey & Rentschler, 1991). Therefore, we want to examine in the present experiment (1) the influence of the eccentricity (distance between the central fixation point and the target), (2) spacing (mutual distance of the different image elements, i.e. visual crowding) and (3) polarity on task performance and visual comfort. In addition to the recommendations for the usage of HMD's that follow from this study, this research lays a foundation how to calculate the "maximal amount of information a user can simultaneously perceive and process" of a HMD. Three eccentricities will be used: 15 deg based on earlier research by Adler, Bahill & Stark (1975), 30 deg based on the current F35 HMD (personal communication Kooi, 2018), followed by 45 deg to test the limits of the participant. Spacing will also consist out of three levels: a small spacing with overlap, a medium spacing in which the end of the letters touch each other and a large spacing with a space between the target and flanker T's. The levels of polarity are the same (black/white) or opposite (black+white/ white+black).

The experiment will be conducted by performing a simple task on a 65 inch LED tv screen. The questions that are asked during the task can be answered by means of the space bar and mouse. In addition, a questionnaire based on the Simulator Sickness Questionnaire (SSQ) by Kennedy, Lane, Berbaum and Lilienthal (1993) will be conducted prior to the examination and after each block (7 times in total), in which open questions are asked about how the participants feel about their health (e.g. fitness, eye complaints, nausea, etc.).

The following research question summarizes our goal: "What is the largest Head Mounted Display Field Of View, that the average person without ocular abnormalities is able to view comfortably (i.e. the absence of eye strain) for a prolonged duration?". We expect to encounter the following effects: first, the eye strain and reaction time (RT) will increase, as the eccentricity increases. Second, the health complaints will increase as the measurements progresses. The last expectation is that the RT will be shorter at the opposite polarity condition than at the same polarity condition, and that this applies especially to the small spacing condition (i.e. opposite polarity will help the most when overlap is present).

Methods

1. Design and conditions

The experiment followed a 2x3x3 within-subjects design; all subjects participated in all research conditions. Trials contained a variation of three independent variables 'polarity', 'eccentricity' and 'spacing'. The polarity variable was divided into two conditions, 1) same polarity: both target T's and flanker T's were black/white, or 2) opposite polarity: the target T's were white and the flanker T's were black or vice versa. Eccentricities (15, 30 or 45 deg) and spacing (small, medium or large) were sequentially presented. Fatigue, headache, nausea, dizziness while sitting during the experiment, dizziness while standing after the experiment, blurry vision, double vision, eye strain and annoyance of the experiment trial were measured as the dependent variables before the experiment and after each block with a questionnaire (7 times). Response time and correctness were also measured as the dependent variables, but throughout the experiment after each trial.

2. Participants

A total of twelve participants between the age of 22 and 56 years (*M = 26.42; SD = 9.44*) voluntarily participated in the experiment at TNO Soesterberg (three males between the age of 23 and 56 (*M = 35; SD = 18.25*) and nine females between the age of 22 and 27 (*M = 23.56*; *SD = 1.59*)).

The participants responded to a written invitation send to TNO employees, colleagues, family and friends. Before taking part in the study, all participants signed the informed consent form (see appendix A). They received a financial compensation of €40,- for participating in the experiment, which lasted for a maximum of three hours. Selection criteria included having normal or corrected to normal vision (two out of twelve participants wore spectacles and two wore lenses); none of the participants reported health problems with their eyes. The phoria and the visual acuity test were used to check whether the participants had a deviation in one or both eyes. Each participant had normal or corrected to normal visual acuity.

3. Materials

3.1 Stimuli

The experiment was created and executed with Spyder.Ink® (www.spyder-ide.org), in conjunction with Python as programming language. The computer used for presenting the stimuli was a Dell Latitude E6540 laptop with an Intel Core i5 processor. The experiment was presented on a Samsung UE65MU6100W LED-smart tv 65-inch screen, set to a resolution of 3840 by 2160 pixels with a refresh rate of 60 Hz.

The target and flanker T's were 20 by 2 pixels (7.7 by 0.77 mm), and were black or white. At the viewing distance of 88 centimeters, the T's had a visual angle of 0.5 x 0.5 degrees (height x width); long enough to be easily visible. They were presented on a grey background with a red fixation T in the center of the screen (see figure 1).

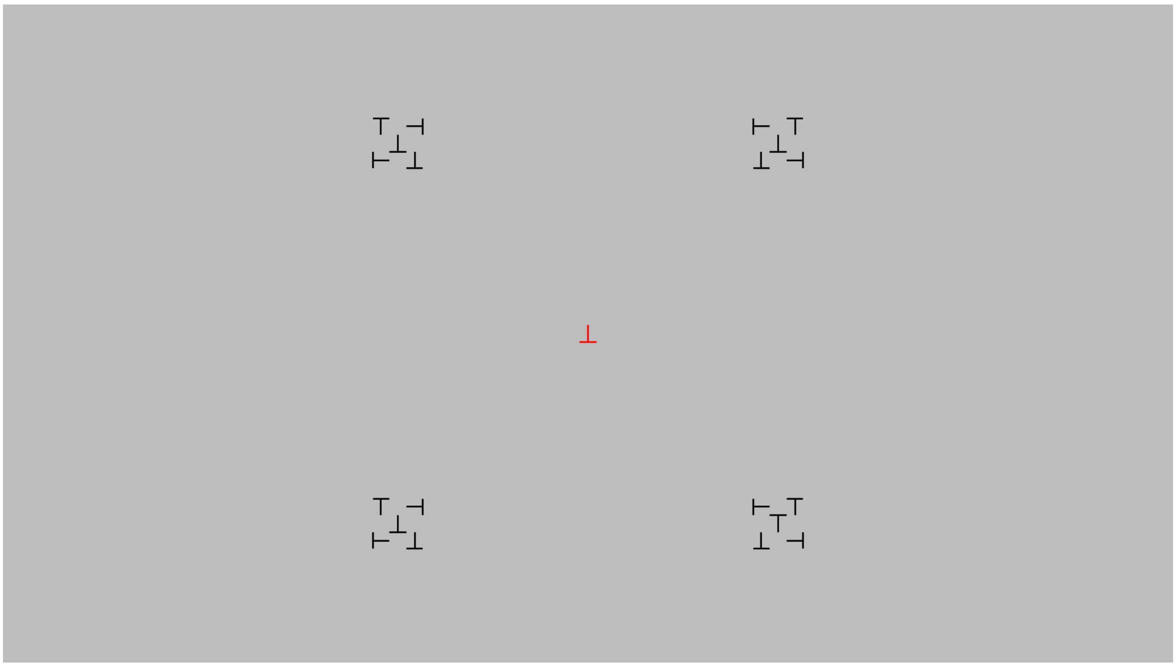

Figure 1. An example of a trial with an eccentricity of 30 degrees, the large spacing and the same color (in this case black) of the polarity condition.

