Measuring embodied immersion through reactive and proactive postural adjustments during a telepresence cycling experience

Gabriel Baud-Bovy[1], Giulia Castagliuolo[2], Vittorio Dalmasso[3] & Claudio de'Sperati[4]

Laboratory of Action Perception and Cognition, School of Psychology, Vita-Salute San Raffaele University, via Olgettina 58, 20132-Milan, Italy

[1]baudbovy.gabriel@unisr.it, [2]g.castagliuolo@studenti.unisr.it, [3]dalmasso.vittorio1@hsr.it, [4]desperati.claudio@unisr.it

DOI: 10.54337/aau.icdvrat26.28

Abstract

Immersion is central to engagement in virtual reality, yet it's often measured through subjective reports. We examined whether motor behaviour could provide an objective, real-time measure of immersion during a first-person cycling experience. Twenty-one participants pedalled on a cycle ergometer while viewing 360° bicycle ride videos through a head-mounted display. Head movements and pedalling cadence were recorded during expected and unexpected stops. Participants reacted with downward head rotation and reduced cadence. Expected stops produced earlier, smoother head movements responses and stronger cadence reductions. These findings indicate motor measures could complement self-reports in assessing immersion and support applications in rehabilitation contexts.

1. Introduction

The effectiveness of VR applications depends, at least in part, on user engagement. A major determinant of engagement is the sense of presence, which is strongly influenced by the degree of immersion afforded by the virtual environment (Schuemie et al., 2001; Riva et al., 2004; Sanchez-Vives and Slater, 2005).

Despite its importance, immersion is typically assessed through subjective user experience (UX) reports, and objective, real-time measures remain limited. However, objective motor responses may provide important complementary evidence, because they may reflect embodiment (Sanchez-Vives and Slater, 2005; Saint-Aubert et al., 2023). Posture and movement may therefore offer informative readouts of the naturalness and congruency of VR environments. So establishing objective behavioural indicators of immersion would be valuable both for research and for rehabilitation applications, where continuous monitoring of user engagement may help optimize intervention delivery.

Given the increasing use of VR-based cycling applications in rehabilitation, including exercise programmes for older adults and long-term care settings (Anderson-Hanley et al., 2012; Arlati et al., 2019; Høeg et al., 2021; Loggia et al., 2021; de'Sperati et al., 2023; www.telecyclette.eu), it seems important to determine how posture and movement during virtual cycling are shaped by visual cues, particularly optic flow (visually-evoked motor responses, VEMRs; Bronstein, 1986). Previous research on optic flow during simulated cycling, however, has mainly focused on perceived or exerted effort (Parry et al., 2012; Yasukawa et al., 2021; Otten et al. 2025).

In this preliminary report, we compared VEMRs elicited by unexpected and expected stops during an immersive first-person virtual bicycle ride. Because VEMRs can be modulated by expectation (Bronstein and Buckwell, 1997; Guerraz et al., 2001; Cooper et al., 2018), we distinguished reactive motor adjustments (RMAs), driven by optic flow changes, from proactive motor adjustments (PMAs), which depend on anticipation. We hypo-thesised that unexpected stops would mainly evoke RMAs, whereas expected stops would mainly evoke PMAs.

2. Methods

1.1. Participants

Twenty-one volunteers recruited by convenience sampling participated in the study (11 males; age range, 21–35 years). History of epilepsy or motion sickness was considered an exclusion criterion. Written informed consent was obtained from all participants before the experiment.

1.2. Stimuli and task

The stimuli consisted of two 12-min pre-recorded 360° videos of a bicycle ride in a suburban area, filmed along the same route in opposite directions. The videos were recorded in 4K resolution at 29.97 fps using a Ricoh Theta Z1 camera mounted on the handlebar. Each video included 12 stops: 6 expected stops, signalled by road signs, and 6 unexpected stops, presented without anticipatory cues. The two videos were counterbalanced across participants.

Participants pedalled on a cycle ergometer with both hands on the handlebar while viewing the pre-recorded cycling video through a Meta Quest 3 head-mounted display (HMD; Fig. 1). Pedalling cadence modulated video speed in real time. Original video speed was attained at a cadence of 50 rpm (maximum video speed = 1.5x).

UX ratings were also collected, including cybersickness assessed with the Simulator Sickness Questionnaire (total score range 0–203), sense of presence assessed with items derived from the Igroup Presence Questionnaire (range: 0–6), and a self-rating of perceived equilibrium during steering (EQ; range: 0–6).

Figure 1: Left: Experimental setup. The participant pedalled on an exercise bike while viewing the 360° video. Right: video frame showing an approaching expected stop (top panel), with concurrent recordings of cadence (top trace) and head movements (middle and bottom traces). In this example, the participant briefly stops pedalling after the cyclist stops at the stop sign (vertical dashed line).

1.3. Data analyses

Head movements were recorded using the HMD tracking system and down-sampled at 90 Hz, whereas pedalling cadence was recorded with a pedal-mounted sensor at 1 Hz.

For each stop, we extracted baseline head position, defined as the mean head position during a 1-s interval beginning 3 s before the stop; head-movement amplitude, defined as the maximum deviation from baseline during the interval from 2 s before to 3 s after the stop; and head-movement onset, defined as the time point preceding the peak at which head position crossed 10% of the maximum excursion. Mean onset times and amplitudes were compared between expected and unexpected stops using two-tailed t-tests.

For each stop, we extracted cadence values at 2 s before the stop, at stop time, and 3 s and 6 s after the stop. Cadence was analysed using a repeated-measures ANOVA with the within-subject factors Time (4 levels) and Stop type (2 levels), with Greenhouse-Geisser correction where appropriate.

