

OBJECT SPEED PERCEPTION DURING LATERAL SELF-MOTION

Björn Jörges¹, Laurence R. Harris^{1}*

¹ Center for Vision Research, York University, 4700 Keele Street, Toronto, ON M3J 1P3, Canada

* Corresponding Author

Abstract

Judging the velocity of objects during observer self-motion requires disambiguating retinal stimulation caused by the observer's own movement and retinal stimulation caused by object movement. According to the Flow Parsing hypothesis, observers first estimate their own motion based on visual and other cues. They then subtract the retinal motion corresponding to their own movement from the total retinal stimulation and interpret the remaining stimulation as pertaining to object motion. While the phenomenon has been studied to some extent for motion-in-depth and rotational motion, lateral motion has been largely neglected. The Flow Parsing hypothesis yields predictions both for the precision and the accuracy of target speed estimation during self-motion: firstly, subtracting noisier self-motion information from retinal input should lead to a decrease in precision when the observer is moving during motion observation. Furthermore, when self-motion is only simulated visually, while other cues such as vestibular sensory information and data from efference copies are unavailable, self-motion is likely to be underestimated, which should yield an overestimation of target speed when target and observer move in opposite directions and an underestimation of target speed when target and observer move in the same direction.

Significance

We rarely stand still while interacting with our inherently dynamic environment. It is crucial for us to obtain accurate and precise estimates of the movement of objects relative to ourselves and relative to the environment even while we are moving. Here, we investigate how we judge the speed of moving objects during visually evoked lateral self-translation. Surprisingly, this measurement has never been attempted before. Estimating the physical speed of objects accurately and precisely is important for a variety of tasks that require an allocentric reference frame.

Introduction

When observing a moving target while an observer is moving, the same retinal speeds can correspond to vastly different physical velocities. When an observer moves in the same direction, parallel to a moving object, the retinal speed of the object is partially cancelled out, and when they move in the direction opposite to the object, the retinal stimulation due to self-motion may be added to the retinal speed of the object. To obtain an accurate estimate of the object's velocity, observers must therefore obtain an accurate estimate of their own velocity and subtract or add the consequences of this movement to the retinal motion of the target. More specifically, the Flow Parsing Hypothesis (Dupin & Wexler, 2013; Rushton & Warren, 2005; Warren & Rushton, 2008, 2009) posits that, to estimate object motion from ambiguous retinal input representing the sum of object and self-motion, observers first

compute which components of retinal stimulation are caused by their own motion in the environment. Then, they subtract this self-motion information from the overall retinal stimulation and attribute the remaining stimulation to object motion in the scene. When self-motion is experienced only visually while undergoing no physical motion, the visual motion creates a conflict between visual and vestibular inputs as a result of which self-motion is likely to be underestimated, leading to biases in judgments of object velocities although oddly this has never been quantified for horizontal translation. The effect has been shown to some extent for vertical observer and object translation (Dyde & Harris, 2008), as well as for rotating observers (Garzorz, Freeman, Ernst, & MacNeilage, 2018; Hogendoorn, Alais, MacDougall, & Verstraten, 2017; Probst, Loose, Niedeggen, & Wist, 1995) and motion-in-depth (Gray, MacUga, & Regan, 2004). Furthermore, it has been argued that self-motion information is noisier than retinal information concerning object motion, especially when observers have only visual information about their own movement at their disposal (Fetsch, Deangelis, & Angelaki, 2010). Subtracting noisy self-motion information from retinal motion in order to obtain an estimate of target velocity should thus decrease precision (Dokka, MacNeilage, DeAngelis, & Angelaki, 2015). Such a subtraction process is relatively straightforward for the consequences of angular self-motion, but for lateral motion, the geometry requires additional computations involving estimates of the distance of the object to the observer and the direction of object motion relative to the observer's motion. More specifically, observers need to first estimate their own motion in an allocentric world frame by using retinal stimulation attributable to the induced motion of static objects in the environment and other sensory and efferent information such as vestibular activity. Then, this estimate needs to be used to generate an estimate of the retinal stimulation expected to be caused by the observer's motion. This estimated retinal stimulation due to self-motion is then subtracted from the total retinal stimulation, which allows the remaining retinal stimulation to be interpreted as external object motion. The process is known as "flow parsing" in which the different aspects of the total optic flow are attributed to these different causes.

