Failure to Replicate the Aubert-Fleischl Effect

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Abstract

For many years the accepted wisdom in vision science has been that humans tend to underestimate the speed of an object when they pursue it with their gaze in comparison to when they fixate a spot in the visual scene and the object moves across the retina, an effect that is referred to as the Aubert-Fleischl phenomenon. However, experiments on the Aubert-Fleischl effect have generally employed a target moving in front of a blank background. For objects moving in the real world, relative motion between the object and the background provides additional cues, potentially allowing the visual system to compensate for the Aubert-Fleischl phenomenon. To test this hypothesis, we asked 50 participants to compare the speed of a single sphere to the speed of a sphere-cloud in a two-interval forced-choice task while they either followed the single sphere with their gaze or kept their eyes on a fixation cross. Stimuli were presented in virtual reality and the sphere's movement could occur either in a completely black environment with no relative motion cues present, or against a visible, textured background behind the moving sphere. The probe sphere-cloud always moved in front of the same background as the target. In a large data set (n = 50), we found no evidence for an Aubert-Fleischl effect, i.e., no evidence for an underestimation of speed during pursuit relative to fixation, in either of the environments. Our results challenge the prevailing notion that object speed is underestimated when the object is pursued versus when fixation is maintained and highlights the necessity to take into account characteristics of the visual scene.

Introduction

The Aubert-Fleischl phenomenon is the underestimation of the perceived speed of a target when an observer pursues it with their gaze compared to when viewing the same target moving across the retina during fixation (Aubert, 1886, 1887; de Graaf et al., 1991; Fleischl, 1882; Gibson et al., 1957; Mack & Herman, 1973; Miyamoto et al., 2021; Wertheim, 1981; Wertheim & Van Gelder, 1990). In a related phenomenon, the Filehne illusion, non-fixated stationary objects can appear to move when their images are dragged across the retina during smooth pursuit of another target (Filehne, 1922; Mack & Herman, 1973, 1978; Wertheim, 1981). Differences between speed perception during pursuit and fixation arise from differences in the speed cues at play: while retinal cues are, in principle, sufficient to estimate the speed of a target moving across a fixated stationary scene, during pursuit the observer has to take into account both retinal and oculomotor cues to speed. The perceived speed of the eyes is thought to be underestimated based on oculomotor cues alone (Aubert, 1887; Garzorz et al., 2018; Mack & Herman, 1973, 1978). This then leads an observer to underestimate object speed when eye velocity is the only

1 source of information (in the Aubert-Fleischl phenomenon) or to illusory motion of the scene (in the
2 Filehne illusion).

3 The Aubert-Fleischl phenomenon is part of the reason why experiments on speed perception and time-
4 to-contact estimation often require observers to keep their gaze on a fixation cross (Jörges & Harris, 2021,
5 2023). Embedding a tracked target into a visual scene provides additional cues to the speed of the eye –
6 specifically relative motion between the target and the background – which should therefore make it
7 easier to estimate the speed of an object accurately both during fixation and smooth pursuit. Credibility
8 is lent to this idea by a study showing that relative motion supersedes absolute retinal motion for speed
9 judgements under a variety of circumstances (Freeman et al., 2009). The – to our knowledge – most recent
10 model on the Aubert-Fleischl effect (Freeman et al., 2010). This model predicts the Aubert-Fleischl
11 phenomenon via the observation that relative speed judgements become less precise, which in turn
12 would make the slow-motion prior (Stocker & Simoncelli, 2006) affect perceived speed more strongly.
13 Overall, this model predicts that adding more reliable motion cues should decrease or potentially even
14 fully eliminate the Aubert-Fleischl effect. And in fact, some of the older studies on the Aubert-Fleischl
15 effect (Gibson et al., 1957), where some relative motion cues were present, failed to find a difference
16 between fixation and pursuit. Even Aubert himself was aware of the fact that relative motion between a
17 moving target and a static target might affect perceived speed but he did not specifically address to what
18 extent the presence of static object or a background might impact the Aubert-Fleischl effect (Aubert,
19 1886, 1887). If the Aubert-Fleischl effect is, indeed, not present under such circumstances, this would
20 provide researchers with more flexibility to allow their participants to pursue targets, have them keep
21 their gaze on a fixation cross, or allow natural free viewing. This project aims to provide conclusive
22 evidence by first attempting to reproduce the original Aubert-Fleischl effect in a VR set-up, and then
23 making it disappear by adding relative motion cues between the target and background. Another practical
24 consideration for research practice is that most of the studies into the Aubert-Fleischl effect (with some
25 notable exceptions; Dodge, 1904; Mack & Herman, 1973; Miyamoto et al., 2021) did not use individual
26 targets for speed judgements, but rather gratings or other repeating patterns (Aubert, 1887; Brown, 1931;
27 de Graaf et al., 1991; Fleischl, 1882; Freeman & Banks, 1998; Freeman et al., 2010; Gibson et al., 1957;
28 Turano & Heidenreich, 1999). Given some studies (Freeman & Banks, 1998; Freeman et al., 2010; Sumnall
29 et al., 2003) investigating the interactions between stimulus characteristics and the Aubert-Fleischl effect,
30 and given that many studies in areas such as time-to-contact estimation and speed perception use single
31 targets rather than target patterns and gratings, it seems important to determine whether the Aubert-
32 Fleischl effect actually applies to individual stimuli.

33 Our two hypotheses are:

34   1. The Aubert-Fleischl effect can occur while tracking a target in a VR display when all relative
35   motion cues between background and target are removed.
36   2. The Aubert-Fleischl effect disappears in the presence of relative motion cues between
37   background and target (as in most VR applications).

38

1 Methods

2 Participants

3 We collected data until 50 participants had successfully completed the initial eye movement training and
4 the two-interval forced-choice task training (see Power Analysis in Appendix C); this was achieved after
5 testing a total of 69 participants (23 men, mean age = 22.5 years; 41 women, mean age = 21.7 years; 4
6 participants declined to answer, mean age = 20.9 years). All participants had normal or corrected-to-
7 normal vision. Participants were recruited between May 2023 and February 2024 from the York University
8 undergraduate participant pool and were rewarded with course credit. The study was approved by the
9 York University Board of Research Ethics and was conducted in accordance with the principles of the
10 Declaration of Helsinki. All participants signed an informed consent form to indicate their written consent.

11 Apparatus

12 Our stimuli were presented in an HTC VIVE Pro Eye head-mounted device with a 90 Hz refresh rate, a
13 diagonal field of view of 110° and a resolution of 1080 x 1200 pixels. Participants responded with the HTC
14 VIVE Pro Eye controllers. The VIVE Pro Eye records eye-movements at 120 Hz (binocular) with a spatial
15 accuracy of 0.5° to 1.1°. The program used to collect data was built in Unity (v. 2020.3.14f). For the "no
16 relative motion" condition (see below), we attached Kodak ND9 filters to the lenses of a VIVE Pro Eye to
17 make sure that the edge between the lenses and the plastic fixture were not visible and did not provide
18 any relative motion cues. This was necessary because even when no ambient lighting is simulated via
19 Unity, the VIVE Pro Eye's pixels never fully turn off, making for a distinctly visible visual edge even at the
20 lowest brightness settings. The VIVE Pro Eye eye-tracker was, unfortunately, not able to record eye
21 movements under these conditions; see below for measures that we put in place to ensure that
22 participants followed gaze instructions even when we could not verify their behavior.

23 Stimulus

24 In a two-alternative forced-choice task, participants judged the speed of a red target sphere that moved
25 from either left to right or from right to left against the speed of a sphere cloud that moved in the same
26 direction as the target and that could be presented either before or after the single red sphere. The reason
27 we chose a sphere cloud as our comparison stimulus is that comparing the speed of a single sphere to the
28 speed of another single sphere would allow the observer to use either the ball's travel distance (when
29 presentation time was matched) or presentation time (when traveled distance was matched) rather than
30 its speed. In this sense, the sphere cloud is akin to a 3D moving Gabor patch in that it allows us to decouple
31 speed, distance, and presentation time. See Figure 2B for the temporal sequence of presentation within
32 each trial.

33 The sphere was simulated as being 7.5 m in front of the observer with a diameter of 0.2 m (corresponding
34 to a visual angle of 1.47° at the midpoint of its trajectory and 1.53° at its right and left-most positions).
35 The wall was simulated as being 0.5 m behind the sphere i.e., 8 m in front of the observer. The sphere was
36 visible for 1.1 s in total, which was divided in three phases: an acceleration or entrainment phase (0.3 s),
37 a constant speed phase (0.5 s) and a deceleration phase (0.3s). Given that the Aubert-Fleischl
38 phenomenon only occurs during smooth pursuit eye-movements, we added an initial acceleration phase
39 to make sure that, in the pursuit condition, no catch-up saccades were executed during the constant speed
40 phase. No such phase was necessary for the sphere cloud as participants were always asked to fixate
41 during that part of the trajectory.

1 The sphere appeared either to the left or to the right of the observer's visual straight-ahead. The initial
2 position (x_0) was chosen such that the overall trajectory, consisting of the space travelled during
3 acceleration (x_{acc}; Equation 2), constant speed (x_{cons}; Equation 3) and deceleration (x_{dec}; Equation 4)
4 was centered in front of the observer (Equation 1). The acceleration (a_{acc}) was chosen such that the
5 sphere accelerated to its final speed (v_{max}; 2, 4, or 6 m/s, which amounted to angular speeds of about
6 15°/s, 30°/s and 45°/s relative to the observer respectively) over 0.3 s (Equation 5).

$$x_0 = -(x_{acc} + x_{cons} + x_{dec})/2 \tag{1}$$

$$x_{acc} = \frac{(a_{acc} * t_{acc}^2)}{2} \tag{2}$$

$$x_{cons} = v_{max} * t_{const} \tag{3}$$

$$x_{dec} = \frac{(-a_{dec} * t_{acc}^2)}{2} \tag{4}$$

$$a_{acc} = \frac{v_{max}}{t_{acc}} \tag{5}$$

With $t_{acc} = 0.3s$

$$a_{dec} = -a_{acc} \tag{6}$$

7 The sphere cloud was presented at the same distance (7.5m) and had a width of 2.5 m (spanning a retinal
8 angle of 38°). Each element of the cloud had the same size, shape and color as the single sphere, was
9 moving in the same direction as the single sphere on the trial, and around 20 spheres were visible at any
10 given moment. The sphere cloud's speed was governed by a PEST staircase (Taylor & Creelman, 1967),
11 one starting 30% above the actual speed of the target and one starting 30% below the actual speed, for a
12 total of two staircases per speed per condition. To restrict the total length of the experiment, each
13 staircase was terminated after 15 trials.