3.2. Calibration

The screen was calibrated beforehand and checked afterwards. In luminance, the grey value (121.05 cd/m^2) of the background was located close to the middle between the white (235.75 cd/m^2) and black values (1.25 cd/m^2). The contrasts of the background in comparison to the stimuli were -0.99 (black) and 0.95 (white). To calculate this, the Weber contrast was used: $((I - I_b) / I_b)$, where I stands for the value of the luminance of the stimuli (I) and background (I_b; Wikipedia, 2018).

3.3 Optometric tests

After the experiment was completed two optometric tests were administered. A phoria test tested the amount of ocular deviation. A red Maddox light was viewed by the participants from the same distance as the experiment (88 cm), with one eye looking through a Maddox glass which blurs the light into a line (Eskridge, Amos & Bartlett, 1991). This test was done to exclude participants with alignment abnormalities (phorias). No angular deviation was measured for any of the participants.

The visual acuity test confirmed all participants could easily distinguish the upright target T's from the upside-down T's. A scaled down version (A5 size) of the TNO Landolt C chart measured resolution at the same distance (88 cm).

4. Data analyses

None of the twelve subjects were excluded from the analysis. The mean of the eye strain, health complaints or RT's per variable is represented in a graph using Microsoft Excel ©. To statistically test the hypotheses, repeated measures ANOVA's were conducted by using IBM SPSS Statistics 25 © to determine the significance.

5. Procedure

The experiment took place in a quiet room at TNO Soesterberg to minimize outside distractions. Before taking part in the experiment, the participants were asked to report their general state of health, if they were wearing glasses or contact lenses (if so, we asked their eyes prescription) and if they felt any discomfort in their eyes at that moment using the Wong-Baker faces pain rating scale (where 0 was "no pain" and 10 was "worst pain possible"; Wong: Personal Communication, Unpublished Data, 1990). Subsequently, the participants also filled in a questionnaire which contained the general statements of the SSQ (i.e. fatigue, headache, nausea, etc.; Kennedy, Lane, Berbaum & Lilienthal, 1993; see appendix B); participants could answer "none", "slightly", "moderate" and "severe". Intermediate answers were allowed (i.e. between "none" and "slightly"). The distance between the "none" and "severe" answer was converted to a 0-10 range, which was not visible for the participants. After filling in these questions, participants could practice until they were familiar with the task and no more mistakes were made (approximately 5 minutes).

To minimize the participant's head movements, participants rested their chin on a chin rest (without forehead rest). The lights behind the participant were turned off, so no reflection could be seen in the screen. They were instructed to focus on the red fixation T in the middle of the screen and only use eye movements to fixate the targets, while not moving their head. Furthermore, participants were asked to carry out the task as quickly and accurately as possible, but to keep the number of errors at a minimum.

As shown in figure 1, at the corners of a virtual square around the fixation T, four target T's each surrounded by four flanker T's were presented. The red fixation T is presented upside-down at the start of each trial. Participants were instructed to fixate the upside-down fixation T, press the space bar when they wanted to start the trial, look at the four target T's in the corners and remember which target T was standing upright, and subsequently press the space bar again to stop the trial. The stop time minus the start time is the viewing duration. Responses were entered in an answer screen by clicking on which of the squares contained an upright target T (see figure 2). After this, the participant started the next presentation by pressing the "continue" button with the mouse. The same red upside-down fixation T appeared in the center of the screen and the next trial started when the participant pressed the space bar. This assignment was repeated numerous times throughout the experiment.

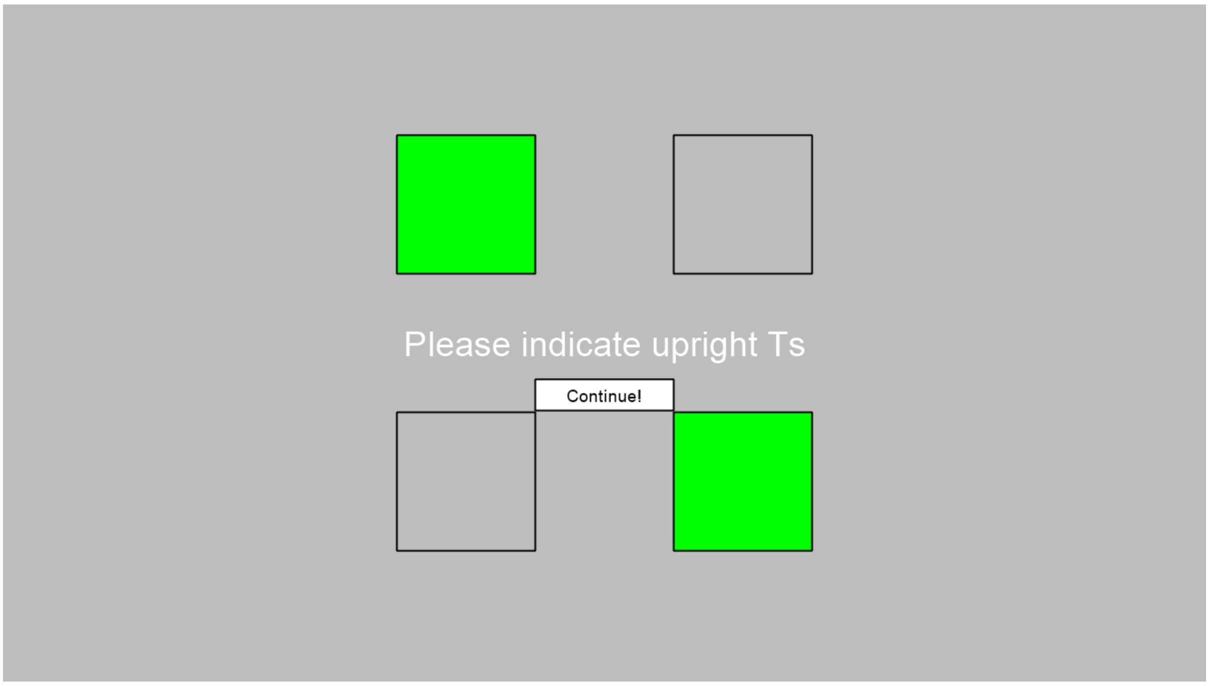

Figure 2. An example of the answer screen. The target T's that were upright are indicated by the green blocks (top-left and bottom-right). The blocks of the upside-down target T's do not need to be colored (top-right and bottom-left).

