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Attentional Tunneling in Pilots During a Visual Tracking Task With a Head Mounted Display

Erik Van der Burg[1,2], Wietse D. Ledegang[1], Frank L. Kooi[1], Mark M. J. Houben[1], and Eric L. Groen[1]

Abstract

Objective: We examined whether active head aiming with a Helmet Mounted Display (HMD) can draw the pilot's attention away from a primary flight task. Furthermore, we examined whether visual clutter increases this effect.

Background: Head up display symbology can result in attentional tunneling, and clutter makes it difficult to identify objects.

Method: Eighteen military pilots had to simultaneously perform an attitude control task while flying in clouds and a head aiming task in a fixed-base flight simulator. The former consisted of manual compensation for roll disturbances of the aircraft, while the latter consisted of keeping a moving visual target inside a small or large head-referenced circle. A "no head aiming" condition served as a baseline. Furthermore, all conditions were performed with or without visual clutter.

Results: Head aiming led to deterioration of the attitude control task performance and an increase of the amount of roll-reversal errors (RREs). This was even the case when head aiming required minimal effort. Head aiming accuracy was significantly lower when the roll disturbances in the attitude control task were large compared to when they were small. Visual clutter had no effect on both tasks.

Conclusion: We suggest that active head aiming of HMD symbology can cause attentional tunneling, as expressed by an increased number of RREs and less accuracy on a simultaneously performed attitude control task.

Application: This study improves our understanding in the perceptual and cognitive effects of (military) HMDs, and has implications for operational use and possibly (re)design of HMDs.

Keywords

attention, flight simulator, head mounted display, visual clutter, spatial disorientation

[1]TNO Human Factors, Soesterberg, The Netherlands
[2]University of Amsterdam, The Netherlands

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Corresponding Author:
Erik Van der Burg, TNO Human factors, Kampweg 55, Soesterberg 3769 DE, The Netherlands;
e-mail: vanderburg.erik@gmail.com

Active head aiming with HMD symbology can draw the pilot's attention away from a primary flight task, leading to less accurate flight performance and an increased risk of spatial disorientation.

Military aircraft often feature collimated see-through displays (i.e., augmented reality), such as a Head-Up Display (HUD), or a Helmet Mounted Display (HMD), for superimposing relevant information onto the primary field-of-view of the pilot. The limited field-of-view of an HUD which is physically fixed to the aircraft requires reorientation of the entire aircraft to make off-axis information visible. Instead, an HMD offers the flexibility to aim symbology towards any direction by reorienting the head. For example, the Lockheed Martin F-35 Lighting II features an HMD, to present information to the pilot. Part of the information is presented in an aircraft-fixed reference frame (e.g., airspeed and altitude), while other symbology is head-fixed (e.g., aiming cross) or earth-fixed (e.g., horizon line and ground target). With an HMD pilots can use active head aiming to acquire information.

See-through displays allow for more heads-up time with less frequent cross-checks to cockpit instruments, which can reduce workload (see Melzer, 2012, for a review). However, research has shown that the use of an HUD/HMD may draw attentional resources away from other tasks or events (Fischer & Haines, 1980; Melzer, 2012; Mustonen et al., 2013; Wickens & Alexander, 2009). For example, Wickens and Alexander (2009) demonstrated that pilots missed a significant proportion of external events, such as an obstacle on the runway, when attending to the HUD. In such situations, attention gets "sucked in" by specific information, at the cost of keeping track of other relevant information, which is called attentional tunneling (Wickens, 2005). In a visual search study without an HUD or HMD (Belopolsky et al., 2007), similar effects were observed when the size of the attentional window (i.e., comparable to an attentional spotlight) was manipulated by instructing participants to either detect a global (diffuse attention) or a local (focused attention) shape before they continued with a search task. Participants searched for a green target letter among green distractor letters. However, one distractor letter was red, hence unique. It is known that a unique distractor automatically captures attention (Duncan & Humphreys, 1989; Theeuwes et al., 2008; Theeuwes & van der Burg, 2008). In the Belopolsky and colleagues study, attention was less frequently directed towards the red distractor letter when the participants processed the local shape than when they processed the global shape prior to the search task (see also Van der Burg et al., 2012). It thus seems that what people perceive in their visual environment is not only determined by where people look at, but that it is also modulated by the extent to which they divide their attention across the visual field. As a result, important information may be missed, even when it is highly salient, under focused conditions relative to distributed settings.

While attentional tunneling (or focused attention) in these previous studies was caused by symbology, it is unknown whether it can also arise from aiming of the head to keep HMD symbology aligned with an external moving object. An HMD features a limited field-of-view (i.e., 30 deg in our study). This means that a pilot should continuously aim his/her head on-axis to see important flight parameters or to make off-axis Earth-fixed information visible. More accurate head aiming (i.e., within 1.5 deg in our study) can be necessary for system/weapon aiming with the helmet mounted cueing system. In the present simulator study we examine whether active head aiming can draw the pilot's attention away from the primary flight task. We asked military pilots to simultaneously perform an attitude control task and a head aiming task with an equal priority. The former consisted of manual compensation for roll disturbances of the aircraft, and the latter consisted of maintaining a moving visual target symbol inside a head-referenced ("slaved") circle. The size of this circle was varied to manipulate the difficulty of the head aiming task. Our hypothesis was that the head aiming task draws attention away from the attitude control task, leading to less accurate control performance. We expected worst performance in the condition with the small aiming circle (i.e., requiring high aiming precision, whereby attention is focused towards a local area) compared to a condition with a large circle and without head aiming.

Although HUD and HMD displays have been developed to increase situational awareness and to facilitate pilot performance, adding symbology (i.e., increasing visual clutter due to excess and/or disorganized items; Rosenholtz et al., 2007) to the visual environment may potentially lead to degradation of performance on both the head aiming and attitude task. Indeed, clutter leads to degradation of performance at some task (Rosenholtz et al., 2007). For instance, it is difficult to recognize a visual object in peripheral vision when surrounded by nearby clutter (i.e., visual crowding; see Whitney & Levi, 2011 for a review), and it is difficult to find a visual target in a cluttered environment (i.e., visual search; Wolfe, 1994). However, performance is only affected by clutter when the target and clutter have similar features, such as orientation, color, shape, luminance, motion, flicker (see, e.g., Bouma, 1970; Cass et al., 2011; Cass & Van der Burg, 2023; Duncan & Humphreys, 1989; Kong et al., 2016, 2017; Kooi et al., 1994; Van der Burg et al., 2017, 2019). In contrast, if a single target feature differs from the clutter feature (e.g., being the only red item among green items), then it becomes easy to find such a salient item (Itti et al., 1998; Wolfe & Horowitz, 2004). In the present study we created a “worst-case” clutter condition by adding both head- and aircraft-referenced objects with similar features as the target symbol, comparable to previous studies investigating visual crowding (see, e.g., Greenwood et al., 2012). In the clutter conditions, we expected that pilots experienced more effort to continuously track the moving target, making it more difficult to perform both the attitude- and head aiming tasks in synchrony.