14 Participants were asked to either:

15   (1) fixate a fixation cross presented at the same distance as the spheres but 0.5 m (3.8°) below the
16   height at which the single sphere was presented (Fixation condition),
17   (2) or follow the sphere with their gaze (Pursuit condition).

18 Participants were asked to always keep their gaze on the fixation cross during presentation of the sphere
19 cloud.

20 The stimuli were presented either:

21   (1) In front of a textured wall backdrop that provided relative motion cues between the target sphere
22   and the background. This was part of a larger virtual 3D environment in which participants were
23   immersed (Relative Motion condition, see Figure 1A and B; see also this video
24   https://osf.io/v23p5)
25   (2) in a uniformly black scene that did not provide any relative motion cues (No Relative Motion
26   condition, see Figure 1*C* and *D*; see also this video https://osf.io/sjb3k),

27 **Eye movements –** We recorded the participants' eye-movements while the sphere or the sphere cloud
28 was visible. These recordings were used later to exclude participants that consistently did not follow the
29 instructions, or individual trials where an otherwise acceptable participant failed to follow the
30 instructions. Please note that eye-movements could not be recorded for the No Relative Motion condition

because the eye cameras required more light to function than was available within the headset during this condition (see below for more information on inclusion criteria for participants and individual trials).

Since managing gaze behavior and our speed discrimination task at the same time is a fairly demanding task, either the single sphere or the fixation point was flashed white intermittently to indicate precisely where participants had to direct their gaze for the first five trials of each block.

The programs used to present stimuli, and the corresponding Unity project can be downloaded from https://osf.io/xcaq3/
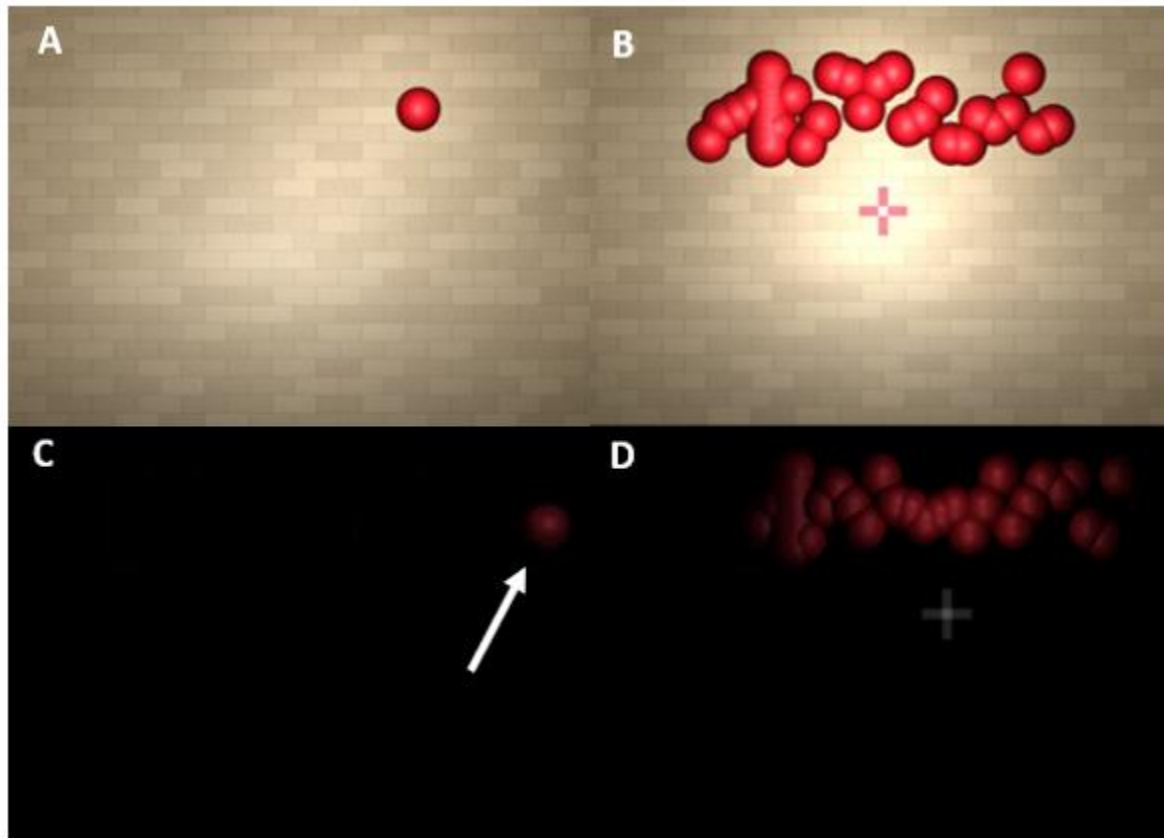
Figure 1: Screenshots from the experiment in the Relative Motion condition (A, B) and the No Relative Motion condition (C, D), for when the single sphere was on screen (A, C) or while the sphere cloud was on screen (B, D). The white arrow in Panel C is meant to make the position of the sphere more obvious to the reader and was not present in the experiment.

Procedure

In total, participants completed 6 stages of the experiment: An eye-movement training session, an eye-movement test, a two-interval forced-choice task training session, the first experimental block (Relative Motion or No Relative Motion, with either Fixation or Pursuit first), another eye-movement assessment, and finally the second experimental block (Relative Motion or No Relative Motion, with either Fixation or Pursuit first). See Figure 2A for a schematic of the sequence of tasks.

Eye-Movement Training – Participants completed one run of 25 trials with a visible backdrop. Participants were instructed to always follow the single sphere with their gaze and keep their eyes on the fixation cross while the sphere cloud was present. They were also instructed to focus mostly on their gaze behavior and,

if necessary, respond randomly to the speed judgement task. After each trial, they were given feedback on whether their gaze behavior matched the criteria established as sufficient performance: their eye speed had to be at least 30% of the sphere's speed when the sphere was present, and it had to be below 30% of the sphere's speed when the sphere cloud was present. Trials were repeated when the gaze behavior did not match the instructions. Throughout this training, the experimenter explained the expected eye behavior as many times as necessary.

Eye-movement assessment – After finishing the eye-movement training, we assessed participants' eye behavior in a 50-trial test (again, with a visible backdrop because eye-movements could not be recorded in the dark condition). Before each trial, participants received instructions as to whether they were supposed to follow the sphere with their eyes or keep their gaze on a fixation cross. At the end of the 50-trial run, the program output the participants median gaze speed throughout the 50 trials, separately for Pursuit and Fixation trials, and separately for those parts of the trial where the sphere was present and those parts where the sphere cloud was present. The median gaze speed had to be at least 30% of the presented speed in the Pursuit condition while the sphere was visible, and below 30% of the presented sphere speed for the Fixation condition, as well as for those parts of the trial where the sphere was presented. Participants who did not satisfy these criteria received another explanation of the expected gaze behavior and underwent a second round of the test. If they still did not meet the criteria, they were sent home. This was the case for 11 participants out of 61 participants who started the experiment.

Two-Interval Forced Choice Task Training – After an explanation of the task, participants were asked to complete a short training which consisted in a reduced (30 trial) version of the main experiment; the speed of the sphere was set to 5 m/s and only one staircases (where the speed of the sphere cloud started 30% above the speed of the single sphere) with a maximum of 25 trials was presented. The training was done in the background condition the respective participant started in, i.e., participants who started with the Relative Motion condition did their training in the Relative Motion condition and participants who started with the No Relative Motion condition also did their training in the No Relative Motion condition. In the training, the fixation cross was absent, and they were allowed to view the stimulus freely. Participants were only asked to continue with the main experiment if the last step size in the staircase was below 0.3 m/s, indicating that they had an acceptable understanding of task and controls. If participants failed to meet this criterion, they received another explanation of the task and were asked to repeat the training. No participants failed the training a second time.

First Experimental Block – Participants then proceeded to the first experimental block. Half of the participants started with the Relative Motion condition and half started with the No Relative Motion condition. Within each relative motion condition, half of participants started with the Fixation condition and half started with the Pursuit condition. Within each gaze condition, we consistently presented the single sphere during the first half, and the sphere cloud first during the second half, or the other way around. Before the start of the No Relative Motion condition, participants sat in the dark for about one minute such that the experiment took fully place after dark adaptation plateaued.

Second eye-movement assessment – After the first experimental block, participants completed another eye-movement test to assess whether they were still following gaze instructions. No participants failed this test.

1 **Second Experimental Block** – Participants then completed the experimental block they had not completed
2 before (Relative Motion or No Relative Motion). The gaze instructions switched, as before, half-way
3 through the block.