The experiment, was divided into six blocks, containing 96 trials each, with small breaks in between. Every block consisted of all spacing and both polarity conditions (see figure 3). The first block contained an eccentricity of 15 deg, the second block of 30 deg, followed by the third block with 45 deg Between block three and four, participants took a break of 15 minutes. After the break, the experiment continued in reverse order (from 45 deg to 30 deg, ending with 15 deg). Before the experiment and after each block participants filled in the questionnaire, in which participants were asked to rate general fitness, ocular complaints, nausea, etc. After completing the experiment, participants were thanked for their participation.

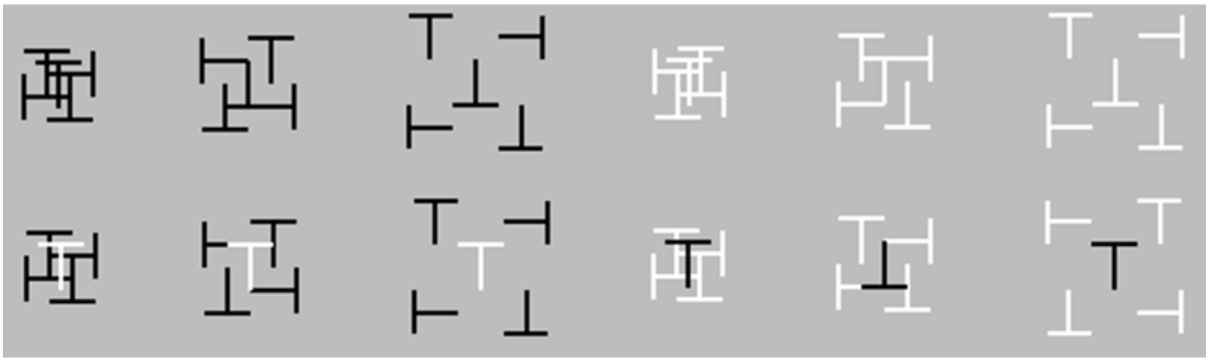

Figure 3. All spacing conditions (small, medium and large) for the two polarity conditions: top row (same polarity) and bottom row (opposite polarity).

Results

The participants' response per question calculated as a percentage correct showed that only a small fraction (< 1.5%) of all trials were answered wrong. Therefore all answers were included in the data analysis.

Questionnaire data

During the experiment, participants filled in a self-made questionnaire several times containing the Wong-Baker faces pain rating scale (Wong: Personal Communication, Unpublished Data, 1990) and statements of the SSQ (Kennedy, Lane, Berbaum & Lilienthal, 1993; see appendix B). The change in eye strain and general health was calculated per participant. This was done by subtracting the values of the first questionnaire, which was filled in before the experiment started (i.e. baseline), from all other blocks. In this way the data of all participants could by analyzed equally. The mean scores and standard deviations of the participants' degree of eye strain (ES) and their general health (GH), are shown below in table 1 per block.

Table 1.

The mean scores and standard deviations of participants' degree of Eye Strain and General Health, subdivided per block.

Block	**Condition**	***M***	***SD***	**N**
After block 1 (15 deg)	ES	.379	.627	12
After block 2 (30 deg)	ES	.563	.446	12
After block 3 (45 deg)	ES	.983	.864	12

After block 4 (45 deg)	ES	.638	.735	12
After block 5 (30 deg)	ES	.717	.812	12
After block 6 (15 deg)	ES	.763	1.077	12
After block 1 (15 deg)	GH	.003	.076	12
After block 2 (30 deg)	GH	.018	.119	12
After block 3 (45 deg)	GH	.165	.264	12
After block 4 (45 deg)	GH	.100	.262	12
After block 5 (30 deg)	GH	.128	.199	12
After block 6 (15 deg)	GH	.126	.176	12

In addition, two separate repeated measures ANOVA's were run to statistically test the data of the GH and degree of ES. When looking at the data of the GH, a significant difference is found ($F_{(2.50,27.50)}$ = 3.641, *p* = .0.31, η^2 = .249). A Least Significant Difference (LSD) post-hoc test revealed that the significant effect is due to the differences between the following blocks (see table 2): the 1st 15 deg and 1st 45 deg (*p* = .018), the 1st 15 deg and 2nd 30 deg (*p* = .009), the 1st 15 deg and 2nd 15 deg (*p* = .010), the 1st 30 deg and 1st 45 deg (*p* = .029), the 1st 30 deg and 2nd 30 deg (*p* = .027) and the 1st 30 deg and 2nd 45 deg (*p* = .038).

In contrast, when analyzing the data of the degree of ES, there is no significant difference found ($F_{(2.87,31.56)}$ = 1.834, *p* = .163, η^2 = .143). However, when looking at the pairwise comparisons of the LSD post-hoc test (see appendix C) between the 1st 45 deg and 2nd 45 deg block, there is a significant difference (*p* = .037).

Table 2.

The significant values of the pairwise comparison of the General Health. Whereas 1st means before and 2nd means after the break.