The attitude control task consisted of three consecutive phases: a continuous roll disturbance of relatively small magnitude (i.e., low disturbance signal), followed by a sudden run-away of roll angle, and a continuous roll disturbances of relatively large magnitude (i.e., high disturbance signal). We expected better performance on both tasks during the low disturbance signal compared to the high disturbance signal. The sudden roll “run-away” was introduced to simulate unrecognized spatial disorientation (SD). SD usually occurs when the pilot’s attention is drawn away from the flight instruments, so that he or she does not notice deviations in aircraft attitude. We expected that the pilots’ response to this run-away will be delayed when engaged in the head aiming task.

During initial try-outs we noticed that several “Roll Reversal Errors” (RREs) were made during the attitude control task. An RRE is a roll control input in the *wrong direction* when a pilot is trying to stabilize the aircraft’s roll angle, leading to an increase, rather than the intended decrease, of roll angle (Landman et al., 2019, 2020; van den Hoed et al., 2022). Based on this observation we decided to also study the effect of head aiming on the number of RREs.

Methods

Participants

We recruited eighteen male pilots with a military background of the Royal Netherlands Airforce. Their mean age was 40.7 years (±standard deviation of 10.3), and they accumulated an average of 3015 (±2,479, ranging from 31 to 7800) flight hours, 607 (±668, ranging from 3 to 3050) simulator hours, and 492 (±635, ranging from 0 to 1950) hours flying with a HMD. Six pilots were not experienced in flying with an HMD. This research complied with the tenets of the Declaration of Helsinki and was approved by the Institutional Review Board at 2021-066 (TNO). Informed consent was obtained from each pilot.

Apparatus

The experiment was conducted in a fixed-base flight simulator of a fighter aircraft, consisting of a seat, sidestick, throttle, pedals and a cockpit display. The simulator was positioned inside a projection dome (h × v: 240 × 155° field-of-view) for presentation of outside imagery. The HMD, featuring 30° field-of-view, was simulated by projecting head-slaved HMD symbology as overlay in the out-the-window visual. The outside imagery, including the HMD symbology overlay, were presented at a visual distance of about 1.5 m. The location of the HMD symbology was driven by a head-tracker mounted on the audio headset. Figure 1 illustrates the experimental setup.

Procedure

The pilots performed an attitude control task, and a head aiming task simultaneously. The attitude control task required the pilot to maintain level flight and manually correct roll disturbances as accurately as possible by maintaining the aircraft wings level using the stick. No outside scenery was visible, requiring the pilots to use the HMD symbology for their attitude control task (i.e., a projected horizon line representing the artificial horizon). The artificial horizon consisted of a

Figure 1. Experimental setup. A pilot in the fixed-base flight simulator countering the roll disturbance with the stick (visually indicated by the horizon line, which spanned the whole outside world) while actively aiming his head (small dotted circle) on the moving visual target, as projected in the dome.

horizontal green line with small vertical lines at the top to indicate "up." The outside visual was uniform grey, like flying in a cloud, allowing the projected symbology to be brighter than the background. A simplified flight model was used which only required lateral input to correct for the roll disturbances. The task was performed without physical motion feedback, without engine sounds, and without cockpit flight instruments.

The roll disturbance was created with a prerecorded sum-of-sine disturbance signal on the aircraft's roll attitude. Within each run of 132 seconds the roll disturbance signal consisted of three consecutive phases. In Phase 1 (0–60 seconds) the sum-of-sine roll perturbation signal started with a small amplitude (low disturbance). In Phase 2 (60–72 seconds) a sustained roll disturbance to one side was introduced to simulate a roll "run-away." The run-away had an angular acceleration of $<3.0°/s^2$, which is around the vestibular threshold, so that in reality no vestibular sensation would occur. In Phase 3 (72–132 seconds) the sum-of-sine roll disturbance signal had a three times larger amplitude (high disturbance) than during Phase 1. Figure 2 illustrates the disturbance signal over time. Note that the roll disturbance signal was kept constant across all runs so that the task difficulty was equal across all six conditions. However, the sign of each phase was flipped randomly so that the pilots could not predict the roll disturbance signal.

The head aiming task required the pilot to continuously keep a moving visual target inside a head-slaved circle, both projected in the outside (uniform grey) imagery, by moving their head. The trajectory of the visual target (consisting of ten correlated sum-of-sines in both directions) was identical in each run to maintain the task difficulty across the different condition (see Figure 3).

The target consisted of a green cross (see Figure 4 for the experimental setup). The difficulty of the head aiming task was varied by using two diameters of the head aiming circle, with the assumption that a smaller circle requires greater (head-) tracking accuracy (i.e., keeping the moving target in the circle). The large circle diameter amounted to 30° (the diameter of current F-35 HMDs), the narrow circle diameter amounted to 1.5°, representative for current system/weapon aiming with helmet mounted cueing system. A control condition without head aiming (circle) was included as a baseline condition to examine whether head aiming had a significant effect on the attitude task performance.

Design

The experiment consisted of six different conditions: three Head aiming conditions, either with or without Clutter (see Figure 4). In the Clutter conditions, a combination of ~27 aircraft- and ~27 head-referenced information elements were added to the simulator projection within the 30 degrees radius. Each clutter element consisted of two crossing line segments with the intersection outside the center (ratio was 6:8) so that the clutter elements appeared noticeably different from the target.

Pilots practiced both tasks to become familiar with the setup, followed by a short questionnaire to verify whether the pilot was ready to conduct the experimental conditions. Subsequently, each pilot completed six runs representing the six conditions.

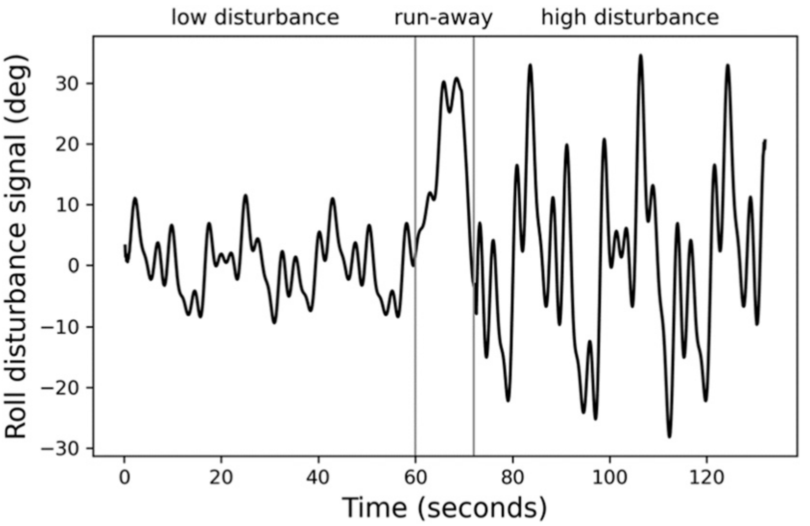

Figure 2. Roll disturbance signal over time. On top of the graph are the different phases signified.