4 Between the eye-movement training and the two eye-movement assessments, we were confident that
5 all included participant displayed the expected eye-movement behavior across both background
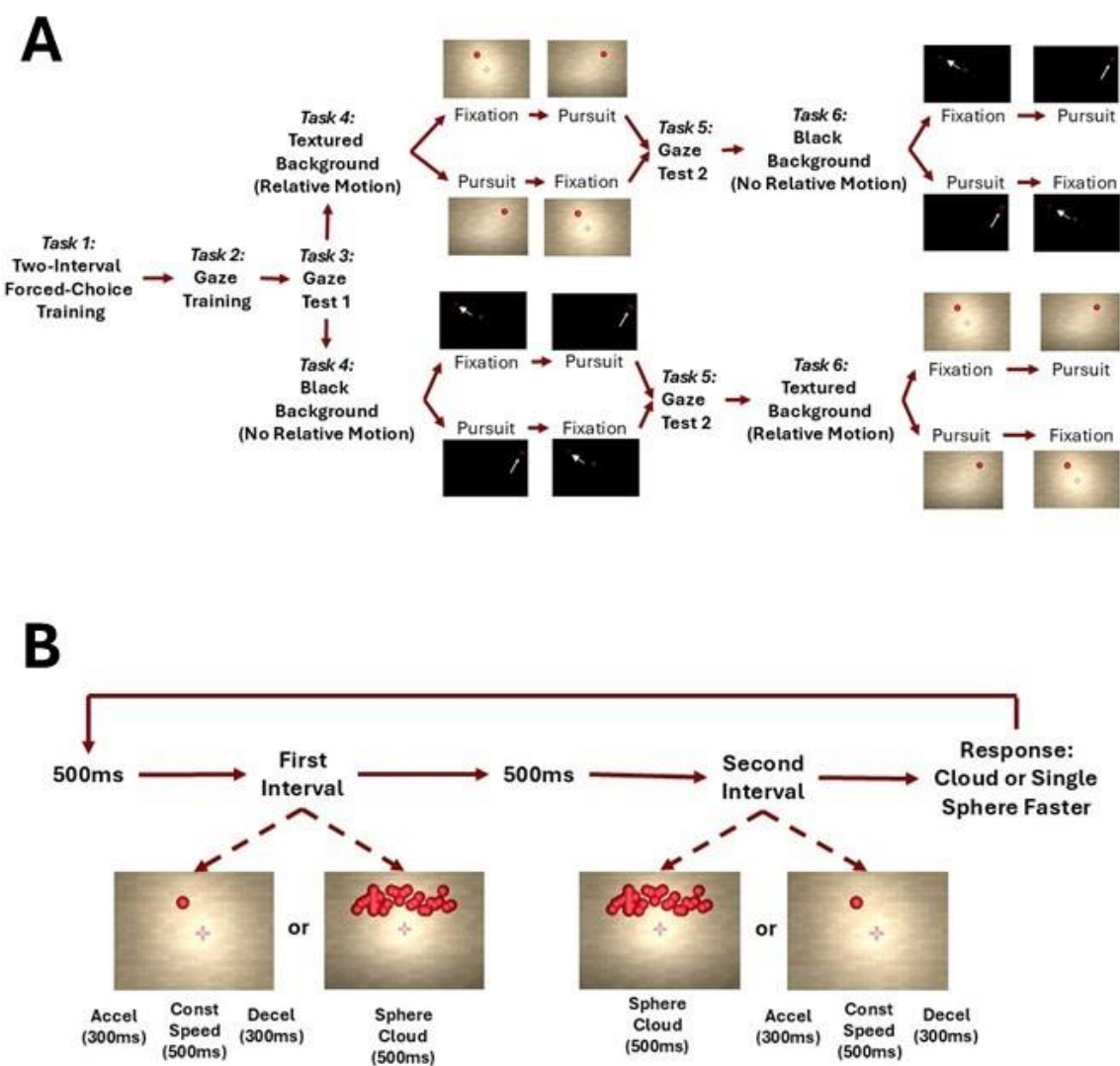6 conditions.

7
8 *Figure 2: A. Sequence of tasks as described in the Procedure section. B. Sequence of presentation along with the respective timings*
9 *within each trial in the main experimental conditions.*

10

11

Predictions

We expected the speed of the sphere to be underestimated when the participant pursued the target with their gaze in comparison to when they maintained fixation in the dark. We expected this difference to disappear when the target moved against the textured background.

Data Analysis

The code used for the analysis along with the data can be downloaded from Open Science Foundation: https://osf.io/u3pkq

Preprocessing of Eye Movement Data

We recorded gaze data in world coordinates in the plane in which the target was presented. Since our target was only moving laterally, we only analyzed the lateral eye speed component. Visual inspection of a random sample of gaze traces confirmed that the vertical component was largely constant across the trial. We smoothed the horizontal component using a Gaussian kernel and computed gaze speed on a frame-to-frame basis. All frames where the eye speed was higher than twice the target speed were marked as saccades (see Figure A5 in the Appendix for a sample of eye traces with saccades marked up of 15 trials from one random participant as well as Figure A6 for the distributions of saccades for each participant in the Pursuit-No Relative Motion condition). We then removed these frames and computed the mean gaze speed across the remaining frames for further analysis.

Outlier Analysis: Step 1

A trial was marked as "instructions not followed" when the average gaze speed was < 50% of the target speed in the Pursuit condition (see Figure A1 in the Appendix), or > 30% of the target speed in the Fixation condition (see Figure A2 in the Appendix; see also Figure A3 for the distributions of mean eye speeds for each participant while the sphere cloud was present). While comparing the gaze speed to the target speed, we accounted for the 50 ms it takes the VIVE Pro Eye to make the eye-tracking data available to the system (Stein et al., 2021). We also excluded all trials where we identified more than 3 saccades. Based on this criterion, we excluded conditions (defined as combinations out of the two Gaze conditions and three target speeds) that, out of 30 trials for any given speed and condition, had 20 or more trials marked as "instructions not followed". We further excluded any participant for who more than one of the conditions was excluded using this criterion, under the assumption that we were not confident enough that their eye behavior matched the instructions in the No Relative Motion condition for which eye data could not be collected. Four participants (n=4) were wholly excluded based on these criteria, and 3 conditions out of a total of 276 (1.1%) from the remaining 46 participants were removed. Finally, out of all remaining trials (8190), we excluded 1400 trials (17.1%). Given that eye-tracking data was not available for the No Relative Motion condition (see apparatus), no conditions or trials were excluded here.

Fitting Psychometric Functions

We then fitted cumulative Gaussian functions separately for each target speed, condition and participant by means of direct likelihood maximization (Knoblauch & Maloney, 2012) as implemented in the quickpsy package (Linares & López-Moliner, 2016) for R (R Core Team, 2017). We then extracted the PSEs (i.e., the 50% values) as a measure of accuracy and the JNDs (i.e., the 84.1% discrimination thresholds) as a measure of precision. Figure 3 illustrates this process for one condition with a single sphere speed of 4 m/s.
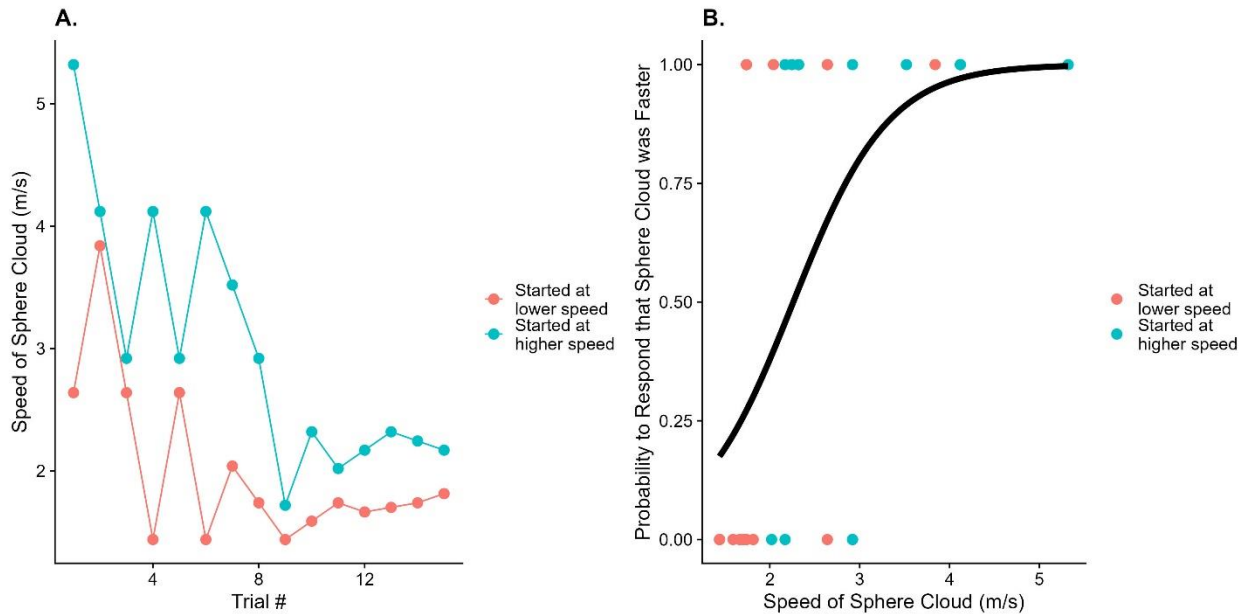

Figure 3: A. Depiction of how the presented speed of the sphere cloud (y axis) developed over the course of the experiment (trial number on the x axis), color-coded for whether the speed of the sphere cloud started out being higher than the speed of the single sphere (blue) or lower (red). This was for a single sphere speed of 4 m/s. B. Example of a fitted psychometric function (solid black line) for the same condition depicted in A. The probability for the participant to respond that the sphere cloud was faster than the single sphere (y axis) is plotted against the speed of the sphere cloud (x axis). Individual responses for trials are shown as dots; 1 equals the response "sphere cloud was faster" and 0 denotes the response "single sphere was faster", color-coded as in A. The Point of Subjective Equality (PSE) is defined as the speed of the sphere cloud at the 50% threshold, indicated by the intersecting dashed lines.

Outlier Analysis: Step 2

Once we fitted the psychometric functions, we removed those conditions for which impossible or unreasonably extreme PSEs or JNDs were obtained: any conditions where PSEs or JNDs below 0 were obtained were excluded, as well as any conditions where PSEs more than 3 times higher than the presented speed were fitted. This led to the exclusion of 100 conditions (out of a total of 549 remaining ones), or 18.2%.

Main Statistical Analysis

Since we expected to detect a difference between Fixation and Pursuit only in the No Relative Motion condition, we separated the Relative Motion condition and the No Relative Motion condition for analysis.Since frequentist approaches are generally ill-suited to quantify evidence for the absence of an effect (such as the absence of a difference between Fixation and Pursuit in the Relative Motion condition), we relied on a Bayesian approach for all analyses.

To test for a difference between Fixation and Pursuit (separately for the Relative Motion and the No Relative Motion conditions), we used Bayesian Linear Mixed Modelling as implemented in the brms package (Bürkner, 2018) for R to test for differences between the experimental conditions. We first fitted a model with the PSEs as dependent variable, the gaze condition (Fixation vs. Pursuit; categorical variable) as fixed effect, as well as random intercepts and random slopes for target speed (in m/s) for the grouping variable Participant. In Wilkinson & Rogers notation (Wilkinson & Rogers, 1973), this model reads as follow:

$$PSE \sim Gaze\ Condition + (1\ +\ Speed_{Sphere}\mid Participant) \qquad (7)$$

We then used the hypothesis() function from the brms package to determine the Bayes Factor for a difference between Fixation and Pursuit. As per our predictions (see Predictions), the Bayes Factor should indicate evidence for the absence of a difference between Fixation and Pursuit in the Relative Motion condition, while indicating evidence for PSEs being underestimation for Pursuit relative to Fixation in the No Relative Motion (the classic Aubert-Fleischl effect).

Results

Figure 4 provides an illustration of the PSEs for all conditions, and Table A1 in Appendix D provides an at-a-glance view of all fitted fixed effects coefficients for all statistical models.