Block	1st 15 deg	1st 30 deg	1st 45 deg	2nd 45 deg	2nd 30 deg	2nd 15 deg
1st 15 deg		.540	.018*	.139	.009*	.010*
1st 30 deg	.540		.029*	.170	.027*	.038*
1st 45 deg	.018*	.029*		.119	.378	.545
2nd 45 deg	.139	.170	.119		.443	.690
2nd 30 deg	.009*	.027*	.378	.443		.946
2nd 15 deg	.010*	.038*	.545	.690	.946	

Note. Significance value computed using α=.05*

Reaction time data

The RT's were calculated by subtracting the end time from the start time of each trial, and subdivided into the different conditions (polarity, spacing and eccentricity). An overview of the mean scores and standard deviations of the RT's per condition is given in table 3. In figure 4 these mean scores are depicted.

Table 3.

The RT mean scores and standard deviations in seconds, subdivided in the three dimensions: polarity, spacing and eccentricity (with the blocks in the same order as in the experiment).

Conditions		***M (s)***	***SD (s)***	**N**
Polarity	Same	3.225	0.941	12
	Opposite	2.818	0.496	12
Spacing	Small	3.223	0.898	12
	Medium	3.095	0.828	12
	Large	2.745	0.458	12
Eccentricity	1st block: 15 deg	3.191	1.036	12
	1st block: 30 deg	3.044	0.664	12
	1st block: 45 deg	3.177	0.876	12
	2nd block: 45 deg	3.131	0.732	12
	2nd block: 30 deg	2.869	0.577	12
	2nd block: 15 deg	2.715	0.562	12

Furthermore, the RT data of polarity (2 levels), spacing (3 levels) and eccentricity (3 levels) was run through a repeated measures ANOVA's. The results in table 4 show that the polarity condition ($F_{(1,11)} = 35.267$, $p < .001$, $\eta^2 = .762$), spacing condition ($F_{(2,22)} = 17.400$, $p < .001$, $\eta^2 = .613$), eccentricity condition ($F_{(2,22)} = 9.826$, $p = .001$, $\eta^2 = .472$), and the interaction between polarity*spacing ($F_{(2,22)} = 7.615$, $p = .003$, $\eta^2 = .409$) are significant. However, all other interactions shown in table 4 are not statistically significant: polarity*eccentricity ($F_{(1.22,13.44)} = 1.542$, $p = .242$, $\eta^2 = .123$), spacing*eccentricity ($F_{(4,44)} = .881$, $p = .483$, $\eta^2 = .074$) and polarity*spacing*eccentricity ($F_{(4,44)} = .842$, $p = .506$, $\eta^2 = .071$).

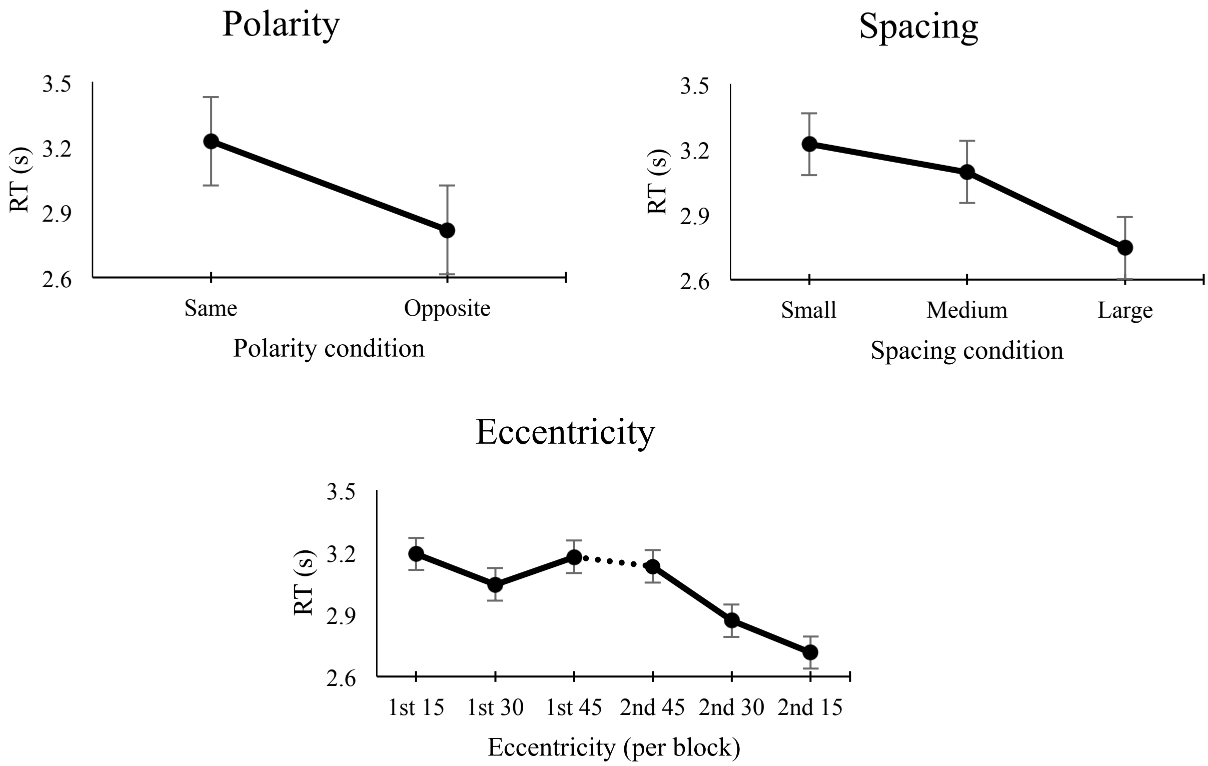

Figure 4. The mean RT (s) and error bars, subdivided in: polarity, spacing and eccentricity. The dots represent the half-way break.

When both runs (before and after the break) are viewed separately and the conditions and interactions are compared with each other, the polarity ($F_{(1,11)} = 33.757$, $p < .001$, $\eta^2 = .754$; $F_{(1,11)} = 29.601$, $p < .001$, $\eta^2 = .729$), spacing ($F_{(2,22)} = 11.647$, $p < .001$, $\eta^2 = .514$; $F_{(2,22)} = 26.348$, $p < .001$, $\eta^2 = .705$) and interaction between polarity*spacing ($F_{(2,22)} = 6.154$, $p = .008$, $\eta^2 = .359$; $F_{(2,22)} = 8.859$, $p = .002$, $\eta^2 = .446$) show a significant effect for both runs. However, only in the second run, the eccentricity condition ($F_{(1.32,14.47)} = 41.334$, $p < .001$, $\eta^2 = .790$) and the interaction between polarity*spacing*eccentricity ($F_{(4,44)} = 2.842$, $p = .035$, $\eta^2 = .205$) differ significantly.