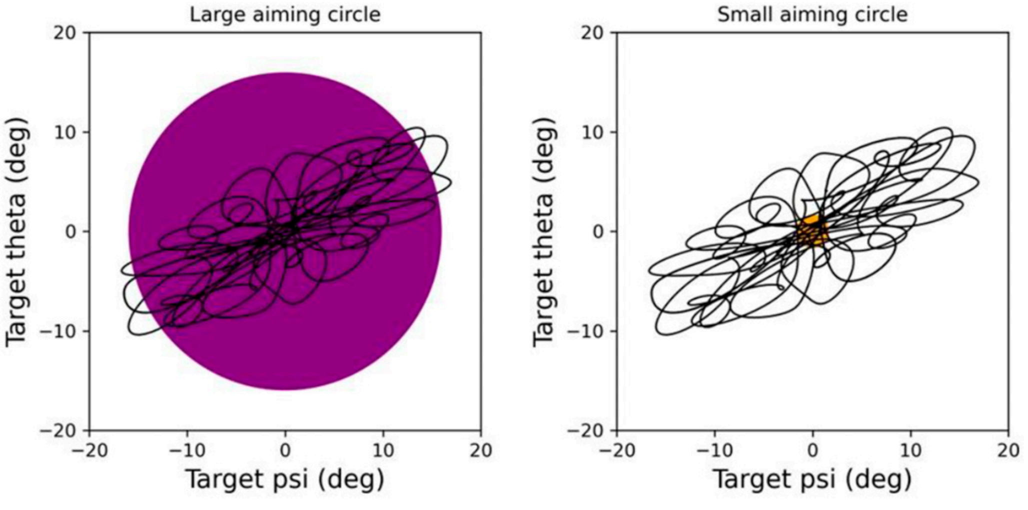

Figure 3. Visual target trajectory for the head aiming task. The big circle indicates the large aiming circle condition, and the small circle reflects the small aiming circle condition. The target trajectory (black lines) was the same across the different conditions. Target psi and target theta represent the horizontal and vertical angle with respect to the center of the aiming circle.

The order of the runs was counterbalanced across pilots using a Latin-square to avoid order effects. Between run 3 and 4 a short break was included. Each run was followed by a brief questionnaire (ratings on 10 cm Visual Analogue Scales (VAS; Gift, 1989)) regarding the perceived task performance and difficulty during the run they completed. Finally, a short postexperiment questionnaire (using VAS) was administered regarding the task interference and impact of clutter in general. The experiment lasted approximately 1.5 hour.

The following objective variables were logged (100 Hz sample frequency): (a) roll control input, (b) aircraft roll angle (i.e., amplitude) to measure

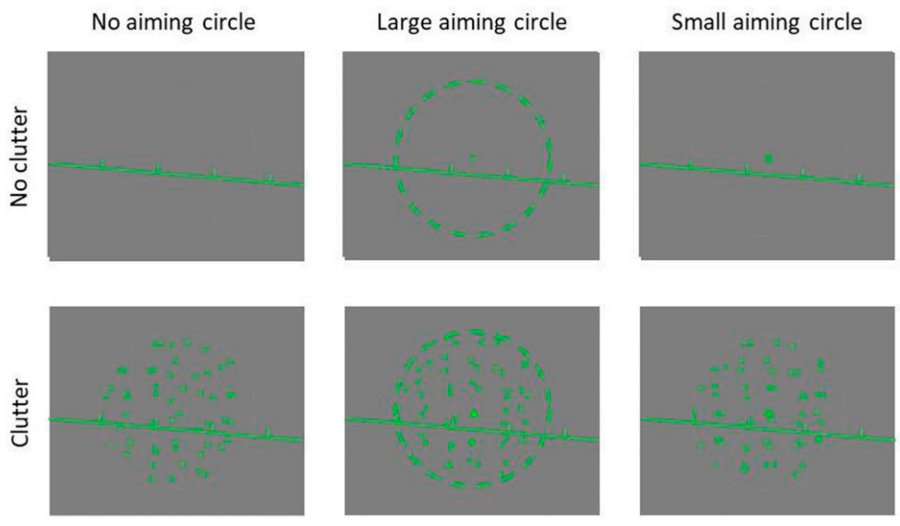

Figure 4. Symbology projected on the dome for the six different conditions: Three head aiming conditions (no head aiming, easy head aiming, difficult head aiming), and two clutter conditions (no clutter, with clutter). The plus-sign indicates the moving target symbol. The horizon line indicates the roll attitude which was shown at the front of the simulator cockpit and covered the entire width of the out-the-window display (see also Figure 1, left panel). The dotted circles indicate the viewing circle that should be aligned with the moving target.

attitude performance (i.e., variations and direction of deviation from straight-and-level, as well as time delay), and (c) deviation of head direction from visual target (i.e., angular distance and variations of deviation) to measure tracking performance. From the roll control input and aircraft roll angle the occurrence of Roll Reversal Error (RRE) was derived, defined as a roll stick movement in the opposite direction than required for wings-level recovery. We determined an RRE based on the criteria defined by Williams et al. (2018), that is, when the stick input >15% in combination with >5° roll error in the wrong direction.

Data Analysis

To allow for the response to "fade-in" we excluded the first 10 seconds of the run before running all the statistical analysis (unless otherwise stated). The data were Gaussian filtered with a kernel of 1 second. The statistics were performed using Just Another Statistical Program (JASP; Love et al., 2019). Alpha was set to .05, and p values were Huyn-Feldt corrected if sphericity was violated.

The analysis consisted of a repeated measures ANOVA on the mean Head aiming accuracy and mean head aiming error (i.e., Euclidean distance between the center of the head aiming circle and the target location) with Head aiming (large and small aiming circle), Clutter presence and roll Disturbance signal (low and high) as within-subject factors.

We conducted an ANOVA on the mean roll error with Disturbance signal, Clutter presence and Head aiming (no, large and small aiming circle) as within-subject factors.

For all conditions we identified RREs. We conducted an ANOVA on the mean number of RREs identified during the first and third phase of the Attitude control task (i.e., excluding the roll run-away phase because of its shorter duration and surprising run-away element) with Clutter, Head aiming and Disturbance signal as within-subject factors. Note that in this analysis all samples were included (also the first 10 seconds) so that the duration for the low and high gain disturbance signal was identical (i.e., 60 seconds), and therefore comparable.

In the run-away phase (i.e., Phase 2, starting at t = 60 s), the maximum roll error (i.e., maximum roll deviation from wings level) was computed at which the pilots responded to the deviating roll attitude. A larger maximum roll error indicates that it took longer to respond to the run-away. We conducted an ANOVA on the group mean number of RREs and maximum roll error with Clutter and Head aiming as within-subjects factors.

Results

In one condition, one pilot made a complete 360° (aileron) roll after ~100 seconds. Because this strategy deviated from the normal response (i.e., rolling back over the shortest distance back to wings level), we decided to only use the first 100 seconds of this pilot for this particular condition. Thus, the high disturbance phase for this pilot was computed between 72 and 100 seconds (instead of 72 and 132 seconds).

Familiarization

After the familiarization the pilots indicated that they were able to conduct the experiment (mean 97.7 ± 5.3, on a 0–100 scale), and confirmed that they were able to execute the control (mean 84.0 ± 12.3) and the head aiming task simultaneously (mean 85.5 ± 11.0).