It is important to note that flow parsing is only necessary when humans need to represent the kinetic properties of their environment in an allocentric frame. For computations performed in an egocentric frame, it is generally sufficient to time interceptive actions and avoid collisions according to the velocity of the target relative to the observer. It is true that ecological, optic-flow-based heuristics have successfully explained human performance in paradigmatic cases such as the outfielder problem (Fink, Foo, & Warren, 2009; Wilson & Golonka, 2013). However, humans are able to recover, represent and use the physical parameters of their environment in a variety of tasks (Burr, Tozzi, & Morrone, 2007; Fajen, Parade, & Matthis, 2013; Ilg, Schumann, & Thier, 2004; Wexler, 2003).

There are two major sources of information about passive self-motion: visual and vestibular cues (Fetsch et al., 2010), which are integrated according to their relative reliability (Fetsch, Turner, DeAngelis, & Angelaki, 2009). How much each sense contributes to the global percept of self-motion seems to depend on different parameters, such as the task and the self-motion profile. Dokka et al. (Dokka et al., 2015), for example, found for direction judgments of a probe presented in the fronto-parallel plane during lateral observer motion that vestibular information in the absence of visual information led to a vast underestimation of self-motion. Visual information only elicited a higher accuracy and having both visual and vestibular cues available increased accuracy only marginally beyond accuracy for visual information only. In a more direct test of perceived self-motion, Harris et al. (Harris et al., 2000) found that vestibular stimulation evoked by moving the observer through the environment was an extremely

potent cue to self-motion which induced a vast overestimation of the distance moved. Visual cues to self-motion were efficient, too, but less so than vestibular cues. However, depending on stimulus parameters such as simulated acceleration, visual cues alone can also lead participants to overestimate their movement (Redlick, Jenkin, & Harris, 2001). For active self-motion (i.e., movements initiated by the observer such as walking through the environment), efference copies and proprioceptive information can serve as further cues. For example, judgments about the distance travelled seem to be more reliable if motion was self-generated as opposed to experienced passively (Becker, Nasios, Raab, & Jürgens, 2002; Frissen, Campos, Souman, & Ernst, 2011; Jürgens & Becker, 2006).

Remarkably, the literature is quite sparse with regards to assessing object motion during lateral, visually simulated observer motion: Warren and Rushton (Warren & Rushton, 2007) found that translational visually evoked self-motion lead observers to perceive the trajectory of a linearly moving probe as tilted towards the direction of the simulated translation. MacNeilage et al. (MacNeilage, Zhang, DeAngelis, & Angelaki, 2012) showed that vestibular cues could help distinguish self-motion from object motion, especially for lateral observer motion. Similarly, Dokka et al. (Dokka et al., 2015) investigated the extent to which observer motion (visual cues only, vestibular cues only, and both visual and vestibular cues) influenced the judged direction of vertical downwards motion with a small lateral component. They found biases in line with insufficient compensation for self-motion in all observer-motion conditions, as well as decreases in sensitivity. Niehorster and Li (Niehorster & Li, 2017) quantified extent to which flow parsing was complete for straight-ahead self-motion by having participants judge the direction of a probe that moved vertically upwards. Importantly, all these studies used direction judgements as proxies to probe the completeness of flow parsing, while a direct psychophysical investigation of perceived velocities is notably missing from the literature. Furthermore, while some of these studies presented their stimuli in compelling stereo 3D, none immersed the observer in a virtual environment. It is not unlikely that flow parsing is facilitated by a more realistic environment. This study aims to shed light on the extent to which visually evoked self-motion influences perceived lateral object speed in a naturalistic setting. This is particularly relevant as the visual system has been shown to use velocity information to extrapolate object trajectories to compensate for noisy online information and neural delays (Aguado & López-Moliner, 2019; Aguilar-Lleyda, Tubau, & López-Moliner, 2018; Jörges & López-Moliner, 2019; López-Moliner, Brenner, Louw, & Smeets, 2010). The aim of this project is thus to verify the impact of visually simulated self-motion on accuracy and precision for object velocity speed judgments during lateral translation, which will further our understanding of Flow Parsing and help us understand the conditions under which Flow Parsing is incomplete. More specifically, our hypotheses are:

- When the observer is static experiences no visual self-motion during object motion observation, we expect the highest accuracy of velocity speed estimation.
- When the visual observer motion is simulated moving opposite to the object motion (e. g. observer moves to the right, object moves to the left) during object motion observation, we expect them to overestimate the observed velocity speed.
- When the visual observer motion is moving simulated in the same direction as the target (e. g. both observer and target move to the right) during object motion observation, we expect them to underestimate the observed velocity speed.
- Furthermore, we expect the precision to be lower when the subject experiences visually simulated self-motion during object motion observation relative to when they are static.

