# Introduction

The Aubert-Fleischl phenomenon consists in a misestimation of the speed of a target when the observer pursues this target with their gaze (Aubert, 1887; Fleischl, 1882). Differences between speed perception during pursuit and speed perception during fixation arise from differences in the speed cues at play: while retinal cues are sufficient to estimate target speed during fixation, the observer has to take into account both retinal cues que oculo-motor cues to speed during pursuit (Garzorz, Freeman, Ernst, & MacNeilage, 2018). It is sometimes assumed that the Aubert-Fleischl phenomenon always leads to an underestimation of target speed. However, it has been shown that when the retinal slip of the background caused by eye-movements goes in the opposite direction of the stimulus (Wertheim & Van Gelder, 1990) the effect can be diminished or even eliminated; and depending on the spatial frequency of the stimulus, the effect can even be reversed; i.e., an overestimation of target speed can be achieved (Dichgans, Wist, Diener, & Brandt, 1975).

The Aubert-Fleischl phenomenon is part of the reason why experiments on speed perception and time-to-contact estimation often require observers to keep their gaze on a fixation cross (e.g., Jörges & Harris, 2022). However, embedding a target into a visual scene might provide additional cues to the speed of the eye, and with that, making it easier to estimate the speed of an object accurately even during smooth pursuit. This in turn would provide researchers with more flexibility in choosing to allow their participants to pursue targets, have them keep their gaze on a fixation cross, or allow natural free viewing.

Our hypothesis is thus specifically that, in a rich environment, biases in perceived speed due to the Aubert-Fleischl phenomenon are negligible.

# Methods

## Participants

We will collect data from XX participants, half of this number will be women and half will be men. We will further test any non-binary participant who signs up. Participants will be recruited from the York University undergraduate participant pool and will be rewarded with course credit. The study has been approved by the local ethics committee and will be conducted in accordance with the Declaration of Helsinki.

## Apparatus

Our stimuli are presented in an HTC VIVE Pro Eye head-mounted device. Participants respond with the HTC VIVE Pro Eye controllers. The VIVE Pro Eye records eye-movements at 60 Hz. The program used to collect data was built in Unity (v. 2021.3.14f).

## Stimulus

In a two-alternative forced-choice task, participants will judge the speed of a red target sphere that moves from either left to right or from right to left against the speed of a ball cloud that moves in the same direction as the target. The sphere is presented 7.5 m in front of the observer and has a diameter of 0.2 m. It is visible for 1.1 s, which are divided in three phases: an acceleration phase (0.3 s), a constant speed phase (0.5 s) and a deceleration phase (0.3s). Given that the Aubert-Fleischl phenomenon only occurs during smooth pursuit eye-movements, we added the initial acceleration phase to make sure that, in the pursuit condition, no catch-up saccades were executed during the constant speed phase.

The sphere appears either to the left or to the right of the observer’s straight-ahead. The initial position was chosen such that the trajectory was centered in front of the observer. It was further given by the acceleration phase, which always lasted 0.3 s. The acceleration was chosen such that the sphere accelerated to its final speed (2, 4, or 6 m/s) over 0.3 s.

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|  | (1) |
|  | (2) |
|  |  |
|  |  |
|  | (3) |
|  | (4) |
| With , |  |
|  | (5) |

The ball cloud was presented at the same depth and had a width of 2.5 m. Each element of the cloud has the same size, shape and color as the single sphere, and around 20 balls are visible at any given moment. The ball cloud’s speed was governed by a PEST staircase (Taylor & Creelman, 1967). A staircase is terminated either when the participant completes 37 trials, or when they complete at least 30 trials and the step size drops below 0.1 m/s.

Participants are asked to either:

1. fixate a fixation cross presented 0.5 m below the height at which the sphere is presented (Fixation condition),
2. or follow the sphere with their gaze (Pursuit condition).

Participants are always asked to keep their gaze on the fixation cross during presentation of the ball cloud. Furthermore, the stimulus is presented either:

1. embedded in a virtual 3D environment (Environment condition, see Figure XX),
2. in a uniformly grey scene that does not provide any additional background cues to eye speed but with stereoscopic cues to depth (No Environment-Stereoscopic condition),
3. in a uniformly grey scene presented monoscopically (No Environment-Monoscopic).