Head Aiming Task: Accuracy

Figure 5(a) shows where the pilots kept the visual target during the head aiming task for each Clutter- and Head aiming combination Figure 5(b). A illustrates the mean Head aiming accuracy as function of time (or sample), for both Head aiming and Clutter conditions.

Figure 5(c) illustrates the mean head aiming accuracy (i.e., the ability to keep the target within the head aiming circle) as function of Head aiming and Clutter presence for the low and high disturbance phases. The ANOVA yielded a significant Head aiming, F (1, 17) = 187.8, p < .001, and Disturbance signal effect, F (1, 17) = 5.310, p = .034. The mean head aiming accuracy was higher with a low disturbance signal (.87) than high disturbance signal (.84). However, the effect of disturbance signal was dependent of Head aiming, as revealed by a significant Disturbance × Head aiming interaction, F (1, 17) = 5.317, p = .033. The effect of the disturbance signal was significant when the Head aiming circle was small (p = .033), but not when the Head aiming circle was large (where the performance was at a ceiling for both disturbance signal conditions: 1.0). All other effects failed to reach significance, all F values <1.

Attitude Control Task: Roll Error

Figure 6(a) illustrates the mean roll error in the attitude control task (i.e., mean roll deviation from wings level) as a function of time, Head aiming and Clutter presence.

Figure 6(b) illustrates the mean roll error as a function of Disturbance signal for each Clutter and Head aiming condition. The ANOVA yielded a significant Head aiming and Disturbance signal main effect, F (2, 34) = 83.464, p < .001, and F (1, 17) = 311.527, p < .001, respectively. Separate t-tests yielded a significant difference between each Head aiming level, all t values ≥5.313, all p values <.001. The Head aiming × Disturbance signal interaction was also significant, F (2, 34) = 5.301, p = .016. There was a trend towards a significant Clutter × Head aiming interaction, F (2, 34) = 3.336, p = .055. All other effects failed to reach significance, all F values <1.

Attitude Control Task: Roll Reversal Error

Figure 6(c) shows the group mean number of RREs as function of Disturbance signal and Clutter presence for each Head aiming condition. The ANOVA yielded a significant Head aiming effect, F (2, 34) = 12.546, p < .001. As revealed by two-tailed t-tests, there was a lower number of RREs when there was no aiming circle (mean 2.8 RREs) than when the aiming circle was large (mean 3.9; t (17) = 3.389, p < .001) and small (mean 4.9; t (17) = 4.099, p < .001). Moreover, the pilots made significantly less RREs in the easy aiming condition than in the difficult aiming condition, t (17) = 2.501, p = .023. Furthermore, the main effect of Disturbance signal was significant, F (1, 17) = 173.521, p < .001, and pilots made more RREs during the high disturbance signal (mean 7.0) compared to the low disturbance signal (mean 0.8). The Head aiming × Disturbance signal interaction was also significant, F (2, 34) = 3.992, p = .028, as the disturbance signal effect was larger when the Head aiming circle was small (mean 7.3) than it was large (mean 5.8; p = .040) and when there was no Head aiming circle (mean 5.3; p =

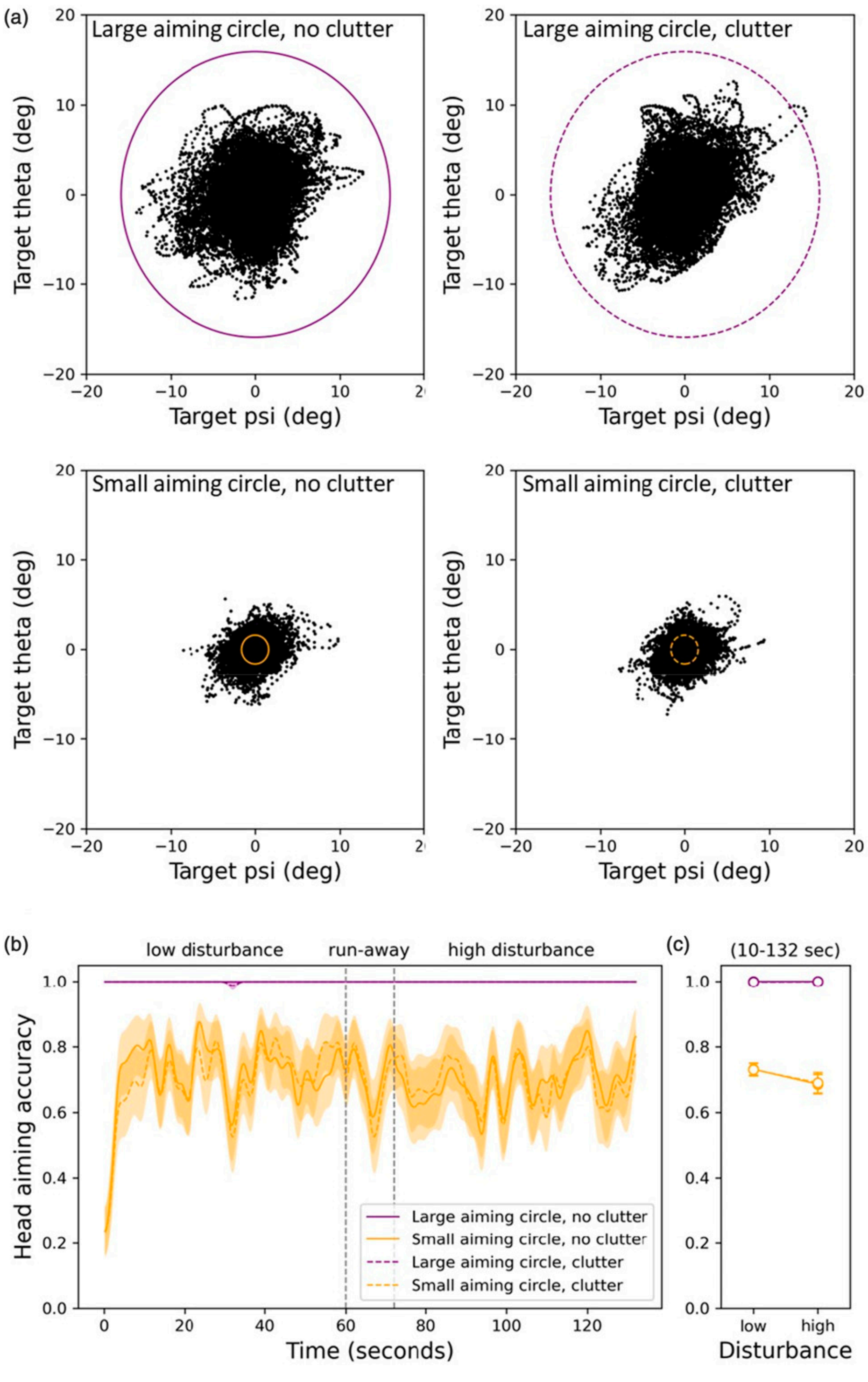

Figure 5. (a) Group mean misalignment of the visual target with respect to the center of the aiming circle for the two Clutter and two Head aiming conditions. Here, target psi and target theta represent the horizontal and vertical angle with respect to the center of the aiming circle. (b) Mean head aiming accuracy (i.e., the ability to keep the target within the head aiming circle) as function of time, Head aiming, and Clutter presence. The vertical dashed lines separate the three phases of roll disturbance (i.e., low disturbance, run-away, and high disturbance). (c) Mean head aiming accuracy as function of Disturbance signal (low or high), Clutter presence for both Head aiming conditions. For the analysis, the first 10 seconds of the response were discarded to account for the "fade-in" effect. The error bars represent the SEM.