126

127 Participants

128 We tested ~~30~~16 participants (see power analysis) from the population of PhD and undergrad students at
129 York University with equal numbers of ~~males and females~~men and women. Due to the culturally
130 independent nature of the phenomenon under study, we do not believe our results are likely to be
131 relevantly skewed by WEIRD people effects (Henrich, Heine, & Norenzayan, 2010). Participants ~~will~~
132 ~~have had~~ normal or corrected-to-normal vision and ~~have had~~ to achieve a stereoacuity of 63 arc seconds
133 or below on the Fly Stereo Acuity Test. The project has received ethics approval from the Human
134 Participant Ethics Review Sub-Committee at York University. Informed consent was obtained from all
135 subjects and the experiment was conducted in accordance with the Code of Ethics of the World Medical
136 Association (Declaration of Helsinki).~~We continued data collection until we tested 30 subjects who~~
137 ~~satisfied the criteria laid out below under “Intended interpretation of visually simulated self-motion and~~
138 ~~task”.~~

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139 ~~Our experiment critically depended on our participants perceiving themselves as moving rather than~~
140 ~~the world as moving. We therefore asked our participants after the training (see below) and after~~
141 ~~conclusion of the experiment, whether they had perceived themselves as having moved. They were~~
142 ~~only included into the confirmatory analyses if they answered “yes” for their perception during the~~
143 ~~test session. Data collection continued until we achieved 16 subjects who had perceived self-motion~~
144 ~~during the test session.~~

145

146 Apparatus

147 All the experiments were performed in virtual reality with participants remaining physically static and
148 seated. We programmed the stimuli in Unity (2019.2.11f1), while object motion, visually simulated self-
149 motion and the psychophysical staircases were controlled in C# via its integration with Unity. The Unity
150 project is available on Open Science Foundation (<https://osf.io/m6ukw/>). Stimuli were presented in an
151 Oculus Rift (CV1, firmware version 709/b1ae4f61ae). Participants responded by means of a finger
152 mouse.

153

154 Setup

155 Our experiment consisted of a Two Interval Forced-Choice Task where participants were asked to
156 indicate which of two intervals contained objects moving at the higher speed.

157 Environment and general layout

158 ~~Our experiment consisted of a Two Interval Forced-Choice Task where participants were asked to~~
159 ~~indicate which of two intervals contained objects moving at the higher velocity.~~ Participants were
160 immersed in a virtual 3D environment that included depth cues from lighting, shadows and the scale of
161 the textures of the floor and the wall backdrop. The ball appeared to the left of the observer if it moved
162 to the right, and to the right of the observer when it moved to the left. The exact position was
163 determined by target speed and visual observer motion (see Equation 1 below). See Figure 1A for a
164 diagram of the visual scene and Figure 1CB for a screenshot from the experiment; furthermore, a short

sequence of the experiment can be ~~viewed-downloaded here (GitHub) under <https://github.com/b-jorges/Motion-Perception-during-SelfMotion/blob/master/Figures/GIF%20of%20stimulus.gif>~~.

Targets and visually simulated self-motion

In one interval participants were presented a ball with a diameter of 0.33 m at a simulated distance of 8 m in front of them, travelling ~~to the right or to the left~~ with 6.6 or 8.0 m/s (~~four-two~~ target motion profiles). ~~The direction in which the targets moved was chosen randomly on each trial.~~ During this interval, participants were either static or experienced visually simulated body movement to the left or to the right with a Gaussian velocityspeed profile (three self-motion profiles), accelerating until reaching peak velocityspeed after 0.25 s and then slowing down until coming to a halt at 0.5 s. The position in time $x(t)$ was given by a cumulative Gaussian distribution with a mean of 0.25 s and a standard deviation of 0.08 s divided by 2, multiplied by -1 for trials with visually simulated self-motion to the left. That is, participants were moved visually 0.5 m over the course of 0.5 s, which amounts to a mean velocityspeed of 1 m/s. The target's initial position was shifted away from the observer for motion in the same direction, and towards the observer when the observer's visual motion occurred opposite to the target motion, such that observer and target motion were symmetrical, i.e., the distance between observer and target at the beginning was the same as the distance at the end of the trial. To achieve this, the starting position of the target was computed in the following manner:

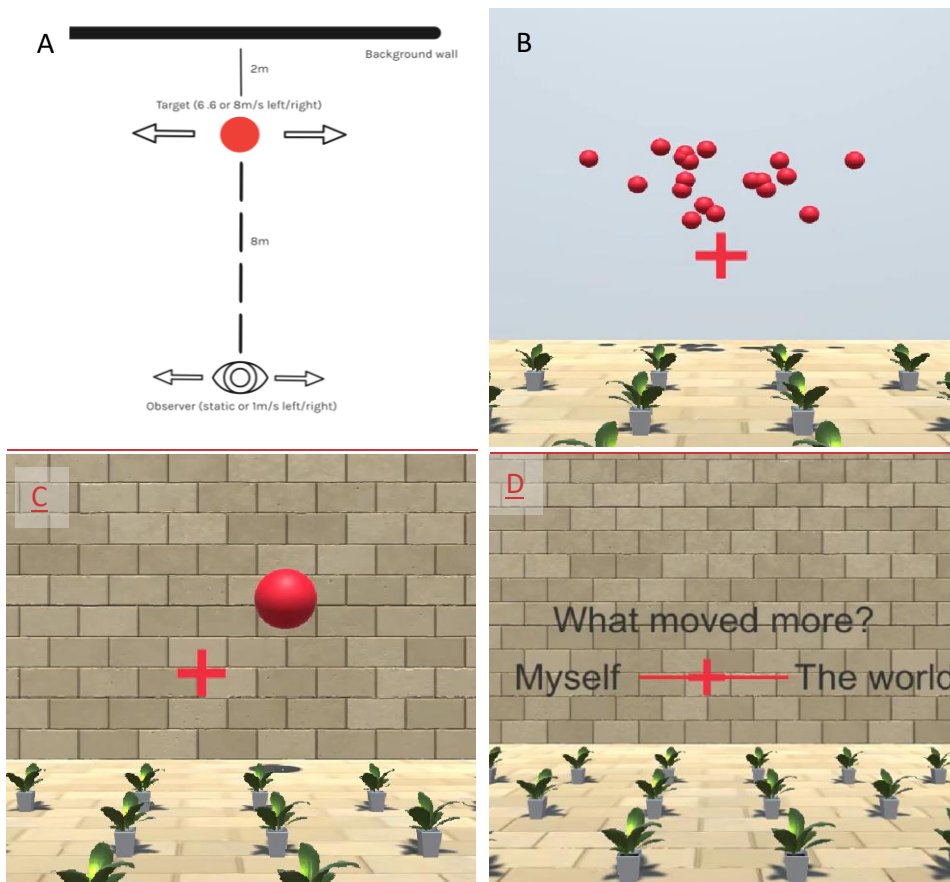
$$x_{initial} = 0.5 * (Distance_{observer} - v_x * t) \quad [1]$$

$x_{initial}$ denotes the initial position of the target relative to the observer, $Distance_{observer}$ is the lateral distance the observer in which the observer is simulated to move, v_x is the horizontal velocityspeed of the target, and t is the duration of the motion interval (0.5 s).

Staircase

In the other interval, participants were shown a cloud of smaller moving balls each with a diameter of 0.1 m, as comparison. The balls appeared 1.25 m to the left of the observer (if the big target in the same trial moved to right) or to the right of the observer (if it moved to the left), then moved in the same direction as the big target and disappeared after having travelled 2.5 m. They were spread out vertically over a distance of 1 m. 10 to 15 balls were visible at any given moment. Observers were asked to maintain their gaze on a fixation cross that was continuously displayed straight ahead of them (i.e., also during visually evoked self-motion), 0.8 m under the target (see Fig 1b). The speed of these smaller balls was controlled by a PEST staircase. We employed two staircases for each combination of visually stimulated self-motion (left, right or static) and object motion (~~-8, -6.6, -6.6 and 8 m/s~~), one of which started 33 % above the target's speed, and the other one 33 % below target speed (two staircases for each combination of target motion and self-motion). ~~The direction (left-to-right or right-to-left) was chosen randomly for each trials.~~ Thus, there was a total of ~~24~~ target speeds x 3 motion conditions x 2 = ~~24-12 interleaved~~ staircases. When participants answered that the ball cloud was faster, a lower velocityspeed was displayed in the next trial of that PEST and vice-versa. The step sizes were governed by the following rules (Taylor & Creelman, 1967): the initial step size was 1.2 m/s. For the first five trials for each PEST, the step size was maintained. Starting from the eleventh trial, after a reversal (subjects answered "PEST is slower" in the second-to-last trial and "PEST is faster" in the last trial or vice-versa), the step size was halved. After the second same answer, the step size was maintained. After the third same answer, the step size was either maintained, when the step size had been doubled before the last reversal, or doubled when the step size had not been doubled before the last reversal. After four same

206 answers, the step size was always doubled. Each PEST ended when it converged (five consecutive trials
 207 with step sizes lower than 0.1) AND participants had judged at least 20 trials of the staircase. If the
 208 staircase did not converge, the PEST was terminated after 3275 trials. The experiment ended when all
 209 24-PESTs, including the control PESTs (see “A possible confound: Induced Motion” below), had
 210 terminated. This took about an hour overall including instructions and breaks, which participants could
 211 take. Every 15 minutes, participants were asked whether they wanted to take a short break.