Table 4.

ANOVA F values of the conditions polarity, spacing and eccentricity displayed before the break (1), after the break(2) and both runs taken together(1+2), wheras GG stands for Greenhouse-Geisser corrected.

Run	Condition	F	Sig.	Partial Eta Squared
1 - Before break	**Polarity**	33.757	.000*	.754
	Spacing	11.647	.000*	.514
	Eccentricity (GG)	1.755	.221	.138
	Polarity*Spacing	6.154	.008*	.359
	Polarity*Eccentricity (GG)	3.244	.092	.228
	Spacing*Eccentricity	1.873	.132	.146
	Polarity*Spacing* Eccentricity	1.439	.237	.116
2 - After break	**Polarity**	29.601	.000*	.729
	Spacing	26.348	.000*	.705
	Eccentricity (GG)	41.334	.000*	.790
	Polarity*Spacing	8.859	.002*	.446
	Polarity*Eccentricity (GG)	1.501	.248	.120
	Spacing*Eccentricity (GG)	1.359	.277	.110
	Polarity*Spacing* Eccentricity	2.842	.035*	.205
1+2	**Polarity**	35.267	.000*	.762
	Spacing	17.400	.000*	.613
	Eccentricity	9.826	.001*	.472
	Polarity*Spacing	7.615	.003*	.409
	Polarity*Eccentricity (GG)	1.542	.242	.123
	Spacing*Eccentricity	.881	.483	.074
	Polarity*Spacing* Eccentricity	.842	.506	.071

Note. Significance value computed using α=.05*

Despite the interaction effect of polarity*spacing, a pairwise comparison table of the LSD post-hoc test has been made for the main effect spacing to see where the difference occurs (see appendix D). It appears that for both the small ($p < .001$) as medium ($p < .001$) spacing relative to the large spacing, the RT difference is significant (see figure 5). The time to respond is composed of multiple elements: 1) eye movement to the target T, 2) visual discrimination, 3) cognitive processing of the task, and 4) responding by a finger press (figure 5 on the left). The cognition and finger response are the 'constant' components in the time-to-react and should be the closest to the fastest reaction time in the data-set (i.e. the opposite polarity, large spacing, and 15 deg eccentricity test condition). To calculate the mean RT (s) differences, we subtracted this estimated baseline; figure 5 on the right therefore shows a best estimate of the perceptual + eye-movement variability which results from the variation in polarity, eccentricity, and spacing. In addition, after conducting a LSD post-hoc test, it appears that the main effect of the condition eccentricity is due to the significant difference between the 15 and 45 deg ($p = .012$) and the 30 and 45 deg ($p < .001$; see appendix E).

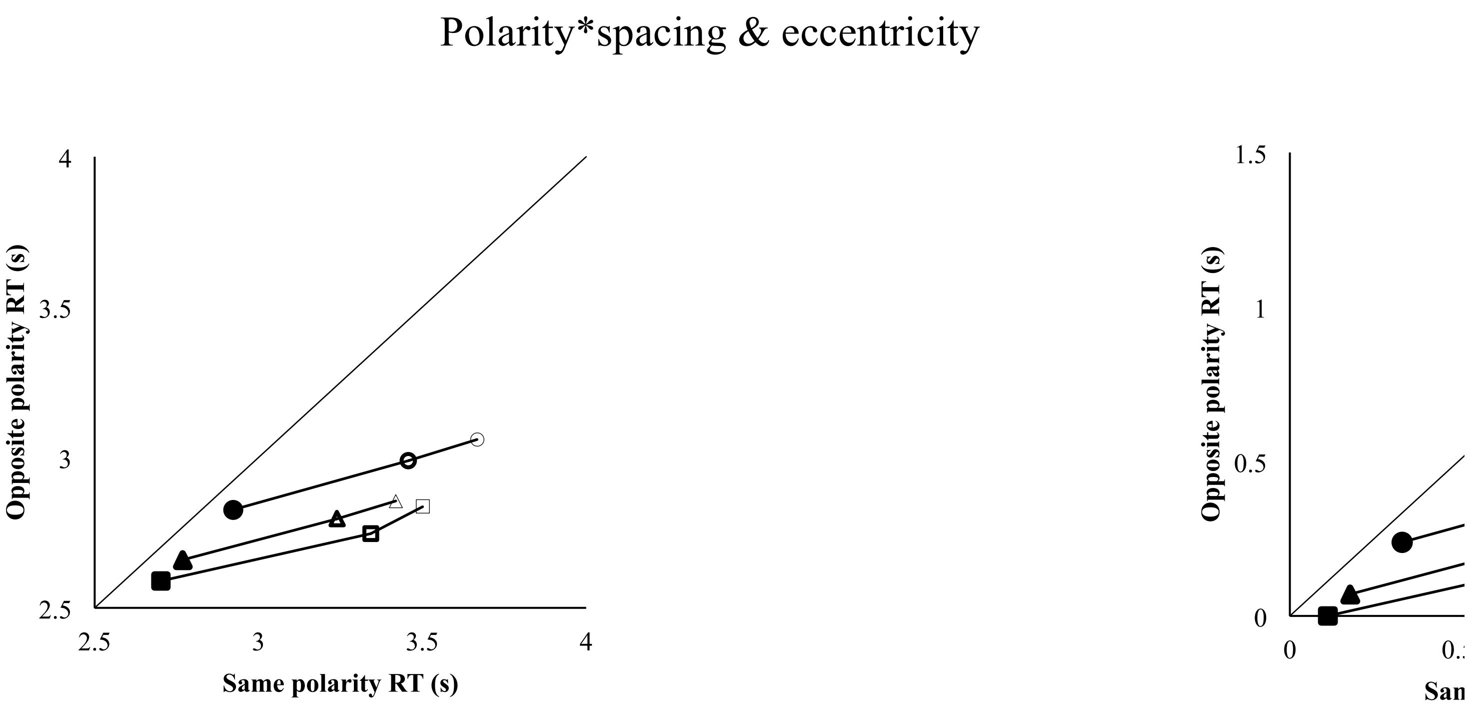

Figure 5. Left: the mean RT (s), and right: the mean RT (s) differences shown for polarity*spacing & eccentricity. The thin line of the figures represents the small spacing condition, the thick line the medium spacing condition and the solid filled figures the large spacing condition.