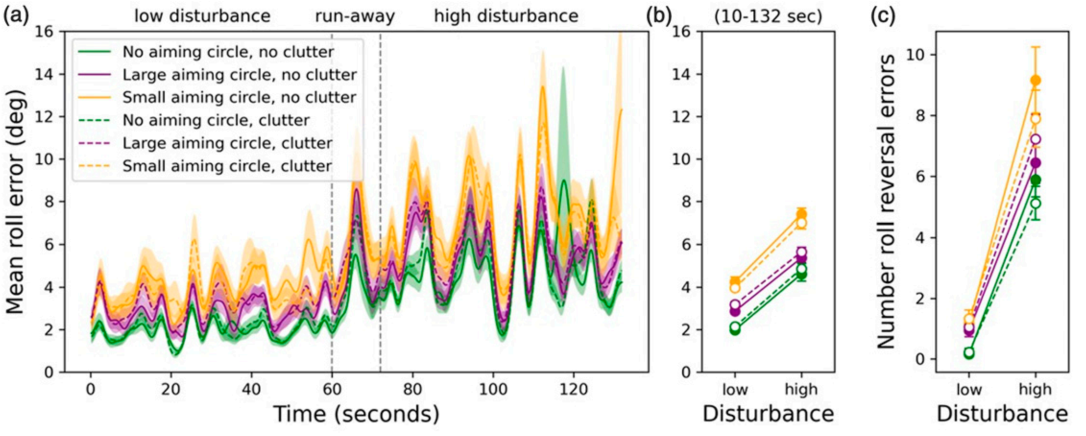

Figure 6. (a) Mean roll error as a function of time, Head aiming and Clutter presence. The vertical dashed lines separate the three phases of the roll disturbance task. (b) Mean roll error as function of Disturbance signal and Clutter presence for each Head aiming condition. The first 10 seconds of the response were discarded to account for any "fade-in" effect. (c) Mean number Roll Reversal Errors (RRE) as a function of disturbance signal and clutter presence for each head aiming condition. The error bars represent the SEM.

.024). The ANOVA yielded no other significant effects, all F values ≤1.647, all p values ≥.217.

Maximum Roll Error During Run-Away

Figure 7(a) shows the group mean maximum roll error for both Clutter conditions and Head aiming conditions during the run-away phase. The ANOVA yielded a significant Head aiming effect, F (2, 34) = 6.754, p = .003. Separate two-tailed t-tests yielded a significant difference between the no aiming circle condition and the small aiming circle condition (11.4° and 17.9°; t (17) = 3.785, p = .001). The large aiming circle condition (14.3°) was not significantly different from the no aiming circle condition, t (17) = 1.889, p = .076, and small aiming circle condition, t (17) = 1.768, p = .095. There was neither a main effect of Clutter, nor a significant two-way interaction, all F values <1.

Roll reversal Error During the Run-Away

Figure 7(b) illustrates the group mean number of RREs as function of Clutter presence for both Head aiming conditions during the run-away phase. The ANOVA yielded a significant head aiming effect, F (2, 34) = 6.554, p = .005. The pilots made fewer RRE when there was no aiming circle (0.2) than when the aiming circle was large (0.9) and small (0.9), t (17) = 2.712, p = .015, and t (17) = 3.688, p = .002, respectively. There was no significant difference between the large and small head aiming circle conditions, t (17) = 0.134, p = .895. The main effect of Clutter and the two-way interaction failed to reach significance, all F values <1.

During the run-away phase (regardless the presence of clutter), 6/18 (33%) pilots made at least one RRE in the no aiming circle condition, 11/18 (61%) in the large aiming circle condition; and 14/18 (78%) in the small aiming circle condition.

Questionnaire After Each Run

Table 1 illustrates the group mean subjective ratings provided after each run.

Subjective Performance on Both Tasks

An ANOVA with Clutter and Head aiming (large and small circle) as within-subject factors, showed that subjective Head aiming performance was rated significantly better when the aiming circle was large than when it was small, F (1, 17) = 14.342, p = .001. An ANOVA on subjective attitude performance with Clutter and Head aiming (No, Small, and Large circle) as within-subjects factors showed that this variable was significantly affected by Head aiming,

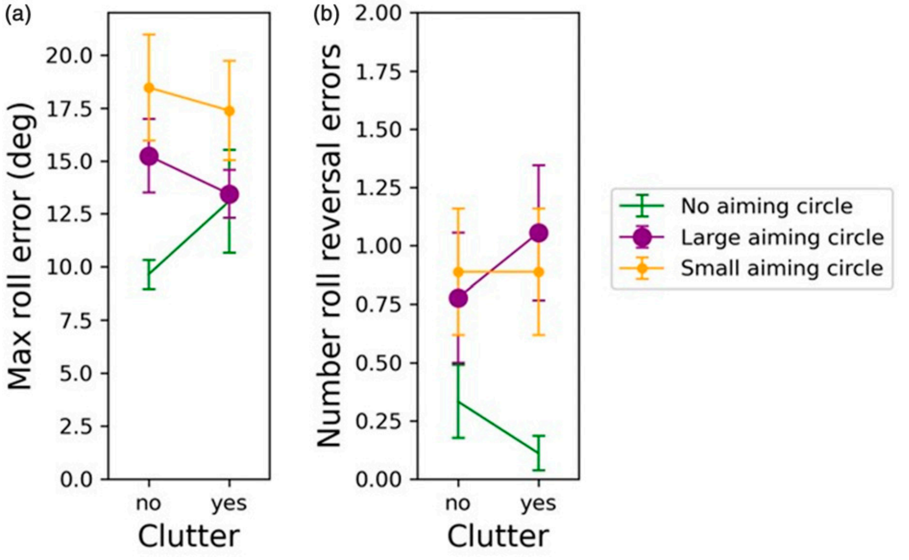

Figure 7. The group mean results of two dependent variables computed during the roll run-away phase as function of Clutter and Head aiming. (a) Maximum roll error. (b) Number of RREs. The error bars represent the SEM.

Table 1. Group Mean (M) Scores and Standard Deviations (SD) for the Subjective Measure After Each run (on a Scale From 0 to 100).