212 Figure 1: A. Top view of the stimulus scene in one of the test trials. The red circle represents the target, which starts on one side
 213 of the midline (see text for details) and moves laterally at 6.6 or 8 m/s for 0.5 s, that is, 3.3 or 4 m. The stylized eye indicates the
 214 position of the observer, who can be static or move to the left or to the right for 0.5 s with a Gaussian motion profile and a mean
 215 velocity/speed of 1 m/s. The target is 8 m away from the observer and 2 m in front of the background wall. B. Screenshot from
 216 the program during presentation of the dot cloud in the untextured wall condition (“Minimal Induced Motion”). C. Screenshot
 217 from the program during presentation of the big target in the textured wall condition (“Minimal Visually Induced Self-Motion”).
 218 D. Screenshot from the self-motion judgment conducted after the main body of the experiment. A short sequence of the stimuli
 219 main experiment can be viewed [here](https://github.com/b-jorges/Motion-Perception-during-Self-Motion/blob/master/Figures/GIF%20of%20Stimulus.gif) (Github). A sequence from the self-motion judgment part of the experiment is available
 220 [here](https://github.com/b-jorges/Motion-Perception-during-Self-Motion/blob/master/Figures/GIF%20of%20Stimulus.gif) (Github) at <https://github.com/b-jorges/Motion-Perception-during-Self-Motion/blob/master/Figures/GIF%20of%20Stimulus.gif>.
 221

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Before starting the actual data collection, participants perform a training session with one PEST where the big target moved at 4 m/s. Subjects were asked to repeat the training if the step size in any of the last five trials was above 0.3 m/s. If they still failed to meet the criterion after a second repetition they were excluded from the experiment.

Intended interpretation of visually simulated self-motion and task

Our experiment critically depended on our participants perceiving themselves as moving rather than the world as moving. We are furthermore interested in participants making the velocity judgments relative to the world, not relative to themselves, and we assume that our instruction will make sure of this. However, there is a possibility that either of these assumptions will not hold. This gives rise to five different scenarios during visually simulated self-motion:

- (1) Participants perceive the world as static and themselves as moving and judge object speed relative to the world. This is the intended case.
- (2) Participants perceive themselves as static and the world as moving and judge object speed relative to the world. In this case we would find no effect of visually simulated self-motion at all, that is, there would be no differences between visually simulated self-motion and a (visually) static observer.
- (3) Participants perceive the world as static and themselves as moving and judge object speed relative to themselves. In this case, participants would add the speed of visually simulated self-motion fully onto the target speed, that is, the PSE would be shifted by roughly the mean value of the visually simulated self-motion.
- (4) Participants perceive themselves as static and the world as moving and judge object speed relative to themselves. In this case, participants would also add the speed of visually simulated self-motion fully onto the target speed, that is, the PSE would be shifted by roughly the mean value of the visually simulated self-motion.

To rule out scenarios (2) and (4), we had our participants judge to what extent they felt themselves or the world moving. They were only included into the confirmatory analyses if they had a mean rating between -1 and -0.6 in their judgments about perceived self-motion versus world-motion (see below), indicating that they fully or mostly perceived the world to move, rather than themselves. To achieve that participants made their judgments relative to the world and not to themselves, thus ruling out scenario (3), we gave them very clear instructions to this effect.

It is furthermore possible that participants judge motion partially relative to the world and partially relative to themselves. This seems to be roughly equivalent to a scenario where participants judge motion relative to the world, but fail to compensate fully for self-motion in their object speed judgments. Shifting from an observer-centered reference frame to a world-centered references has been suggested as the mechanism behind the accuracy-precision trade-off observed by Dokka et al. (Dokka et al., 2015): in this view, transposing a percept into a world-centered reference frame increases accuracy, i.e., enhances compensation for self-motion, at the cost of a decrease in precision.