Pre-Registered Analysis on the Aubert-Fleischl Effect Without Relative Motion Contrary to our prediction, we found weak evidence in favor of the hypothesis that PSEs were equal between Fixation and Pursuit (Bayes Factor = 2.3). Numerically, PSEs were 0.1 m/s (95% credible interval = [-0.17 m/s; 0.36 m/s]) higher in the Pursuit condition than in the Fixation condition.

Pre-Registered Analysis on the Aubert-Fleischl Effect with Relative Motion Regarding our hypothesis that there would be no difference between Pursuit and Fixation in the Relative Motion condition, we found weak evidence in favor of the absence of an effect (Bayes Factor = 2.9), with numerically higher PSEs in the Pursuit condition than in the Fixation condition (by 0.1 m/s, 95% Credible Interval = [-0.15 m/s; 0.28 m/s]).

These results were highly unexpected. Not only did we not find confirmation of our main hypothesis (namely that speed would be underestimated during pursuit relative to fixation, but only when no relative motion was present). Rather, we found that the perceived speed was numerically higher in the pursuit condition in both the Relative Motion condition and the No Relative Motion condition – which would constitute a *reverse* Aubert-Fleischl effect. We therefore also performed a (Bayesian) Generalized Linear Mixed Model analysis, which was previously found to boast higher statistical power (Jörges, 2021; Moscatelli & Lacquaniti, 2012) and which we had initially only pre-registered out of methodological interest (see Appendix A), in order to verify whether these unexpected findings would be further supported.

Secondary Pre-Registered Generalized Linear Mixed Model Analysis on the Aubert-Fleischl Effect without Relative Motion – This analysis provided moderate evidence that Pursuit elicited the same

1 likelihood of responding "cloud faster" as Fixation (Bayes Factor = 5.76). Rather than reporting (hard to
2 interpret) regression coefficients, we used the method outlined by Moscatelli et al. (Moscatelli &
3 Lacquaniti, 2012) to convert these regression coefficients into PSEs. This showed that PSEs were
4 numerically higher in the Pursuit condition than in the Fixation condition (by 0.09 m/s, 95% Credible
5 Interval = [-0.19 m/s; 0.37 m/s]).

6 **Secondary Pre-Registered Bayesian Generalized Linear Mixed Model Analysis on the Aubert-Fleischl**
7 **Effect with Relative Motion** – For the Relative Motion condition, we found inconclusive evidence
8 for/against a difference between Pursuit and Fixation (Bayes Factor = 0.97). Numerically, the PSEs were
9 higher for Pursuit than for Fixation (by 0.16, 95% Credible Interval = [0.01 m/s; 0.31 m/s]).

10 These analyses were in line with the main pre-registered analyses reported above but provided a higher
11 degree of statistical power, as evidenced by the smaller credible (BGLMM) intervals (see Figure 5) they
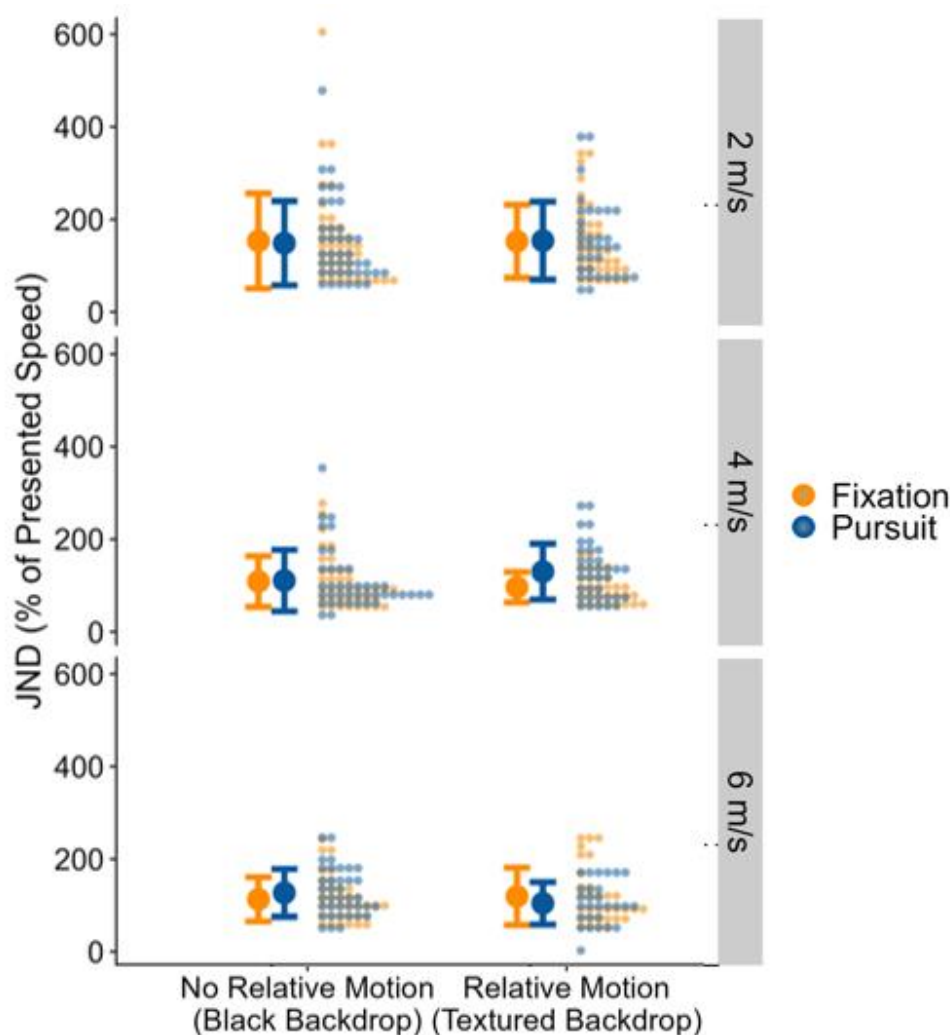12 provide on their parameter estimates.

13

14 *Figure 4: Full distributions of the fitted PSEs (y axis) for the two relative motion conditions (x axis), eye behavior conditions (color-*
15 *coded) and sphere speeds (panels), along with the means (bold dots) and +-1 standard deviation (error bars) across all data points*

3   Given these surprising results, we conducted two additional, **exploratory** (Generalized Linear Mixed

4   Model-based) analyses to investigate whether pursuit really increased perceived speed: for the first one,

5   we assessed whether trials where the participants' eyes moved faster were more likely to lead to

6   responses that the sphere was faster, i.e., did faster eye motion on a trial-by-trial basis bias participants

7   to perceive the sphere as faster? To this end, we added the mean eye speed (in m/s in the target plane)

8   for each trial as a fixed effect to the Generalized Linear Mixed Model used above:

$$Response \sim Speed_{Eyes} + Number\ of\ Saccades + Speed_{Cloud} + Speed_{Sphere} \qquad (9)$$
$$+ \left(1 + Number\ of\ Saccades + Speed_{Cloud}\right.$$
$$\left. + Speed_{Sphere} \middle| Participant\right)$$

9   For the second, conceptually very similar analysis, we labelled trials as either "eye speed above criterion"

10   (i.e., above 50% of the speed of the sphere) or "eye speed below criterion" (i.e., below 50% of the speed

11   of the sphere), thus splitting the data set in two parts. We then compared whether performance differed

12   between the two types of trials:

$$Response \sim Trial\ Type + Number\ of\ Saccades + Speed_{Cloud} + Speed_{Sphere} \qquad (10)$$
$$+ \left(1 + Number\ of\ Saccades + Speed_{Cloud}\right.$$
$$\left. + Speed_{Sphere} \middle| Participant\right)$$

13   We conducted both of these analyses over all pursuit trials from the relative motion condition, including

14   those trials where the eye criterion was not satisfied.

15

16   **Exploratory Analysis: were trials with a higher gaze speed more likely to lead to "sphere is faster"**

17   **responses?** – We found strong evidence that gaze did not affect perceived speed (Bayes Factor = 20.7).

18

19   **Exploratory Analysis: were trials that satisfy the eye behavior criteria more likely to lead to "sphere is**

20   **faster" responses?** – This analysis provided moderate evidence that Pursuit trials where the eye criterion

21   was met did not elicit different PSEs than trials where it wasn't met (Bayes Factor = 7.01).

22

23   **Exploratory Analysis: Is there any interaction between Gaze condition and Relative Motion condition?**

24   – Lastly, we also included an analysis to directly test whether there was an interaction between Gaze

25   condition and Relative Motion condition to support our pre-registered split analyses above. We fitted a

26   Bayesian Generalized Linear Mixed Model as described in Appendix A, except that we added Relative

27   Motion condition and the interaction between Gaze condition and Relative Motion condition as fixed

28   effects. The full model structure was the following:

$$Response \sim Gaze\ Condition * Relative\ Motion\ Condition + Number\ of\ Saccades \quad (10)$$
$$+ Speed_{Cloud} + Speed_{Sphere}$$
$$+ (1 + Number\ of\ Saccades + Speed_{Cloud}$$
$$+ Speed_{Sphere}|Participant)$$