	No Clutter						Clutter					
	Small Aiming Circle		Large Aiming Circle		No Aiming Circle		Small Aiming Circle		Large Aiming Circle		No Aiming Circle	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Perform attitude control	69.5	16.4	82.8	14.3	92.5	8.2	71.7	16.9	82.6	15.4	91.3	9.3
Aware of roll attitude	64.0	25.9	79.7	26.8	97.3	4.9	69.7	22.3	81.1	24.5	95.2	8.8
Perform head aiming	73.5	19.4	88.5	10.6			74.8	20.9	86.8	13.1		
Attentional focus	53.1	37.6	29.2	33.6			52.6	31.2	25.8	28.3		
Attention attitude contr	38.3	12.5	52.2	19.3			40.8	12.0	52.5	15.4		
Attention head aiming	61.7	12.5	47.8	19.3			59.2	12.0	47.5	15.4		
Dual task effort	49.6	27.9	29.7	26.7			50.4	28.7	33.3	25.9		
Clutter irritation							42.2	23.7	36.9	23.9	16.6	19.5

$F(2, 34) = 33.974$, $p < .001$. The subjective Attitude performance was rated significantly lower when the head aiming circle was small than when it was large, $t(17) = 5.432$, $p < .001$, and no head aiming condition, $t(17) = 6.678$, $p < .001$. The subjective attitude performance were also significantly lower when the head aiming circle was large compared to when there was no head aiming circle, $t(17) = 4.100$, $p < .001$. The effect of Clutter and the two-way interaction were not significant for both subjective measures, all F values <1.

Attitude Awareness and Attentional Focus

Similar to the analysis of the subjective performance, we conducted two separate ANOVAs on these two variables. The ANOVA on attentional focus yielded a significant Head aiming effect, as the pilots experienced more attentional focus when the head aiming circle was small than when it was large, F (1, 17) = 17.369, $p <$ .001. There was also a significant effect of Head aiming difficulty on the attitude awareness rating, F (2, 34) = 19.395, $p < .001$. Further examination by t-tests, showed that pilots were more aware of the roll attitude when there was no head aiming circle than when the head aiming circle was large, t (17) = 3.239, $p = .005$, and small, t (17) = 5.364, $p < .001$. Furthermore, pilots were more aware of the roll attitude when the aiming circle was large than when it was, t (17) = 3.760, $p = .002$. For both ANOVAs, all other effects failed to reach significance, all F values ≤1.416, all p values ≥.257.

Attention Percentage

An ANOVA on the mean percentage of attention dedicated to the head aiming task, with Clutter and Head aiming conditions as within-subject factors, showed a significant Head aiming effect, F (1, 17) = 14.079, $p = .002$. On average, the pilots devoted more attention to the head aiming task when the head aiming circle was small than when it was large. All other effects failed to reach significance, all F values <1.

We conducted a similar ANOVA on the mean dual task effort. There was a significant Head aiming effect, F (1, 17) = 51.676, $p < .001$, indicating that more effort was required to perform both tasks when the head aiming circle was small than when it was large. The Clutter effect and the two-way interaction were not significant, F (1, 17) = 3.168, $p = .093$, and F <1, respectively.

Clutter Effect

Finally, an ANOVA on the mean rating with Head aiming (no, large or small circle) as within-subject factor showed a significant Head aiming effect, F (2, 34) = 8.781, $p = .002$. The tasks were rated as less difficult with no aiming circle than with a large, t (17) = 2.966, $p = .009$, and small head aiming circle, t (17) = 3.284, $p = .004$. The small and large aiming circle conditions were not significantly different from each other, t (17) = 1.280, $p = .218$.

Postexperiment Questionnaire

The ratings on Attitude priority and Head aiming priority, obtained in the postexperiment questionnaire, amounted to 59.9 (±32.8), and 52.6 (±28.9), respectively. This indicates that both tasks were prioritized equally. Furthermore, an average rating of 88.3 (±19.2) for Head aiming difficulty shows that the small circle made the task more difficult to perform. In comparison, the impact of visual clutter was rated on average by 49.2 (±32.5).

According to the answers to the open questions in the postexperiment questionnaire, the pilots applied different strategies for the different conditions, mostly driven by the required accuracy of the head aiming task. While keeping the moving visual target within the large circle, most pilots focused on the Attitude control task in the easy head aiming conditions. Attention distribution was the other way around in the difficult head aiming condition as head aiming required more attention. To perform the attitude control task in this condition, the pilots kept the artificial horizon more in their peripheral vision.

Furthermore, all pilots indicated that the roll run-away had a significant impact on their performance. The sudden and sustained roll disturbance resulted in a shift of attention towards the Attitude control task at the expense of the Head aiming task. One pilot indicated that this run-away was a reason to adjust his steering behavior from closed-loop steering to open-loop steering (i.e., giving short inputs and assessing the effect, instead of giving a continuous steering signal).

Finally, 16 out the 18 pilots reported to have experienced one or more RREs during the experiment. Some comments indicated that RREs were more likely to occur during large head movements required to follow the moving target, especially when the head aiming circle was small. Other comments indicated that RREs were more frequent in the clutter conditions.

Discussion

We examined whether an active head aiming task using an HMD increases the risk of attentional tunneling by drawing attention away from the manual control task. These two tasks are highly relevant in military flight operations, where pilots monitor and control the aircraft's attitude, while directing their head to aim HMD symbology on external (moving) objects.

The objective results showed interference between the attitude control and head aiming task. On the one hand, the head aiming accuracy was significantly lower when the roll disturbances in the attitude control task were large, compared to the phase in which the roll disturbances were small. On the other hand, the performance of the attitude control task deteriorated when the pilots were performing the head aiming task. These findings are supported by the subjective ratings of the pilots, indicating that both tasks influenced each other equally. Interestingly, the negative effect of head aiming on the attitude control task was even present in the exceptionally easy head aiming condition with the large aiming circle. This effect further increased when the head aiming circle was small, which required more precision and most likely forced the pilots to adapt a small attentional window (i.e., by focusing attention to the moving target). Because the diameter of the small circle is representative of HMD symbology (e.g., weapon aiming), these results indicate that such aiming task may draw attention away from the flight task. Hence, in addition to the previously reported attentional tunneling caused by the HMD symbology itself (Melzer, 2012; Mustonen et al., 2013; Wickens & Alexander, 2009), our results suggest that active head aiming of that symbology towards external targets may increase the risk of attentional tunneling even more while flying in degraded visual environments.

Roll Reversal Errors

Besides the negative effect of head aiming on the accuracy of the attitude control task, it also resulted in more RRE occurrences during low and high disturbance signals. Subjectively, the pilots were more aware of making RREs when there was no head aiming circle than the other head aiming conditions. This supports the notion that the pilots' attention was captured by the head aiming task at the cost of the attitude control task. The maximum roll error in the run-away phase showed that pilots responded later, that is, at a larger roll error, with a small head aiming circle. The increased response time suggests that the attention for the head aiming task increased the risk of unrecognized SD (so-called SD type I). Head aiming not only increased the response time in a "run-away" scenario, it also increased the chance to make an RRE. The proportion of pilots making RREs increased with decreasing head aiming circle size from 33% to 77%.

Whereas in previous studies RREs were attributed to an inside-out versus inside-in misinterpretation of the artificial horizon shown on the attitude indicator (e.g., Landman et al., 2019, 2020; van den Hoed et al., 2022). The pilots in our study relied on the "true" horizon as a visual overlay in the out-the-window visuals. This means that it is unlikely to explain the RREs in the run-away phase by a misinterpretation of the horizon symbology. Possibly it can be explained by a perceptual/cognitive effect. Often it is the moving part on a visual display that is being controlled, whereas in our study both the projected horizon and the head aiming circle were moving. Whereas the pilot moved their head *with* the moving visual target symbol, a control input in *opposite* direction was required to compensate a roll disturbance. This inconsistency in direction (i.e., incompatible motion, Sanders & McCormick, 1993; Wickens, 1992) may explain the confusion in which direction to compensate the attitude disturbance (i.e., the horizon symbology) and head aiming task (i.e., the moving target symbol).