Note. The diagonal line represents equal RT's for same and opposite polarity (i.e. no difference).

Discussion

As mentioned before, the current study is inspired by the methods of previous studies by Kooi (1997) and Kooi, Toet, Tripathy and Levi (1994), and investigates whether eccentricity, spacing and polarity have an influence on task performance and visual comfort. Our main goal is to answer the following question: "*What is the largest Head Mounted Display Field Of View, that the average person without ocular abnormalities is able to view comfortably (i.e. the absence of eye strain) for a prolonged duration?*".

Expected was that the eye strain and RT would increase, as the eccentricity increased. When looking at the reported degree of eye strain in general, none of the participants reported higher than a four ('moderate') out of ten ('worst pain possible'). This indicates that none of the participants experienced severe eye strain during the experiment. This is confirmed when no significant effect was found (p = .163) by running a repeated measure ANOVA, and thus leads to the rejection of this part of the first hypothesis. However, when looking more closely to the pairwise comparison, a significant difference in reported degree of eye strain has been found between the 1^{st} 45 deg and 2^{nd} 45 deg blocks (p = .037; see appendix C). Despite the fact that both contained the same eccentricity, thus expect the participants to have at least the same degree of eye strain, this result may be due to the break between these blocks: the reported degree of eye strain was lower after, than before the break (see appendix F). This break has given participants the opportunity to take a rest, as a result of which they probably experienced even less eye strain after the break.

When looking at the second part of the first hypothesis (regarding to the RT), a significant main effect has been found (p = .001). According to the results, it can be concluded that this is due to the difference between the 15 deg and 45 deg (p = .012) and the 30 deg and 45 deg (p < .001; see appendix E). It turns out that there is no significant difference between the 15 deg and 30 deg (p = .944), which means that the difference in RT between the 15 deg and 30 deg is negligibly small. So, it can be concluded that the RT does significantly increase as the eccentricity increases (even when starting at 30 deg). However, after analyzing the differences between the first and second run (before and after the break), it appeared that only a significant effect was found in the second run for the eccentricity condition (p < .001). When visually analyzing the data (see figure 4), it appears that the average RT of the 1^{st} 15 deg block has the longest RT of all six blocks. This may indicate that participants were still focusing on practicing the task during this block. In future research it could be useful to extend the practice block to make participants more familiar with the task (i.e. no learning effect), which could possibly lead to a stronger effect.

In addition, it was also expected that the health complaints would increase as the experiment lasted longer. According to the results, a significant effect is found for the General Health (p = .031; Greenhouse-Geisser corrected). As shown in table 1, participants reported to have more health complaints in the block before the break (1^{st} 45 deg) than the first block after the break (2^{nd} 45 deg), even though the block after the break contained the same eccentricity. The health complaints increased again in the fifth block (2^{nd} 30 deg) and remained about the same in the last block of the experiment (2^{nd} 15 deg). Once again, the break could have resulted in a decrease of the health complaints, because the participants had rested for a while. Most likely the health complaints had increased more during the fourth, fifth and last block, without a break. Taken this into account when looking at these results in general, it can be concluded that this hypothesis can be accepted.

As a part of the last hypothesis, we expected that the RT would be shorter at the opposite polarity condition than at the same polarity condition. A main effect of the polarity condition has been found (p < .001); indicating a difference in RT mean scores between the same and opposite polarity. Giving the data a closer look, the RT's of the opposite polarity condition are consistently shorter than the ones of the same polarity condition (see figure 5; amounts to 0,407 seconds), i.e. a quicker distinction can be made between target and flankers T's when they have the opposite polarity of each other. These results of the current study replicates earlier findings by Kooi, Toet, Tripathy and Levi (1994).

Finally, we also expected that this RT difference would be the longest for the small spacing condition. A main effect has been found for spacing (p < .001), which indicates that there is a difference between the small, medium and large spacing. However, a significant interaction effect of the polarity*spacing conditions was also found (p = .003), indicating that the small, medium and large spacing do not differ from each other in the same way (something we expected to happen according to earlier findings by Kooi, Toet, Tripathy & Levi, 1994). In addition, not just the small, but also the medium spacing significantly differs from the large spacing (both with p <.001; see appendix D). Therefore, using the opposite polarity for the target and flanker T's will have a negligible difference in RT when a large spacing is used, in contrast to the small and medium spacing (see figure 5).

Some aspects during the experiment should be avoided in future studies to increase the specificity of the results. Firstly, the participants that took part in this study, were 22 to 56 years of age. According to Arnett and Hughes (2012), people between the age of 20 and 25 have the shortest response times. In the current study, three out of twelve participants fell outside this range. Therefore, the age range should be considered.

Secondly, despite the fact that the experiment was conducted in a quiet room, participants were sometimes distracted by surrounding sounds. In addition, other conditions than the participants' general health, such as autism (too focused) or ADHD (too easily distracted) were not included in the selection criteria. This could have been of (minor) influence on the participant's responsiveness or concentration, and thus RT. Though the effect on the RT is not likely to be large, it is of interest to have stricter selection criteria in future research.

In this experiment, the eccentricity of 15 deg and 30 deg did not significantly differ from each other. The maximum FOV must lie somewhere between the 30 deg and 45 deg; a fine-grained follow-up will fill in the critical range. In addition, the conditions should last longer than 10-15 minutes (e.g. 60-120 minutes; a longer time protocol) to see to what extent this affects the eye strain, health complaints and RT of the participant (the F35 has a range of ± two hours without refueling; Ministerie van Defensie, 2018).

The results show that the RT increases as the target and flanker T's have the same polarity and the spacing decreases. Opposite polarity is not an option in a fighter jet HMD, e.g. the HMDS in a F35 is monochrome (uses only one color). A large spacing is a last resort to keep the RT within bounds. Large spacings are not practical if a lot of information needs to be displayed. Therefore, other options of decluttering should be considered, such as a stereo display, including the effect on eye strain, health complaints and task performance.