Each combination of these experimental conditions is presented in blocks; the experiment thus consists of 6 blocks whose order is drawn randomly for each participant. Overall, the experiment takes about an hour to complete.

We record the participants’ eye-movements while either the sphere or the sphere cloud is visible. Trials are repeated when the gaze behavior does not match the instructions:

1. While the sphere is visible in the pursuit condition, the absolute mean speed of the eyes (in depth) has to be >= 50% of the target speed across the 0.5 s during which the stimulus travels at constant speed, and the eyes have to move in the same direction as the target.
2. While the sphere is visible in the fixation condition, the absolute mean speed of the eyes (in depth) has to be below 25% of the target speed.
3. While the sphere cloud is visible, the absolute mean speed of the eyes (in depth) has to be below 25% of the target speed.

While computing the gaze speed, we account for the 50 ms it takes the VIVE Pro Eye to make the eye-tracking data available to the system (Stein et al., 2021). The eye-tracking data is further used to light up the fixation cross – whenever present – when the participant’s gaze is within the 0.3 m tolerance of its center to indicate that they are fixating as instructed.

The program used to present stimuli can be downloaded here (XXXX, on OSF), and the Unity project can be downloaded here (XXXX, on OSF).

## Predictions

We expect the speed of the sphere to be estimated accurately when the participant maintains fixation, and we expect it to be underestimated when they pursue the sphere with their gaze. We expect this effect to be absent when a virtual environment is provided, that is, participants should estimate the sphere’s speed accurately in a virtual environment even when they follow it with their gaze.

## Data Analysis

We first fit cumulative Gaussian functions separately for each target speed and experimental condition 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 extract the PSEs (i.e., the 50% thresholds) and use them as a measure of accuracy.

We use linear mixed modelling to test for statistical differences between the experimental conditions. We first fit a model with the PSEs as dependent variable, the fixation condition (Fixation vs. Pursuit), the environment condition (Environment vs. No Environment-Stereoscopic vs. No Environment-Monoscopic), and the interaction between fixation condition and environment condition as fixed effects, as well as random intercepts and random slopes for target speed for the grouping variable Participant. In Wilkinson & Rogers notation (Wilkinson & Rogers, 1973), this model reads as follow:

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|  | (5) |

To assess statistical significance, we use the confint function from base R to compute bootstrapped 95% confidence intervals on the regression coefficients pertaining to the fixed effects.

If we don’t find significant differences between the Fixation and Pursuit conditions, we will further employ Bayesian linear mixed modelling as implemented in the brms package (Bürkner, 2018) for R to determine whether we can find support in favor of the null hypothesis. We will do this separately for each environment condition.

To this end, we fit for each environment condition separately a model with the PSE as dependent variable, the fixation condition as fixed effect, and random intercepts as well as random slopes per target speed for the grouping variable Participant as a test model:

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|  | (5) |

We then fit a null model with the same random effects, but without Fixation as a fixed effect:

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|  | (5) |

Finally, we obtain the Bayes Factor by first computing the marginal likelihood via the bridge\_sample function from the brms package for each model and then comparing them with the bayes\_factor function.

The code used for the analysis can be downloaded here (XXXXX, GitHub).

## Power Analysis

Considering that one of the goals of this study is to provide evidence whether the Aubert-Fleischl phenomenon should be considered in future research on speed perception in virtual environments, it is relevant to define the smallest effect size of interest. Powering the study for an adequately small smallest effect size of interest will also provide a sample size big enough to obtain strong enough evidence for the absence of an effect (via the Bayes factor). We stipulate that any difference in perceived speed below 1% is too small to be of interest in most contexts. [MORE JUSTIFICATION, do some literature search]

We then perform a power analysis as outlined by Jörges (Jörges, 2021). This method relies on simulating full data sets based on assumptions about different sources of variability and the expected effect size or the smallest effect of interest. Each simulated data set is then analyzed (via the process outlined above under Data Analysis), and the fraction of cases in which a significant difference between the relevant conditions is detected is an adequate approximation of the power of these statistical tests. Since the example used in (Jörges, 2021) was a very similar task, we maintain most of the assumptions outlined there. We approximate power only for the environment in which we expect the smallest effect, that is, the Environment condition.

The code used for the power analysis can be downloaded here (XXXXX, GitHub).