Effects of Clutter

The pilots indicated that they experienced the clutter as more disturbing when performing a head aiming task compared to the no head aiming condition. This corroborates a study reporting that high-clutter displays increases the subjective workload compared to low-clutter displays during a landing procedure (Alexander et al., 2012). Nevertheless, in our study the presence of clutter had no significant effect on the objective performance measures. The lack of a clutter effect was surprising since it is known from the literature that it is difficult to find or identify a visual target when it is surrounded by nearby *similar* distractor objects (Bouma, 1970; Cass et al., 2011; Cass & Van der Burg, 2023; Duncan & Humphreys, 1989; Kong et al., 2016, 2017; Kooi et al., 1994; Rosenholtz et al., 2007; Van der Burg et al., 2017;

Whitney & Levi, 2011). In our case, the clutter was similar to the target in terms of size, color, luminance, orientation and even shape and, the clutter made it even more difficult to track the moving target due to occlusion (see Figure 4). An explanation for the lack of a clutter effect was that tracking of the target was (too) easy since it moved in an unpredictable, and hence salient, manner compared to the aircraft-fixed objects, and also to the head-fixed objects. As a result, the target was unique in terms of motion direction (compared to the distractor motion directions), making it easy to track the target and to ignore the clutter. This is consistent with a recent study, showing that a moving target captures attention among other moving objects (clutter), if these objects move briefly in other directions (Van der Burg et al., 2019). Although this might explain why we did not objectively observe a clutter effect, it does not explain why the pilots experienced the clutter as disturbing. Alternatively, it is feasible that due to the densely cluttered environment, the presence of clutter actually forced the pilots to continuously fixate on the moving target while performing the attitude task in peripheral vision. This may explain why pilots experienced the clutter as disturbing. Furthermore, it may also explain why we did not find an effect of clutter on objective measures, since it is difficult to distinguish the target from clutter when observed in peripheral vision, but not when one fixates at the target (i.e., foveal vision; Bouma, 1970).

Limitations and Strengths

This study had several limitations that should be acknowledged when generalizing the results to (military) operational practice. First, the experiment was performed in a fixed-base simulator, so that the pilots did not receive physical motion feedback on the attitude control task. However, the sustained disturbance had an angular acceleration of $<3.0°/s^2$, which is around the vestibular threshold, so that in reality no vestibular sensation would occur. Nevertheless, in the future it would be interesting to replicate the experiment using a motion platform to examine whether motion feedback affects the performance on the attitude and head aiming tasks, with the same and even larger angular accelerations. Second, a generic flight model was used with control authority in roll direction only, which simplified the attitude control task significantly. Third, instead of using a real HMD, the symbology was projected as a head-slaved overlay in the out-the-window visuals. Nevertheless, the results provide evidence for the phenomenon of attentional tunneling in an empty simulation environment when using head-slaved symbology. Finally, it is important to mention that participants had no view of the outside world (as if they were flying in clouds) so that they were forced to use the artificial horizon line only. This raises the question whether the findings of the current study exclusively pertain to zero-visibility conditions. However, it is important to emphasize that the artificial horizon remained clearly visible during the experiment and that pilots could easily perform the task. Consequently, it is possible that the outcomes hold relevance for scenarios where pilots can access naturalistic horizons or employ alternative resources such as cockpit instruments to perform the attitude task. This is particularly pertinent when natural horizons may be obscured by geographical features (e.g., mountains or clouds), requiring pilots to focus on specific horizon segments or even turn their head towards the cockpit instruments. Future research could explore the impact of head aiming on the attitude control task under various visual conditions, encompassing scenarios where pilots have the freedom to use cockpit instruments, or the naturalistic horizon to perform both tasks concurrently.

Besides these limitations, the study also had several strengths. First, we deliberately used simple and abstract stimuli, allowing us to demonstrate the effect of aiming head-slaved symbology on attentional tunneling in a controlled manner, without the distractions involved in more complex, operational tasks. In fact, by using a visual target that was so similar (in terms of color, luminance, size, orientation, and shape) to the clutter symbols, we were able to create a kind of "worst case" clutter condition. In contrast, in natural scenes it is much easier to segregate visual objects from each other due to complex structures (making them all very different and unique), making it unlikely that clutter has any effect on the attitude- or head aiming task. A final strength that we identify is that any differences across the conditions cannot be attributed to the trajectory of the visual target nor to the disturbance signal (i.e., task difficulty) as they were kept constant across the different conditions and pilots. As a result, the differences between conditions can only be explained by the size of the head aiming circle, and the amplitude of the roll disturbance signal.

Taken together, the results show that a visual tracking task with an HMD may increase the risk of attentional tunneling in pilots while flying in the clouds, leading to an increment of RREs and less accuracy on a simultaneously performed attitude control task, which may increase the risk for unrecognized spatial disorientation. Further research could explore which solutions, such as changing symbology or implementing training, can reduce attentional tunneling.

Key Points

- A visual tracking task with an HMD may increase the risk of attentional tunneling in pilots while flying in the clouds, leading to less accuracy on a simultaneously performed attitude control task.
- Attentional tunneling may increase the risk for unrecognized spatial disorientation.
- The presence of clutter had no significant effect on the objective performance measures, but increased subjective disturbance.

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Declaration of Conflicting Interests

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ORCID iD

Erik Van der Burg https://orcid.org/0000-0003-2522-7925

References

Alexander, A. L., Kaber, D. B., Kim, S.-H., Stelzer, E. M., Kaufmann, K., & Prinzel, L. J. (2012). Measurement and modeling of display clutter in advanced flight deck technologies. *The International Journal of Aviation Psychology*, *22*(4), 299–318. https://doi.org/10.1080/10508414.2012.718233

Belopolsky, A. V., Zwaan, L., Theeuwes, J., & Kramer, A. F. (2007). The size of an attentional window modulates attentional capture by color singletons. *Psychonomic Bulletin & Review*, *14*(5), 934–938. https://doi.org/10.3758/BF03194124

Bouma, H. (1970). Interaction effects in parafoveal letter recognition. *Nature*, *226*(5241). 177. https://doi.org/10.1038/226177a0

Cass, J. & Van der Burg, E. (2023). Visual crowding: Double dissociation between orientation and brightness judgments. *Journal of Vision*, *23*(5), 7. https://doi.org/10.1167/jov.23.5.7

Cass, J., Van der Burg, E., & Alais, D. (2011). Finding flicker: Critical differences in temporal frequency capture attention. *Frontiers in Psychology*, *2*(320), 320. https://doi.org/10.3389/fpsyg.2011.00320

Duncan, J. & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review*, *96*(3), 433–458. https://doi.org/10.1037/0033-295X.96.3.433

Fischer, E. & Haines, R. F. (1980). *Cognitive issues in head-up displays*. https://ntrs.nasa.gov/citations/19810005125