1   This analysis provided strong evidence that there was no interaction between Gaze condition and Relative
2   Motion condition (Bayes Factor = 9.21).Figure 5 shows the parameter estimates of all relevant statistical
3   comparisons reported, along with their 95% confidence (for the frequentist analyses) or credible (for the
4   Bayesian analyses) intervals.
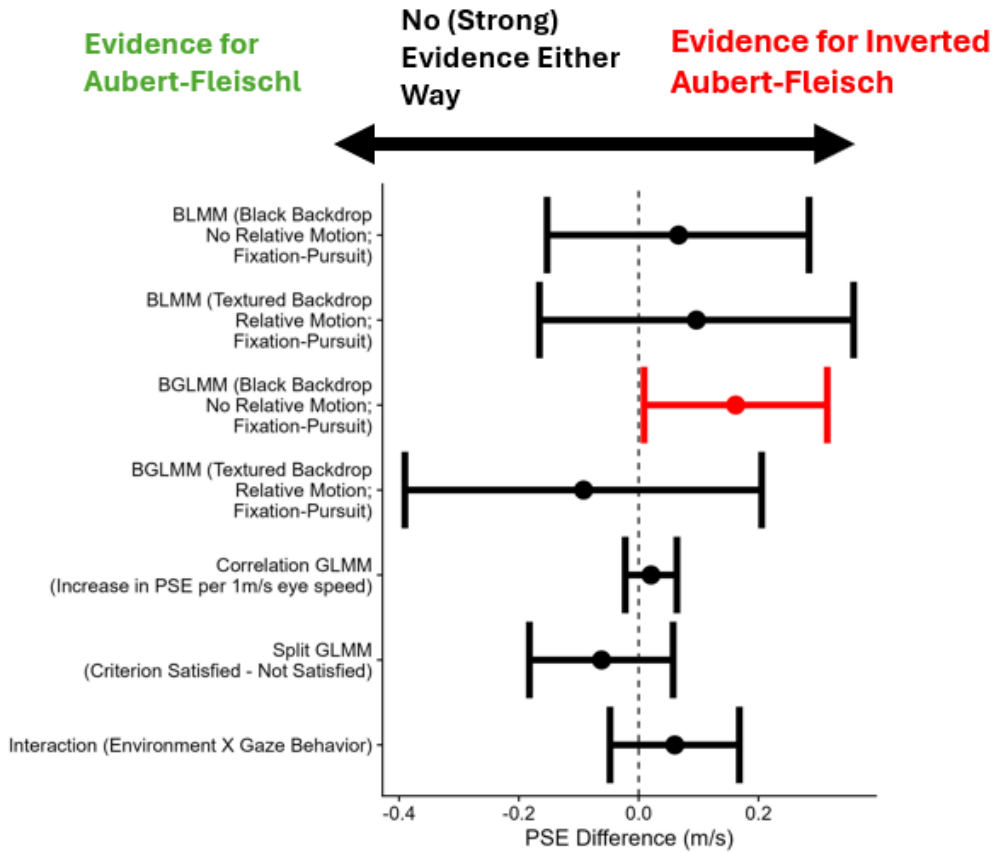
5

6   *Figure 5: Difference contrasts between Fixation and Pursuit (1-4), regression coefficient for the association between the eye*
7   *speed and the likelihood to respond: "sphere faster", (5) and the difference contrast between those trials that satisfied the eye*
8   *behavior criterion versus those trials that did not. The error bars indicate the 95% confidence intervals (1, 3, 5, 6) or the 95%*
9   *credible intervals (2, 4). The vertical line indicates no effect, while values below zero (to the left of the line) are consistent with*
10   *the Aubert-Fleischl effect and values above zero (to the right of the dashed line) are consistent with an inverted Aubert-Fleischl*
11   *effect (where object speed is overestimated in the presence of pursuit rather than underestimated). Statistical tests that provide*
12   *evidence for an inverted Aubert-Fleischl effect are colored in red, while those colored in black do not provide (strong) evidence*
13   *either way.*

14

15   **Exploratory Analysis: did precision vary between fixation and pursuit?** – Finally, as a last exploratory
16   analysis, we assessed whether any differences in precision were appreciable between Fixation and
17   Pursuit. Precision was previously shown to be lower during pursuit, which Freeman et al. (Freeman et al.,

1   2010) used, in conjunction with a slow motion prior (Stocker & Simoncelli, 2006), to explain the Aubert-
2   Fleischl effect. To test whether our data were consistent with this model, we fitted a Bayesian Linear
3   Mixed Model similar to our accuracy analyses, where we used the fitted JNDs of the psychometric
4   functions as dependent variable, Relative Motion (Relative Motion vs. No Relative Motion) and Gaze
5   condition (Fixation versus Pursuit) as fixed effects and the same random effects as above:

$$JND \sim Gaze\ Condition + Relative\ Motion + \left(1\ +\ Speed_{Sphere}\ \middle|\ Participant\right) \qquad (11)$$

6   We found anecdotal evidence for there not being a difference in JNDs between Pursuit and Fixation (1.5).
7   Numerically, JNDs were higher during Pursuit than during Fixation (by 0.16 m/s, 95% Credible Interval = [-
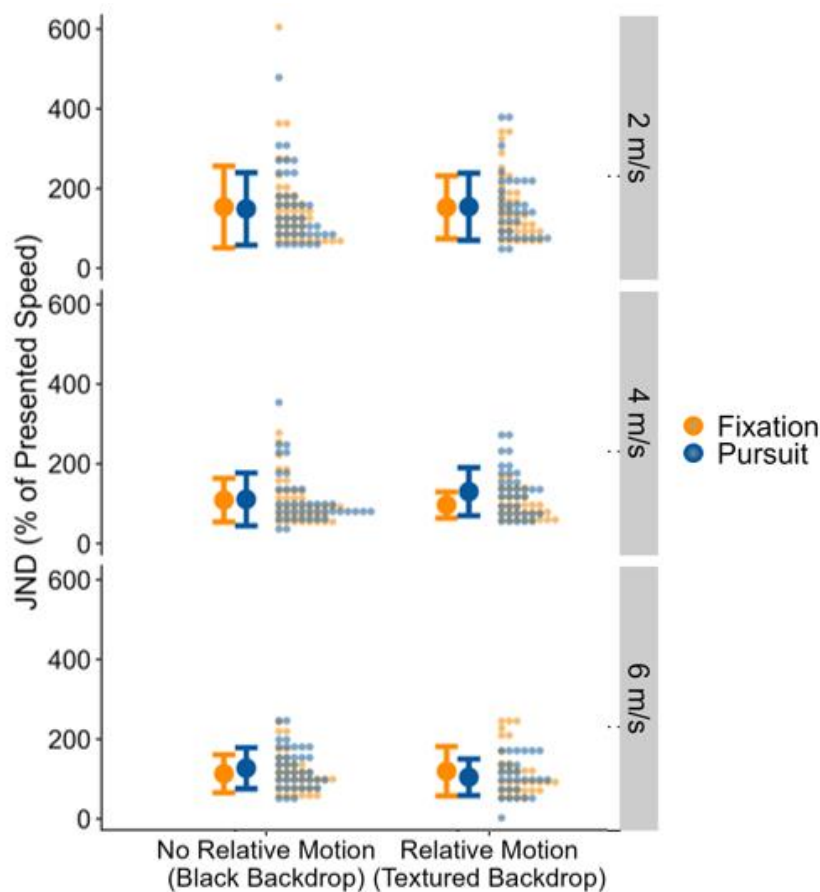8   0.22 m/s; 0.54 m/s].

9

Figure 6. Full distributions of the fitted JNDs (y axis) for the two relative motion conditions (x axis), eye behavior conditions
(color-coded) and sphere speeds (panels), along with the means (bold dots) and +-1 standard deviation (error bars) across all
data points in that condition. The panels represent the different ball speeds.

13 Table A1 in Appendix D provides an overview over all difference contrasts considered in the models
14 along with 95% credible intervals.

15

14

Discussion

Contrary to our hypotheses, and contrary to what has generally been reported in the literature (Aubert, 1886, 1887; Brown, 1931; de Graaf et al., 1991, 1991; Dichgans et al., 1969, 1975; Dodge, 1904; Fleischl, 1882; Freeman & Banks, 1998; Freeman et al., 2010; Körner & Dichgans, 1967; Mack & Herman, 1978; Miyamoto et al., 2021; Turano & Heidenreich, 1999), we found evidence that perceived speed is unaffected when following an object with the gaze in comparison to when the gaze is kept on a fixation cross.

Comparable results have been previously reported by Gibson et al. (1957), and some conditions reported by Dichgans et al. (1975), and Freeman & Banks (1998) but do seem not to have made it into general awareness. Gibson himself (1957) showed participants two downwards moving bands with dots on them. In the pursuit condition, they were instructed to follow one dot on one band to get an impression of its speed, then look over to the other band and adjust its speed while fixating a black fixation square that was positioned next to the band. In the fixation condition, they executed the same task but fixated black fixation squares for both stimuli. In both conditions, they were allowed to go back and forth between the two stimuli until they felt they had matched the speeds correctly. While speed was numerically overestimated in the fixation condition and underestimated in the pursuit condition, this difference did not rise to significance.

A model that could potentially account for the absence of any difference between Fixation and Pursuit in our data was suggested by Freeman et al. (2010). This Bayesian model is based on the assumption that the perception of object speed becomes less precise during pursuit, which would make speed perception more susceptible to the slow motion prior (Stocker & Simoncelli, 2006) and thus decrease PSEs. Despite our fairly large number of participants, we did not find any differences in JNDs between fixation and pursuit with or without a textured background. Without differences in JNDs this model would predict no differences in PSEs. A potential reason for why we found no difference in precision (and therefore in accuracy, as per the Freeman model) might be difference in stimulus speed: studies that find Aubert-Fleischl effects tend to use stimulus speeds in the range of 5 to 15 °/s, while our stimulus was much faster (15, 30, or 45 °/s). Freeman et al.'s data (2010) suggest that the discrepancy in precision between fixation and pursuit might decrease as stimulus speed increases. While this is an appealing explanation of why we found evidence for the absence of any Aubert-Fleischl effects, there are two empirical studies that cast some doubt on these conclusions. First, Wertheim and van Gelder's study (1990) demonstrated an Aubert—Fleischl effect at 25.7 °/s, which is within our range of tested stimulus speeds. Further, de la Malla et al. (Malla et al., 2022)) provided evidence that, within the regular range of stimulus speeds of 5-12 °/s, perceptual precision was *increased* during pursuit in comparison to fixation, Under such circumstance, the Freeman model would predict a reversal of the Aubert-Fleischl phenomenon, i.e., an underestimation of perceived speed during fixation relative to pursuit. Overall, this nonetheless provides a promising direction for future research into the circumstances under which ocular pursuit decreases perceived speed.

Another explanation might be found when examining the impact of spatial frequency on the Aubert-Fleischl effect. Dichgans et al. (1975) found no differences between fixation and pursuit in a design where a single edge moved across a screen. Only for higher spatial frequencies, i.e., when a pattern of several vertical stripes was presented, did they find the expected Aubert-Fleischl effect. Drawing on these ideas

about the effect of spatial frequency content, Freeman & Banks (Freeman & Banks, 1998) proposed a model that predicted a reversal of the Aubert-Fleischl effect at low spatial frequencies and supported this reversal experimentally. This is compatible with our results: the spatial frequency associated with our 1.5 deg wide stimulus would be primarily around 0.3 c/deg. The spatial frequency of the whole scene was much higher in the Relative Motion condition (where a tiled wall was simulated behind the stimulus), but the stimulus sphere itself had the same low spatial frequency. This makes the Freeman & Banks model, which assumes that all retinal motion is caused by the stimulus whose speed is to be assessed, not directly applicable to our case.