A possible confound: Induced Motion

Induced motion occurs when a stimulus is contained within a moving reference frame. Even in a virtual reality 3D presentation, a texture background might be construed as such reference frame and therefore induce motion. Induced motion would bias perceived speed in the opposite direction to the background motion and could therefore mask potential effects of self-motion. That is, any induced

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264 motion would tend to cancel out incomplete compensation for self-motion which would otherwise
265 reveal itself as motion in the same direction as the background, leading to an overall accurate speed
266 estimate. The strength of induced motion depends on several factors: The adjacency principle, which
267 states that stimuli that are closer together in space (in all three dimensions) lead to stronger induced
268 motion (Gogel & Koslow, 1972; Gogel & MacCracken, 1979). Furthermore, enclosure seems to be
269 important. Experiments on induced motion without a full rectangular reference frame are rare, but even
270 moving dots have been shown to induce some motion, albeit to a much lesser extent than a full frame.
271 Brosgole & Whalen (Brosgole & Whalen, 1967), for example, found that induced motion was halved
272 when using a dot as the inducing stimulus moving 0.2° from the induced stimulus, in comparison to the
273 effect of a full rectangular frame at the same distance. Duncker (Duncker, 1929), furthermore observed
274 that a horizontal line moving horizontally induced much less motion than a vertical line moving
275 horizontally or a full rectangle, which is arguably a scenario that comes closest to our display.

276 **Control Conditions: Setup** – To account for this possible confound, we added two additional conditions.
277 In the first condition (“Minimal Induced Motion”), we minimized possible induced motion effects by
278 using an untextured wall backdrop (Figure 1B). Motion might still be induced by the other objects in the
279 visual scene, but in absence of any traditional frame, induced motion should be minimal. All other
280 experimental parameters were the same as for the main experiment. In the second condition (“Minimal
281 Self-Motion”), we aimed to minimize perceived self-motion while keeping the induced motion
282 component of the effect intact. We achieved this by moving only the (textured) wall backdrop of the
283 stimuli, while keeping the rest of the visual scene (textured floor, context objects) static. The wall
284 backdrop moved with the same motion profile as the observer was moved visually in the other
285 conditions. This added another 14 staircases (six per control condition) that were interleaved in a
286 random order with the staircases described above.

287 **Probing perceived self-motion** – To assess whether this manipulation worked as intended, after
288 conclusion of the main body of the experiment, we showed the participants the different conditions (full
289 visually evoked self-motion, Minimal Induced Motion and Minimal Self-Motion) without the object
290 motion. After they experienced the stimulus (i.e., visually simulated self-motion in the full room, visually
291 simulated self-motion with the untextured wall background or no visually simulated self-motion, but a
292 moving wall backdrop), we asked them to rate on a continuous scale within the virtual environment (see
293 Figure 1D) to which extent they had perceived themselves or the world/wall as moving. Figure 1D shows
294 a screenshot taken from the judgment phase of the task. We repeated this procedure four times for
295 each condition and direction for a total of 24 trials. This took about two minutes. We included only
296 those participants whose mean ratings per condition were within 0.4 of the expected value (i.e., [-1;-
297 0.6], indicating observer motion, for Minimal Induced Motion; [0.6;1], indicating wall motion, for
298 Minimal Self-Motion; and [-1;-0.6], indicating observer motion, for the regular visually simulated self-
299 motion condition). Data collection continued until we achieved the desired number of participants (see
300 power analysis below).

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302 Analysis of Pilot Data

303 Main Hypotheses: Visually Simulated Self-Motion

304 To test our main hypotheses regarding the influence of visually simulated self-motion on precision and
305 accuracy, we performed the following tests over the main conditions, i.e., when the wall backdrop was
306 textured and the participant was moved visually, not the wall backdrop.

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307 To assess the **Just Noticeable Difference (JND)** as a measure of precision, we employ General Linear
308 Mixed Modelling, implemented in the R package lme4, according to the recommendations in
309 (Moscatelli, Mezzetti, & Lacquaniti, 2012). We first established a Test Model, in which responses were
310 fitted to a cumulative Gaussian, with subject ID ("Subject") and horizontal ~~velocity~~speed
311 (~~Velocity~~Speed_{horizontal}, with values -8, -6.6, 6.6 and 8 m/s) as random effects with random intercepts
312 and random slopes per speed difference between target and ball cloud ("Difference"), and self-motion
313 (binary variable "Subject Motion" with the values "Yes" and "No") and difference in ~~velocity~~speed
314 between target and ball cloud ("Difference") and their interaction as fixed effects. In lme4 syntax, this
315 corresponds to:

$$\begin{aligned} \text{Subject Motion} * \text{Difference} + (\text{Difference} | \text{Subject}) & \quad [2] \\ + (\text{Difference} | \text{VelocitySpeed}_{\text{Target}}) \end{aligned}$$