Finally, a 65 inch LED tv screen was used to simulate the FOV of a HMD. The results can be validated by using a HMD in future research, while participants perform the same task. When the results of both studies show a (strong) correlation, the method and equipment's that are used in the current study, offer an easier and less expensive solution for future research into HMD's.

According to the findings of the current study, eye strain did not significantly vary amongst eccentricity. However, health complaints increased as the participants participated longer in the experiment. Bearing in mind time-critical missions of F35 pilots, the eccentricity with the shortest RT and lowest health complaints should be taken into account when using the HMD's (e.g. an eccentricity of 30 deg does not lead to eye strain, nor health complaints, yet a shorter RT). In conclusion, this study yields input data to calculate the "maximal amount of information a user can simultaneously perceive and process" as a function of the Field Of View, and includes visual comfort in the data.

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Appendix

Appendix A)

Informed consent statement

Feb-May 2018

Signed by participant:

Name ____

Date of birth ____

declares to participate on a voluntary basis in the research entitled

"Dynamic clutter experiment" at TNO.

Selection criteria to which you must comply:
- You have corrected to normal vision in both eyes and do not wear spectacles.

I confirm that I have read the information about the above study.
I understand the information.

The intentions of the experiment and the approach followed are explained to my satisfaction.

I had the opportunity to ask additional questions and these questions were answered satisfactorily.

I have had enough time to think about participation.

I know that my participation in the study is entirely voluntary and that I can withdraw my consent at any time without having to give a reason for it.

I give permission to process my personal data for the purposes as described in the information.

I give permission for keeping the data and that authorized members of the investigation team and authorized inspectors have access to this.

Furthermore, I declare that I have no known 'obstacles' to participate in the experiment.

Place, date ______________________________________

Signature of person: ______________________________________

ADMISSION
I have made sure this subject is well informed about the research in which he / she is going to participate. I have confirmed that this subject fulfills the selection criteria to be able to participate in the aforementioned research.

Name, signature and date signature of the research leader:

Name of the research leader: Sofie Hoving
Date and place: ...... - ...... -2018, Soesterberg

Signature

____

Appendix B)

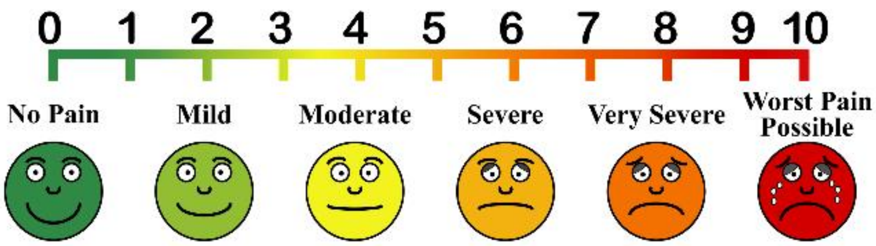
Before the experiment

What is your general state of health (*Wat is uw algemene gezondheidstoestand*)?

Are your eyes healthy (*Zijn uw ogen gezond*)?

Do you wear glasses/contact lenses (*Draagt u een bril/contactlenzen*)?
If so, what is your eyes prescription (*Zo ja, wat is uw sterkte per oog*)?
Left eye (l*inker oog*):
Right eye (*rechter oog*):

How do you feel right now (eye strain)? Answer this in the scale presented down below (0-10).
Hoe voelt u zich op dit moment (kijklast)? Geef dit aan op onderstaande schaal (0-10).



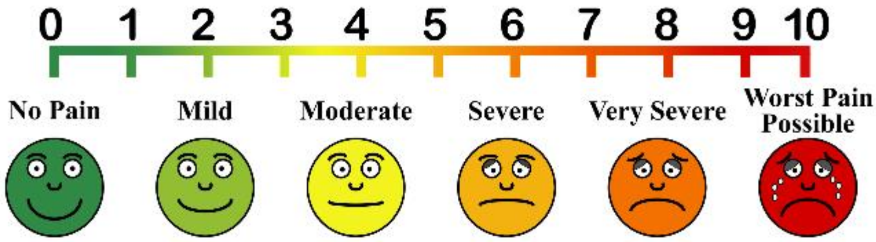
When filling in you can choose from the answers below (*Bij het invullen kunt u kiezen uit de onderstaande antwoorden*).
Please fill in your answer as (*Uw antwoord graag weergeven als*): ☒
Please indicate correction of a wrong answer as *(correctie van een fout antwoord graag weergeven als*): ■

	None (niet/geen)	Slightly (lichtjes)	Moderate (matig)	Severe (ernstig)
Fatigue (vermoeidheid)	□	□	□	□
Headache (hoofdpijn)	□	□	□	□
Nausea (misselijkheid)	□	□	□	□
Dizziness while sitting during the experiment (duizeligheid zittend tijdens het experiment)	□	□	□	□
Blurry vision (wazig beeld)	□	□	□	□
Double vision (dubbel beeld)	□	□	□	□
Eye strain (pijn in/achter ogen)	□	□	□	□

Other physical complaints (overige lichamelijke klachten):
Note. Please use the words "none, slightly, moderate or severe" as an indication (Opmerking. Graag gebruik maken van de woorden "niet/geen, lichtjes, matig of ernstig" als indicatie).

After block 1 - 5

How do you feel right now (eye strain)? Answer this in the scale presented down below (0-10).
Hoe voelt u zich op dit moment (kijklast)? Geef dit aan op onderstaande schaal (0-10).