However, it is worth considering the assumptions of their model, namely that the perceived head-centric speed of a moving object can be calculated as a simple sum of perceived eye speed and perceived retinal image velocity. Contrary to many accounts of the Aubert-Fleischl phenomenon, which attribute it to an underestimation of eye speed (Aubert, 1887; Garzorz et al., 2018; Mack & Herman, 1973, 1978), they posit that the phenomenon is instead caused by a misestimation of retinal image velocity (whose perception has been shown to be influenced by factors such as spatial frequency of the stimulus). This is, to some extent, in agreement with the fact that neither of our analyses show a significant difference between fixation and pursuit in the No Relative Motion condition: here, the difference in retinal image velocity between fixation and pursuit is negligible. On the flipside, in the Relative Motion condition, retinal image speeds are vastly higher during pursuit than during fixation because of the stationary background being dragged across the retina. This retinal motion goes in the opposite direction of the world-centric direction of the sphere. If some of this retinal motion were to be misattributed – perhaps as world motion, or as the consequence of bodily self-motion – the speed of the object might be slightly overestimated, potentially accounting for our data.

Neural basis –The dorsal stream (Goodale & Milner, 1992; Ungerleider & Mishkin, 1982) plays an important role in spatial awareness and is crucial for planning movements to locations in space and for transforming visually defined locations into movement coordinates. Cells in the medial superior temporal sulcus (MST) in the dorsal pathway process signal related to target motion, background motion (Chen et al., 2008), and vestibular information about body motion (Gu et al., 2007). Cells in MST also receive an efference copy of eye velocity during pursuit movements (Ilg et al., 2004) and may be useful for interpreting the motion of potential pursuit targets (Eifuku & Wurtz, 1998). Their behaviour may underlie the Aubert-Fleischl phenomenon and the Filehne Illusion (Pack et al., 2001). Our psychophysical results suggest that MST may be able to do a better job than at deducing the speed of a pursued object than was previously thought from experiments in primates.

Limitations – There are several potential limitations to this study, the most important one being our inability to verify participants' eye movements in the No Relative Motion condition. While we mitigated this shortcoming of our technology by having participants complete eye movement tests before each experimental block, the question remains whether the visual differences between the Relative Motion and the No Relative Motion conditions might lead to systematic changes in eye movements. Lower contrast between targe, for example, may lead to less successful ocular pursuit, which in turn could lead to a decrease in the Aubert-Fleischl effect as reported in the literature. However, such effects of the

stimulus on pursuit or saccades are limited to low contrasts close to threshold – much lower than those employed in our experiment (Spering et al., 2005). It seems therefore highly unlikely that differences in gaze behavior would be the reason for the absence of an Aubert-Fleischl effect in our experiment.

Second, our method of entraining smooth pursuit (an acceleration phase in the presented stimulus) entailed slower speeds in the beginning of each trajectory. and some studies have found early motion information to be privileged over later information (Yates et al., 2017). In the fixation condition, the acceleration phase was presented in the periphery while these slower parts of the trajectory would be presented much closer to central vision. While this is an aspect of our experiment that we did not control for, peripheral vision tends to be about as sensitive to speed information as central vision (e.g., Traschütz et al., 2012), making it unlikely as a confound.

Conclusions

Contrary to our predictions, we did not find large differences in perceived object speed during fixation in comparison to when the object was pursued. While our data do not support a Bayesian model (Freeman et al., 2010) based on the idea that decreased precision during pursuit could make judgements more vulnerable to a slow motion prior, another model (Freeman & Banks, 1998) positing that object speed is judged accurately during pursuit but is more susceptible to stimulus properties like spatial frequency during fixation, provides a promising starting point for further investigation.

Overall, our results from a large sample of 50 participants suggest that the Aubert-Fleischl effect is unlikely to affect perceived speed drastically in any context where an observer pursues a single moving object with their gaze. We conclude that it is important for research and other VR applications to appreciate that the Aubert-Fleischl effect is highly context dependent.

Open Science

All data and code can be found on OSF (https://osf.io/u3pkq), as well as the Unity projects (https://osf.io/6mkp8) used to generate the executables (https://osf.io/hqwra).

The pre-registration can be accessed here (https://osf.io/byhg8).

We made the following changes with regards to the pre-registration:

- We improved the performance of the program while the sphere cloud is on screen.
- We mistakenly described the number of trials per PEST staircase as 20 in the pre-registration. The actual number is 15.
- We added an eye-movement training in the beginning of the experiment and eye-movement tests before each experimental block.
- We changed the link function of the GLMMs from "logit" to "probit" in order to be able to use the method described by Moscatelli and Lacquaniti (2012) to obtain PSE estimates from the fitted GLMMs.
- We gave the GLMM analyses described in the Appendix of the pre-registration a more prominent role in the manuscript.
- We added three exploratory analyses which are marked as such in the manuscript.

1   -   We now compute the mean gaze speed per trial only based on non-saccade frames.

2   -   We have changed the structure of the Bayesian Generalized Linear Mixed Models.

3   -   We switched all remaining frequentist analyses to Bayesian analyses.

4   -   We added an exploratory analysis regarding the interaction between Gaze condition and

5   Environment condition.

6   -   We excluded all trials where participants executed more than three saccades.

7   -   The original (pre-registered) data analysis script can be found here: https://osf.io/p9kwm

8

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4

5

Appendix A: Secondary Statistical Analysis using Generalized Linear Mixed Modelling

7 Since this project also served as a case study for a methods paper on power analyses for psychophysical
8 designs, we also performed a secondary analysis that some of our simulations have shown to be
9 somewhat more sensitive than the two-step approach outlined above (Jörges, 2021). This approach uses
10 Generalized Linear Mixed Modelling (as implemented in the lme4 package for R) to fit one statistical
11 model across all data points, rather than first fitting psychometric functions and then performing the
12 statistical analysis over PSEs and/or JNDs (Moscatelli & Lacquaniti, 2012).

13 **Outlier Analysis** – We used the same outlier analysis related to eye-movements as before. Additionally,
14 we excluded all data points where a sphere cloud speed was presented that was more than 3 times higher
15 than the target speed, under the assumption that such extreme values could only occur if the participant
16 made mistakes early in the staircase.

17 **Statistical Analysis** – To assess the impact of the Gaze condition in the No Relative Motion condition, we
18 fitted a Generalized Linear Mixed Model with a logit link function with the participants' responses as
19 dependent variable, Gaze Condition, the number of saccades, the speed of the sphere cloud, as well as
20 the speed of the sphere as fixed effects, as well as random intercepts and random slopes for the number
21 of saccades, the speed of the sphere cloud and the sphere speed per participant:

$$Response \sim Gaze\ Condition + Number\ of\ Saccades + Speed_{Cloud} + Speed_{Sphere} \quad (8)$$
$$+ \left(1 + Number\ of\ Saccades + Speed_{Cloud} \right.$$
$$\left. + Speed_{Sphere} \middle| Participant \right)$$

22 We fitted the 95% bootstrapped confidence intervals to assess statistical significance.

23 The random effect structure was determined by starting with a maximal model with random slopes for
24 Gaze condition, number of saccades, cloud speed and sphere speed per participant. We then used
25 Likelihood Ratio Tests (as implemented in the anova() function from base R) to determine whether this
26 maximal model was significantly better than all simpler models. Where an additional parameter did not
27 improve the model fit, we removed it. This led to the exclusive of random slopes for Gaze condition per
28 participant, leaving us with the random effect structure described above.

29 For the Relative Motion condition, we fitted an equivalent Bayesian Generalized Linear Mixed Model:

$$Response \sim Gaze\ Condition + Number\ of\ Saccades + Speed_{Cloud} + Speed_{Sphere} \quad (9)$$
$$+ \left(+Number\ of\ Saccades + Speed_{Sphere} \middle| Participant \right)$$

1   As for the two-step approach used in the main analysis, we used the hypothesis() function to determine

2   the Bayes Factor associated with the Gaze condition.

3   In case of discrepancies between the results of the main analysis and this analysis, the main analysis

4   prevails.