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316 We furthermore established a Null Model with subject and horizontal ~~velocity~~speed as random effects
317 with random intercepts, and subject motion profile and difference in ~~velocity~~speed between target and
318 ball cloud as fixed effects, but not their interaction:

$$\begin{aligned} \text{Subject Motion} + \text{Difference} + (\text{Difference} | \text{Subject}) & \quad [3] \\ + (\text{Difference} | \text{VelocitySpeed}_{\text{Target}}) \end{aligned}$$

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corrected error

319 We then use an ANOVA to test whether the test model was significantly better than the null model. If
320 the interaction term improved the model significantly, the subject motion profile has a relevant
321 influence on the slope of the fitted cumulative Gaussian. We expected the interaction parameter to be
322 lower for Motion = "Congruent" and Motion = "Incongruent", thus putting into evidence that visually
323 simulated self-motion decreases precision in object ~~velocity~~speed judgments during self-motion.

324 To assess the **Point of Subjective Equivalence (PSE)**, our Test Model contained the same random effects
325 as above and the self-motion profile (ternary variable "Motion Profile" with the values "Congruent",
326 "No Motion" and "Incongruent") and the ~~velocity~~speed difference between target and ball cloud
327 ("Difference") as fixed effects (Moscatelli et al., 2012). The lme4 syntax is:

$$\text{Motion Profile} + \text{Difference} + (\text{Difference} | \text{Subject}) + (\text{Difference} | \text{Velocity}_{\text{Target}}) \quad [4]$$

328 The Null Model contained the same random effects, and only the difference in speed between target
329 and ball cloud as a fixed effect.

$$\text{Difference} + (\text{Difference} | \text{Subject}) + (\text{Difference} | \text{Velocity}_{\text{Target}}) \quad [5]$$

330 We compared both models with an ANOVA and expected the Test Model to be significantly better than
331 the Null Model, indicating that visually simulated self-motion had an impact on the PSE. Visually evoked
332 self-motion in the same direction as the target should decrease perceived target ~~velocity~~speed, and

visually evoked self-motion in the opposite direction of the target should increase perceived target velocity/speed.

Control conditions
For the control conditions (Minimal Self-Motion and Minimal Induced Motion), we used the model comparison [4]/[5] to assess whether wall motion (Minimal Self-Motion) or visually simulated self-motion (Minimal Induced Motion), respectively, led to any biases in perceived velocity. For Minimal Induced Motion, we expected that same pattern as for the main condition, but a slightly less complete compensation, with the untextured wall backdrop giving fewer cues about visually simulated self-motion. Furthermore, there should be next to no induced motion effects, which should augment the observed effect further. For Minimal Self-Motion, we expected a small effect of induced motion in the opposite direction of the effect of visually simulated self-motion, i.e., an overestimation of speed when observer and wall move in opposite directions, and an underestimation of speed when observer and wall move in the same direction.

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Power Analysis

Based on the analysis plan above, we proceeded to a power analysis via simulation. We computed the power for the main condition (visually simulated self-motion with a textured wall backdrop). The R code used for this power analysis is available online under <https://github.com/b-jorges/Motion-Perception-during-Self-Motion/blob/master/PowerAnalysisMotionEstimation.R>. We first created datasets that would roughly resemble the data we are expecting to collect. At the core of the simulation of these datasets is the assumptions that responses could be described by a cumulative Gaussian function (which approximates what is commonly known as “Psychometric Function”). The mean of the cumulative Gaussian corresponds to the PSE, and its standard deviation is proportional to the JND. We varied the means of the Gaussian according to the self-motion profile. Pilot data (see below) show consistently a bias to interpret the dot cloud as faster; when the observer is static, we thus assume a PSE of 2/3 of the presented velocity/speed. When the observer moved opposite to the target, we expected the PSE to be higher than in the static condition, and when the observer moved with the target, we expect the PSE to be lower. We conducted the power analysis assuming a difference of 1/8 of the mean presented self-motion-velocity/speed of the visually evoked self-motion; (Dokka et al., 2015) found biases up to 50 % of the visually simulated self-motion. Their task, directionality judgments about downward motion with a lateral left- or rightward component, bears some similarities to ours, but is different enough to warrant a more conservative estimate for the sake of the power analysis. Furthermore, we use a more naturalistic environment which may render flow parsing more complete. For the standard deviation, we parted from a Weber fraction of 7 % for the static condition (McKee, 1981), which corresponds roughly to a standard deviation of 10 % of the PSE. Where the observer is moving, we expected increased JNDs and therefore an increased standard deviation. For the sake of this power analysis, we assume that the standard deviation in this case might be 1/4 higher than the standard deviation for a static observer. (Dokka et al., 2015) found increases of up to 200 % in thresholds from no self-motion to visually simulated self-motion. We choose a much more conservative value to account for task differences. Additionally, we varied the PSE and SD per subject by multiplying them with random values drawn from a normal distribution with a mean of 1 and a standard deviation of 0.1. To account for the fact that our