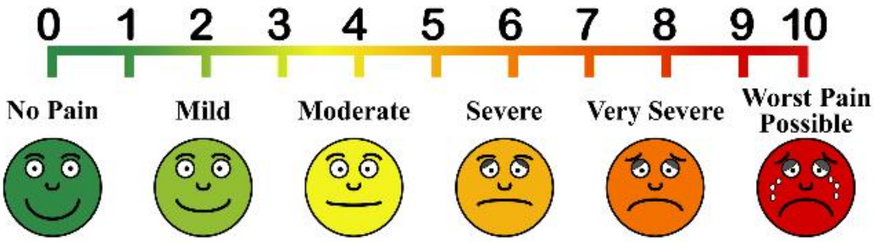
When filling in you can choose from the answers below (*Bij het invullen kunt u kiezen uit de onderstaande antwoorden*).
Please fill in your answer as (*Uw antwoord graag weergeven als*): ☒
Please indicate correction of a wrong answer as *(correctie van een fout antwoord graag weergeven als*): ■

TIJDENS het experiment, tenzij anders aangegeven	None (niet/geen)	Slightly (lichtjes)	Moderate (matig)	Severe (ernstig)
Fatigue (vermoeidheid)	□	□	□	□
Headache (hoofdpijn)	□	□	□	□
Nausea (misselijkheid)	□	□	□	□
Dizziness while sitting during the experiment (duizeligheid zittend tijdens het experiment)	□	□	□	□
Dizziness while standing **after** the experiment (duizeligheid staand **na** het experiment)	□	□	□	□
Blurry vision (wazig beeld)	□	□	□	□
Double vision (dubbel beeld)	□	□	□	□
Eye strain (pijn in/achter ogen)	□	□	□	□
How annoying was this block (hoe vervelend vond u deze ronde)?	□	□	□	□

Other physical complaints (overige lichamelijke klachten):
Note. Please use the words "none, slightly, moderate or severe" as an indication (Opmerking. Graag gebruik maken van de woorden "niet/geen, lichtjes, matig of ernstig" als indicatie).

After block 6

How do you feel right now (eye strain)? Answer this in the scale presented down below (0-10).
Hoe voelt u zich op dit moment (kijklast)? Geef dit aan op onderstaande schaal (0-10).



When filling in you can choose from the answers below (*Bij het invullen kunt u kiezen uit de onderstaande antwoorden*).
Please fill in your answer as (*Uw antwoord graag weergeven als*): ☒
Please indicate correction of a wrong answer as *(correctie van een fout antwoord graag weergeven als*): ■

<u>TIJDENS</u> het experiment, tenzij anders aangegeven	None (niet/geen)	Slightly (lichtjes)	Moderate (matig)	Severe (ernstig)
Fatigue (vermoeidheid)	☐	☐	☐	☐
Headache (hoofdpijn)	☐	☐	☐	☐
Nausea (misselijkheid)	☐	☐	☐	☐
Dizziness while sitting during the experiment (duizeligheid zittend tijdens het experiment)	☐	☐	☐	☐
Dizziness while standing **<u>after</u>** the experiment (duizeligheid staand **<u>na</u>** het experiment)	☐	☐	☐	☐
Blurry vision (wazig beeld)	☐	☐	☐	☐
Double vision (dubbel beeld)	☐	☐	☐	☐
Eye strain (pijn in/achter ogen)	☐	☐	☐	☐
How annoying was this block (hoe vervelend vond u deze ronde)?	☐	☐	☐	☐

Other physical complaints (overige lichamelijke klachten): *Note. Please use the words "none, slightly, moderate or severe" as an indication (Opmerking. Graag gebruik maken van de woorden "niet/geen, lichtjes, matig of ernstig" als indicatie).*

Which block (1 to 6) did you experience as the most annoying (*Welke ronde (1 t/m 6) vond u het meest vervelend*)?

Block *(Ronde)*:

Why *(Waarom)*?:

Other comments about the experiment (*Overige opmerkingen over het experiment*):

Appendix C)

Table 5.

The significant values of the pairwise comparison of the degree of eye strain.

Block	1st 15 deg	1st 30 deg	1st 45 deg	2nd 45 deg	2nd 30 deg	2nd 15 deg
1st 15 deg		.288	.056	.293	.124	.139
1st 30 deg	.288		.092	.714	.454	.455
1st 45 deg	.056	.092		.037*	.173	.450
2nd 45 deg	.293	.714	.037*		.456	.589
2nd 30 deg	.124	.454	.173	.456		.745
2nd 15 deg	.139	.455	.450	.589	.754	

Note. Significance value computed using α=.05*

Appendix D)

Table 6.

The significant values of the pairwise comparison of the spacing condition.

Spacing	**Small**	**Medium**	**Large**
Small		.193	.000*
Medium	.193		.000*
Large	.000*	.000*	

Note. Significance value computed using α=.05*

Appendix E)

Table 7.

The significant values of the pairwise comparison of the eccentricity condition.

Eccentricity	**15 deg**	**30 deg**	**45 deg**
15 deg		.944	.012*
30 deg	.944		.000*
45 deg	.012*	.000*	

Note. Significance value computed using α=.05*

Appendix F)

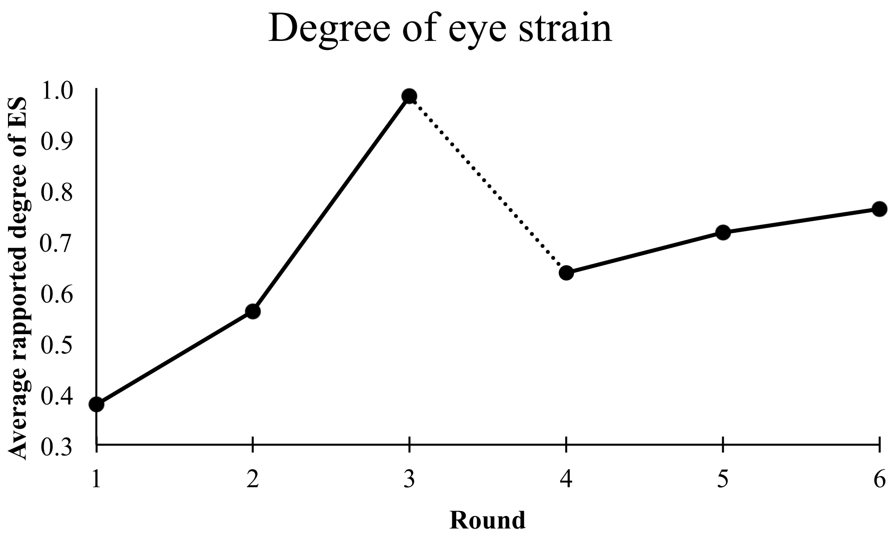


Figure 6. The average degree of eye strain shown for each block. The dots represent the half-way break.