5

1 Appendix B: Plots of eye behavior per participant

2
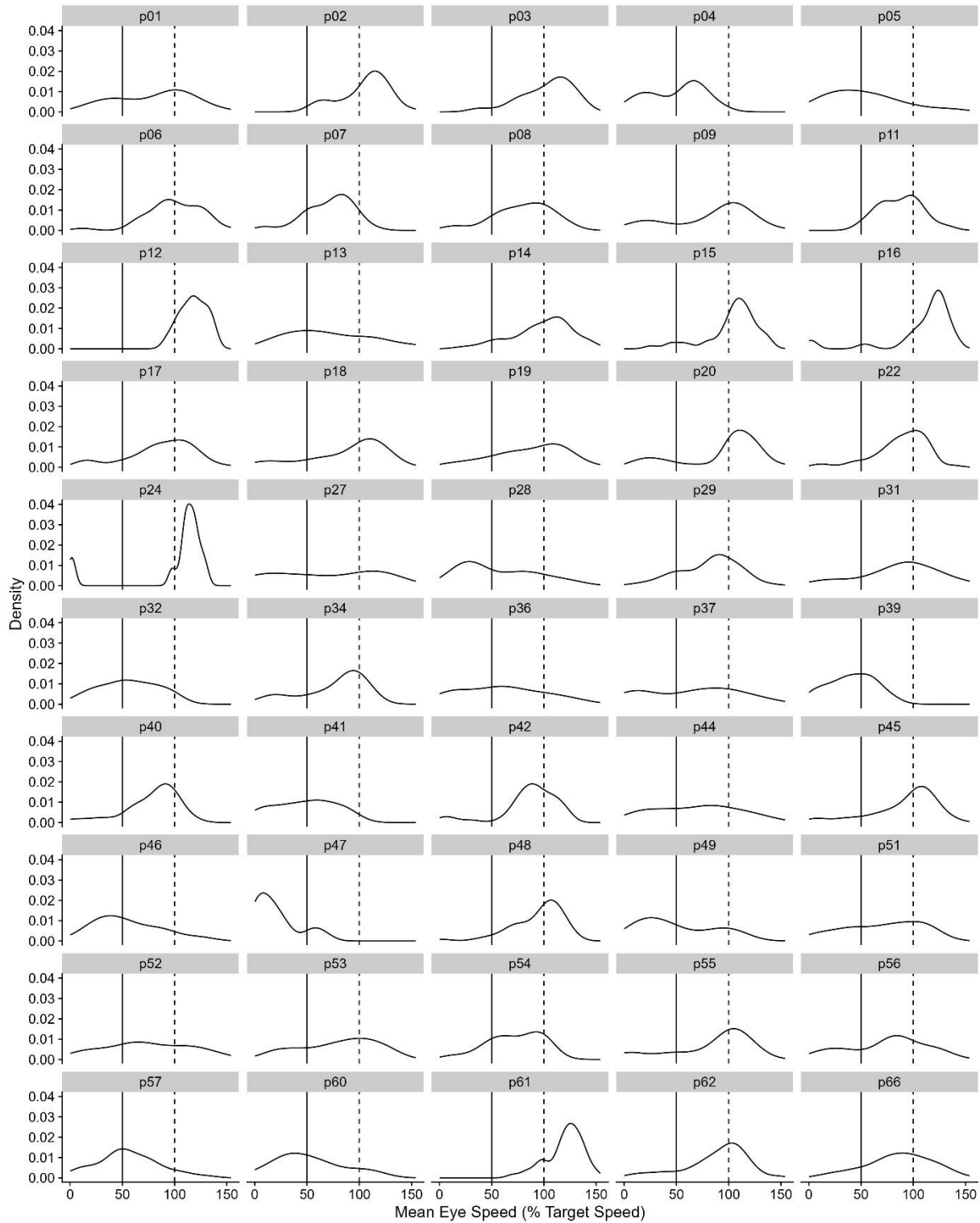
Figure A1: Distributions of mean eye speed for the sphere part of each trial for all pursuit trials per participant (panels). The solid vertical line indicates the criterion (eye speed must be at least 50% of the sphere speed), i.e., participants displayed acceptable eye behavior for the part of the distribution to the right of the line and unacceptable ones for the part of the distribution to the left of the line. The dashed line indicates when the eyes moved at the same speed as the target (100%).
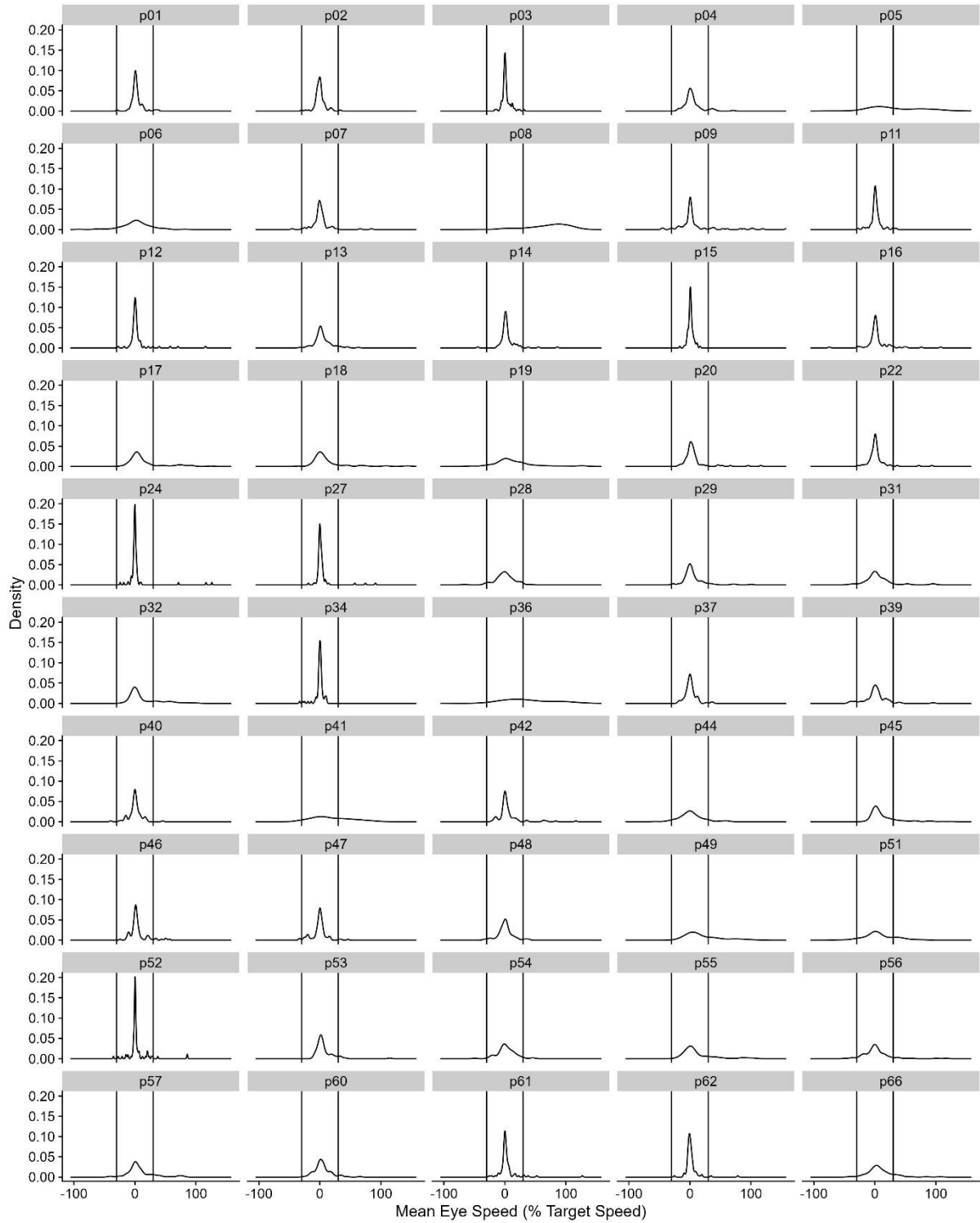
Figure A2: Distributions of mean eye speed for each trial for the sphere part of all fixation trials per participant (panels). The vertical lines indicate the criterion (eye speed must lower than 30% of the sphere speed), i.e., participants displayed acceptable eye behavior for the part of the distribution between the two vertical lines.
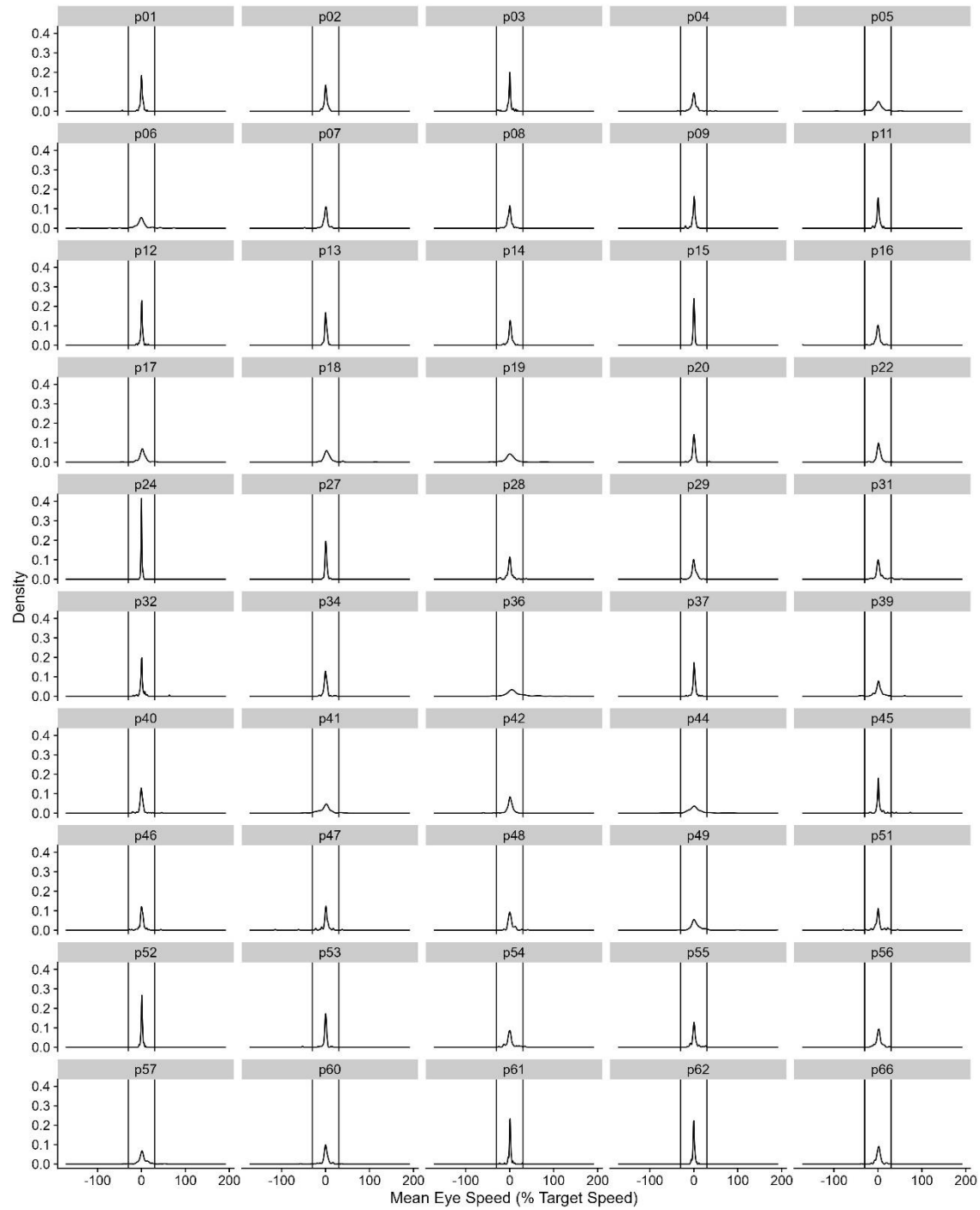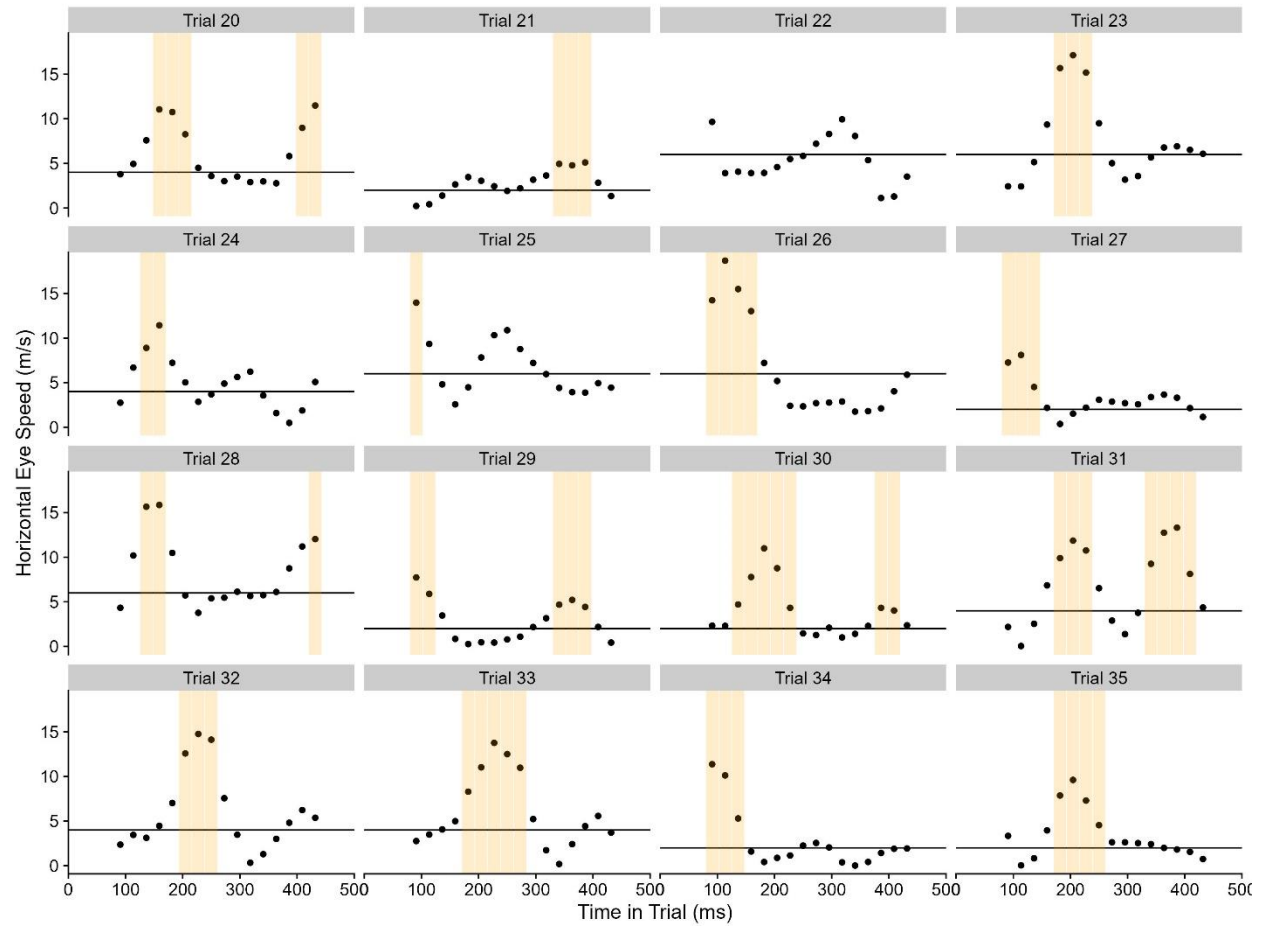
1