Gift, A. G. (1989). Visual analogue scales: Measurement of subjective phenomena. *Nursing Research*, *38*(5), 286–288. https://doi.org/10.1097/00006199-198909000-00006

Greenwood, J. A., Bex, P. J., & Dakin, S. C. (2012). Crowding follows the binding of relative position and orientation. *Journal of Vision*, *12*(3), 18. https://doi.org/10.1167/12.3.18

Itti, L., Koch, C., & Niebur, E. (1998). A model of saliency-based visual attention for rapid scene analysis. *IEEE Transactions on Pattern Analysis and*

Machine Intelligence, *20*(11), 1254–1259. https://doi.org/10.1109/34.730558

Kong, G., Alais, D., & Van der Burg, E. (2016). An investigation of linear separability in visual search for color suggests a role of recognizability. *Journal of Experimental Psychology. Human Perception and Performance*, *42*(11), 1724–1738. https://doi.org/10.1037/xhp0000249

Kong, G., Alais, D., & Van der Burg, E. (2017). Orientation categories used in guidance of attention in visual search can differ in strength. *Attention, Perception, & Psychophysics*, *79*(8), 2246–2256. https://doi.org/10.3758/s13414-017-1387-5

Kooi, F. L., Toet, A., Tripathy, S. P., & Levi, D. M. (1994). The effect of similarity and duration on spatial interaction in peripheral vision. *Spatial Vision*, *8*(2), 255–279. https://doi.org/10.1163/156856894x00350

Landman, A., Davies, S., Groen, E. L., van Paassen, M. M., Lawson, N. J., Bronkhorst, A. W., & Mulder, M. (2019). In-flight spatial disorientation induces roll reversal errors when using the attitude indicator. *Applied Ergonomics*, *81*(2), Article 102905. https://doi.org/10.1016/j.apergo.2019.102905

Landman, A., Groen, E. L., van Paassen, M. M., Bronkhorst, A. W., & Mulder, M. (2020). Expectation causes misperception of the attitude indicator in nonpilots: A fixed-base simulator experiment. *Perception*, *49*(2), 155–168. https://doi.org/10.1177/0301006619901053

Love, J., Selker, R., Marsman, M., Jamil, T., Dropmann, D., Verhagen, J., Ly, A., Gronau, Q. F., Šmíra, M., Epskamp, S., Matzke, D., Wild, A., Knight, P., Rouder, J. N., Morey, R. D., & Wagenmakers, E.-J. (2019). JASP: Graphical statistical software for common statistical designs. *Journal of Statistical Software*, *88*(2), 1–17. https://doi.org/10.18637/jss.v088.i02

Melzer, J. (2012). HMDs as enablers of situation awareness: The OODA loop and sense-making. In Proceedings of SPIE - The international society for optical engineering (Vol. *8383*). SPIE. https://doi.org/10.1117/12.920844

Mustonen, T., Berg, M., Kaistinen, J., Kawai, T., & Häkkinen, J. (2013). Visual task performance using a monocular see-through head-mounted display (HMD) while walking. *Journal of Experimental Psychology. Applied*, *19*(4), 333–344. https://doi.org/10.1037/a0034635

Rosenholtz, R., Li, Y., & Nakano, L. (2007). Measuring visual clutter. *Journal of Vision*, *7*(2), 17. https://doi.org/10.1167/7.2.17

Sanders, M. S. & McCormick, E. J. (1993). *Human factors in engineering and design*, 7th ed. (pp. xiii, 790). Mcgraw-Hill Book Company.

Theeuwes, J. & van der Burg, E. (2008). The role of cueing in attentional capture. *Visual Cognition*, *16*(2-3), 232–247. https://doi.org/10.1080/13506280701462525

Theeuwes, J., Van der Burg, E., & Belopolsky, A. (2008). Detecting the presence of a singleton involves focal attention. *Psychonomic Bulletin & Review*, *15*(3), 555–560. https://doi.org/10.3758/PBR.15.3.555

van den Hoed, A., Landman, A., Van Baelen, D., Stroosma, O., van Paassen, M. M. R., Groen, E. L., & Mulder, M. (2022). Leans illusion in hexapod simulator facilitates erroneous responses to artificial horizon in airline pilots. *Human Factors*, *64*(6), 962–972. https://doi.org/10.1177/0018720820975248

Van der Burg, E., Cass, J., & Theeuwes, J. (2019). Changes (but not differences) in motion direction fail to capture attention. *Vision Research*, *165*, 54–63. https://doi.org/10.1016/j.visres.2019.09.008

Van der Burg, E., Olivers, C. N. L., & Cass, J. (2017). Evolving the keys to visual crowding. *Journal of Experimental Psychology: Human Perception and Performance*, *43*(4), 690–699. https://doi.org/10.1037/xhp0000337

Van der Burg, E., Olivers, C. N. L., & Theeuwes, J. (2012). The attentional window modulates capture by audiovisual events. *PLoS One*, *7*(7), Article e39137. https://doi.org/10.1371/journal.pone.0039137

Whitney, D. & Levi, D. M. (2011). Visual crowding: A fundamental limit on conscious perception and object recognition. *Trends in Cognitive Sciences*, *15*(4), 160–168. https://doi.org/10.1016/j.tics.2011.02.005

Wickens, C. D. (1992). *Engineering psychology and human performance*, 2nd ed. (pp. xv, 560). HarperCollins Publishers.

Wickens, C. D. (2005). Attentional tunneling and task management.

Wickens, C. D. & Alexander, A. L. (2009). Attentional tunneling and task management in synthetic vision displays. *The International Journal of Aviation Psychology*, *19*(2), 182–199. https://doi.org/10.1080/10508410902766549

Williams, H. P., Horning, D. S., Lawson, B. D., Powell, C. R., & Patterson, F. R. (2018). *Effects of various types of cockpit workload on incidence of spatial disorientation in simulated flight*. https://apps.dtic.mil/sti/citations/AD1063191

Wolfe, J. M. (1994). Guided Search 2.0 A revised model of visual search. *Psychonomic Bulletin & Review*, *1*(2), 202–238. https://doi.org/10.3758/BF03200774

Wolfe, J. M. & Horowitz, T. S. (2004). What attributes guide the deployment of visual attention and how do they do it? *Nature Reviews Neuroscience*, *5*(6). 495. https://doi.org/10.1038/nrn1411

Author Biographies

Erik Van der Burg, TNO Human Factors, Soesterberg, Netherlands, and Brain and Cognition, University of Amsterdam, Netherlands, PhD (Cognitive Psychology, 2009, Vrije Universiteit Amsterdam).

Wietse Ledegang, TNO Human Factors, Soesterberg, Netherlands, MSc (Aerospace Engineering, 2008, Delft University of Technology)

Frank L. Kooi, TNO Human Factors, Soesterberg, Netherlands, PhD (Physiological Optics, 1990, University of California at Berkeley).

Mark M.J. Houben, TNO Human Factors, Soesterberg, Netherlands, PhD (Psychoacoustics, 2002, Eindhoven University of Technology)

Eric L. Groen, TNO Human Factors, Soesterberg, Netherlands, and Visiting Professor, Cranfield University, UK, PhD (Human Physiology, 1997, Utrecht University).