2. Results

Participants reported a relatively high sense of presence ($M = 4.0$, $SD = 1.3$) but with some cybersickness symptoms (total score: $M = 50.8$, $SD = 45.6$), possibly partly due to discomfort related to loss of equilibrium during observed steering ($M = 4.7$, $SD = 1.5$). Informal complaints for lack of bike control were also noted.

During the virtual ride, participants tended to rotate the head downward and reduce pedalling cadence when the cyclist stopped, with some notable differences between expected and unexpected stops (Fig. 2). To avoid possible smoothing effects in the average traces due to trial-by-trial asynchronies, individual measures were taken trial-wise (Tab. 1).

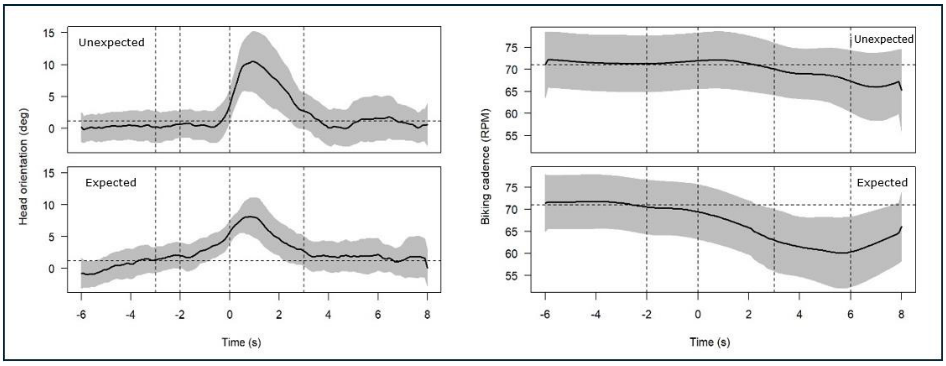

Figure 2: Left: mean head orientation (black line) ± SD (grey area) around stop time in the video (t = 0). Positive values indicate downward rotation, with 0° representing the mean head orientation across the entire 12-min recording. Right: mean cadence (black line) ± SD (grey area). Horizontal lines denote average baseline level across all trials. Vertical dashed lines indicate the time points used for statistical analyses.

Head movements differed significantly between stop types. Movement amplitude was larger for unexpected than for expected stops ($t_{19} = 2.193$, $p = .041$), whereas movement onset occurred earlier for expected than for unexpected stops ($t_{19} = 2.634$, $p = .016$).

Cadence decreased around both expected and unexpected stops. The ANOVA revealed significant effects of Time ($F(3,57) = 10.07$, $\varepsilon = 0.492$, $p = .001$), Stop type ($F(1,19) = 11.87$, $\varepsilon = 1.0$, $p = .003$), and their interaction ($F(3,57) = 5.12$, $\varepsilon = 0.707$, $p = .006$). Post hoc comparisons showed that cadence was already lower for expected than for unexpected stops at stop time, indicating anticipatory slowing in the expected-stop condition.

	Unexpected stop	Expected stop	t_{19}	P value
Head rotation in the sagittal plane				
t start (s)	-0.40 ± 0.35	-0.66 ± 0.39	2.634	0.016
amplitude (deg)	11.79 ± 10.46	7.55 ± 6.66	2.193	0.041
Cadence (rpm)				
Cadence at *t* = -2 s	71.26 ± 14.53	70.50 ± 14.00	0.726	0.477
Cadence at *t* = 0 s	71.95 ± 14.46	69.42 ± 14.09	2.865	0.010
Cadence at *t* = 3 s	70.08 ± 13.45	62.95 ± 16.02	3.203	0.005
Cadence at *t* = 6 s	67.32 ± 15.94	60.31 ± 18.14	2.958	0.008

Table 1: Head rotation and cadence (mean ± between-subject SD) and t-test results comparing expected and unexpected stops.

3. Discussion

The main aim of this study was to investigate VEMRs elicited by expected and unexpected stops during an immersive first-person virtual bicycle ride. More specifically, we asked whether these responses could dissociate reactive from proactive motor adjustments.

The results support this interpretation. Participants responded to the cyclist's stops with downward head movements and reduced pedalling cadence. Unexpected stops elicited clear downward head movements, followed by a moderate cadence reduction, consistent with a reactive response (RMA), whereas expected stops induced earlier and more moderate head movements, as well as earlier and stronger cadence reduction, consistent with anticipatory control (PMA). Thus, during simulated cycling, environmental predictability modulates otherwise automatic motor responses (Bronstein and Buckwell, 1997; Guerraz et al., 2001; Cooper et al., 2018).

Several limitations should be acknowledged. First, we did not find any strong correlation between objective and subjective measures of the sense of presence. However, no definitive conclusions can be drawn because of the small sample size of this study. Second, because the objective measures depended on the type of stops, future studies should include separate subjective assessments for VR experiences involving expected and unexpected stops. Finally, our study used pre-recorded videos rather than an interactive VR environment with real-time cyclist interaction, which may have influenced both the objective and subjective measures of the sense of presence.

These findings support the use of motor measures as a complement to self-report questionnaires in the assessment of immersion. Unlike retrospective ratings, such measures provide a real-time embodiment index of how users respond to a virtual environment. This may be especially relevant for VR applications, where immersion and engagement are important for rehabilitation use (Riva et al., 2004; Høeg et al., 2021; de'Sperati et al. 2023).

Acknowledgements

The study received partial financial support from Velux Stiftung (project no. 1767 – Get Grandparents on bikes: the Telecyclette project; www.telecyclette.eu).

Preferences

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