Figure A3: Distributions of mean eye speed for each trial for the sphere cloud part of all trials per participant (panels). The
vertical line indicates the criterion (eye speed must be at least 50% of the sphere speed), i.e., participants displayed acceptable
eye behavior for the part of the distribution between the two vertical lines.

Figure A5: Horizontal eye speed (y axis) over the course of the constant speed phases (x axis) of 16 trials (panels) from a randomly drawn participant (p05). The horizontal eye speed is computed in the target plane, for ease of comparison to the target speed (horizontal line in each panel). The orange shaded areas are those frames that our algorithm flagged as saccades.

Figure A6: Number of saccades while the target was presented during the Pursuit-Relative Motion condition (y axis) divided up by target speeds (color-coded), separately for each participant (panels).

1

Appendix C: Power Analysis

3 There were two parts to the analysis for which we wanted the study to have adequate power:

4   (1) the replication of the Aubert-Fleischl effect in our set up in the No Relative Motion condition
5   (2) the absence of the Aubert-Fleischl effect in our set up in the Relative Motion condition

6 For our goal (1), we performed a power analysis as outlined by Jörges (2021). This method relies on
7 simulating full data sets based on assumptions about different sources of variability and the expected
8 effect size or the smallest effect of interest. Each simulated data set is then analyzed (via the process
9 outlined above under Data Analysis), and the fraction of cases in which a significant difference between
10 the relevant conditions is detected is an adequate approximation of the power of these statistical tests.

11 Since we had a relatively large pilot data set available (n = 11 included participants), we used the values
12 extracted from that data set for our power analysis. We fitted the LMM outlined in the Data Analysis
13 section as well as an equivalent model but with the JNDs as dependent variable. The scripts used to extract
14 the values from the pilot data, the script that runs the power analysis and the pilot data can be
15 downloaded from OSF: https://osf.io/yd2j6. Further, a poster on the pilot data can be viewed on OSF as
16 well: https://osf.io/2z7d8

17 Bayesian power analyses could, in principle, be set up in a similar way: we simulated a large number of
18 data sets, fit Bayesian models to each and obtain posterior estimates for the contrast in question. Instead
19 of assessing whether a p value was below or above a certain cut-off, one could assess how wide the
20 posterior distributions, and/or how much spread there is in their means for a given number of
21 participants. However, on a practical level, Bayesian models (using the brms package for R) can take
22 several hours to run, making it unfeasible to simulate and analyze a large-enough dataset within a
23 reasonable time frame. We therefore used the frequentist power analysis for our first hypothesis as a
24 proxy that should yield sufficient precision for the Bayesian statistics used for our second hypothesis.

25
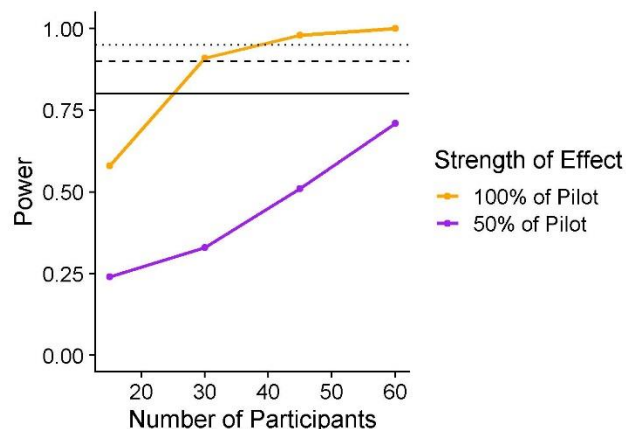
26 *Figure A7: Power (y axis) for a given number of participants (x axis) and assumed effect strength (color-coded).*

27 As evident from Figure 7, even with a large number of participants (n = 60 included participants) only an
28 unsatisfying power of about 0.7 could be achieved if the effect is much smaller (50% of the effect strength
29 in the pilot) than expected. However, given that the effect observed in the pilot data is about as strong as

1 has been reported in the literature (20% more or less), we were relatively confident about the pilot effect

2 size. Under this assumption, a sample size of about 50 (included) participants should allow us to detect

3 the Aubert-Fleischl effect reliably (with a power of > 0.95) in the No Relative Motion condition, and

4 furthermore give us enough power to achieve strong evidence for the absence of the effect in the Relative

5 Motion condition.

6

7 Appendix D – Summary of all difference contrasts of all variables in all statistical models
8 fitted in this paper

9 *Table A1: Regression coefficients and 95% Credible Intervals for all tested difference contrasts, as well as the Bayes Factors for*
10 *all tested hypotheses.*

	Difference Contrast	95% Credible Interval (Lower Bound)	95% Credible Interval (Upper Bound)	Bayes Factor (Evidence for absence of effect)
Bayesian Linear Mixed Model (Relative Motion)				
Intercept	0.97	0.6	1.31	
Pursuit (vs. Fixation)	*0.07*	*-0.15*	*0.28*	*2.91*
Bayesian Linear Mixed Model (No Relative Motion)				
Intercept	1.33	0.94	1.69	
Pursuit (vs. Fixation)	*0.1*	*-0.17*	*0.36*	*2.31*
Bayesian Generalized Linear Mixed Model (Relative Motion)				
Intercept	0.91	0.51	1.33	
Pursuit (vs. Fixation)	*0.16*	*0.01*	*0.31*	*0.95*
# of Saccades (increase in PSE per Saccade)	0	-0.07	0.07	
Ball Speed (4m/s vs. 2m/s)	0.68	0.48	0.88	
Ball Speed (6m/s vs. 2m/s)	1.67	1.39	1.94	
Bayesian Generalized Linear Mixed Model (No Relative Motion)				
Intercept	1.2	0.76	1.62	
Pursuit (vs. Fixation)	*0.09*	*-0.19*	*0.37*	*5.76*
Ball Speed (4m/s vs. 2m/s)	0.95	0.73	1.16	
Ball Speed (6m/s vs. 2m/s)	2.06	1.72	2.39	
Bayesian Generalized Linear Mixed Model (Correlation)				
Intercept	1.15	0.63	1.68	

Eye Speed (increase in PSE per m/s eye speed)	*0.02*	*-0.02*	*0.06*	*20.7*
# of Saccades (increase in PSE per Saccade)	0.01	-0.06	0.07	
Ball Speed (4m/s vs. 2m/s)	0.91	0.62	1.22	
Ball Speed (6m/s vs. 2m/s)	2.01	1.57	2.49	
Bayesian Generalized Linear Mixed Model (Criterion)				
Intercept	1.18	0.67	1.7	
Below Cutoff (vs. Above)	*-0.06*	*-0.18*	*0.06*	*7.01*
# of Saccades (increase in PSE per Saccade)	0.01	-0.05	0.08	
Ball Speed (4m/s vs. 2m/s)	0.95	0.68	1.24	
Ball Speed (6m/s vs. 2m/s)	2.08	1.63	2.56	
Bayesian Generalized Linear Mixed Model (Interaction)				
Intercept	1.05	0.63	-0.15	
Pursuit (vs. Fixation)	0.19	0.01	0.37	
No Relative Motion (vs. Relative Motion)	0.11	0.03	0.18	
Ball Speed (4m/s vs. 2m/s)	0.86	0.67	1.04	
Ball Speed (6m/s vs. 2m/s)	1.96	1.67	2.26	
Interaction (Relative Motion Condition vs. Gaze Condition)	*-0.06*	*-0.17*	*0.05*	*9.21*
Bayesian Linear Mixed Model (Precision)				
Intercept	3.42	2.68	4.08	
Pursuit (vs. Fixation)	*0.16*	*-0.22*	*0.54*	*1.5*
No Relative Motion (vs. Relative Motion)	-0.01	-0.4	0.38	

1