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staircase leads to a concentration of responses around the PSE, we drew the stimulus strengths from a Cauchy distribution with a location of 1 and a scale of 0.04. We drew 55 stimulus strengths for this distribution (per combination of target velocityspeed and self-motion, we use two PESTs with about 27 trials each; see above) and fed them into the cumulative Gaussian we established per condition and subject. This yielded the answer probability per trial. We then used these probabilities to draw binary answers (PEST faster yes/no) from a Bernoulli distribution for each trial.

We simulated 500 of these data sets, conducted the analyses described above over each for 10, 12, 14, 16, 18 and 20, 22, 24, 26, 28 and 30 subjectsparticipants. We report the percentage where the Test Model was significantly better than the Null Model in Table 1.

n	Power Accuracy	Power Precision
<u>20</u> 40	1	<u>0.83</u> 0.744
<u>0.744</u> 1222	1	<u>0.88</u> 0.800
<u>24</u> 44	1	<u>0.91</u> 0.812
<u>26</u> 46	1	<u>0.96</u> 0.852
<u>28</u> 48	1	<u>0.94</u> 0.876
<u>30</u> 20	1	<u>0.98</u> 0.910

Table 1: Simulated power values for 10, 12, 14, 16, 18 and 20, 22, 24, 26, 28 and 30 participants.

While the effect should be easily detectable for the accuracy-based hypothesis, the precision hypothesis is somewhat harder to detect and requires at least 14-30 subjects (for a power above 0.9). ~~As it is not very costly for us to add more subjects, we aim for a power of 0.95, which should be achieved with roughly 16 subjects.~~ Note that, as the simulation process involves several sources of uncertainty, some variability is to be expected in the results, which explains why the simulated-power difference between 22 and 24 participants is smaller than the difference between 24 and 26 participants. ~~for 18 subjects is lower than the power simulated for 16 subjects.~~

Our predictions for the effect of induced motion, which we want to probe for in the control conditions, are about accuracy. Considering that it is generally easier to detect accuracy differences than precision differences with the above method, we are confident that the participant number that allows us to detect the precision main effect will also allow us to detect any relevant effect of induced motion.

Commented [BJ8]: new

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Pre-existing Data

We collected data from seven pilot participants in the main condition (visually simulated self-motion with a texture wall backdrop). One (s07) was excluded because some of her PESTs did not converge. Two participants (s01 and s02) had previously done the task in 2D, but only their 3D data were included in the analysis. Pilot results are largely in line with our predictions: In terms of JNDs, we found that our Test Model was significantly better than the Null Model ($p = 0.02$), and effects trended in the direction of our hypothesis (regression coefficients of -0.078 , $SE = 0.034$, for the interaction between visually simulated self-motion present and the difference in velocityspeed, which corresponds to a lower precision). For the PSEs, we found that our Test Model was significantly better than the Null Model ($p < 0.001$), and the effects go largely in the expected direction (regression coefficients of 0.072 , $SE = 0.05$, for the main effect of congruent motion, and -0.25 , $SE = 0.053$, for the main effect of incongruent motion; which corresponds to a lower perceived speed for congruent motion and visually evoked self-

409 motion, and a higher perceived speed for incongruent motion and visually evoked self-motion). The
410 code used for this analysis as well as the pilot data are available under on GitHub[https://github.com/b-](https://github.com/b-jorges/Motion-Perception-during-Self-Motion/blob/master/AnalysisPilotData.R)
411 [jorges/Motion-Perception-during-Self-Motion/blob/master/AnalysisPilotData.R](https://github.com/b-jorges/Motion-Perception-during-Self-Motion/blob/master/AnalysisPilotData.R).

412 The pilot data were not included into the final analysis; we recruited 3046 new subjects.

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414 Open Practices

415 All raw data collected during this project are published in the GitHub repository [https://github.com/b-](https://github.com/b-jorges/Motion-Perception-during-Self-Motion/)
416 [jorges/Motion-Perception-during-Self-Motion/](https://github.com/b-jorges/Motion-Perception-during-Self-Motion/), as well as all the code used for analysis. Furthermore,
417 the Unity projects used to present the stimuli and collect data is available on OSF under
418 <https://osf.io/m6ukw/>.

Field Code Changed

Commented [BJ10]: upload code for experiment when done

Field Code Changed

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