Long-term Adaptation in VR: Retention of Altered Sensorimotor Contingencies through Redirected Walking

Niklas Hypki*, Taravat Anvari*, Frank Steinicke, and Markus Lappe

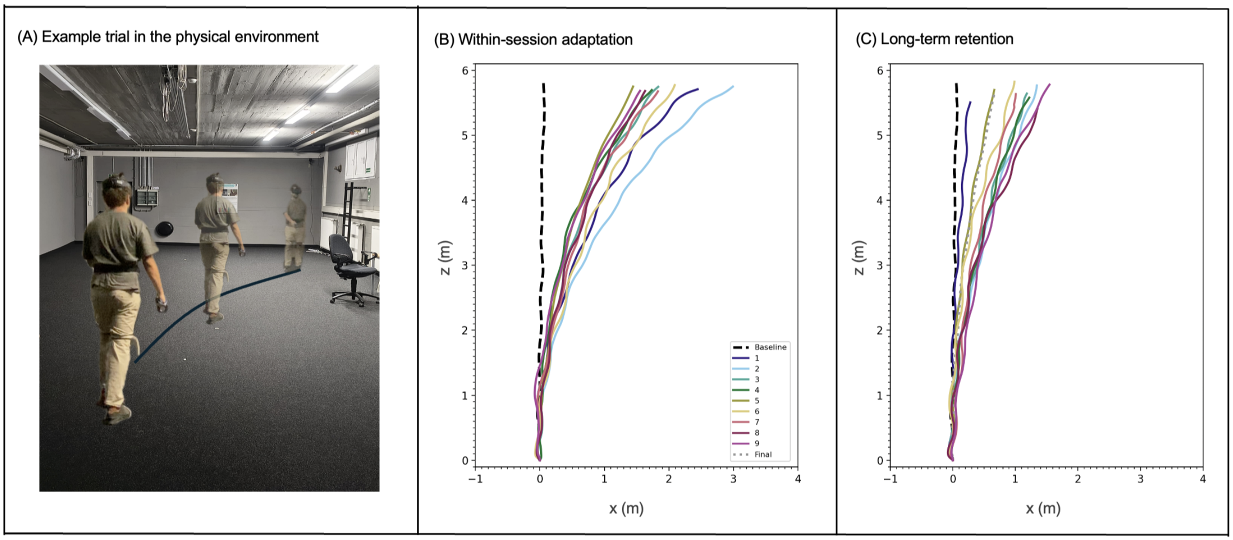

Fig. 1: Illustration of motor adaptation across sessions.Participants were instructed to walk straight in VR. (A) Physical environment: example trial where the physical path is curved due to an applied curvature gain. The semi-transparent avatar represents an earlier time point, while the opaque avatar indicate the later position, illustrating the temporal progression of the movement. (B) Within-session adaptation. The participant walked straight in the Baseline (dashed) session and followed a curved trajectory directly after the adaptation phase (sessions 1–9). (C) Long-term retention. The participant walked straight in the Baseline (dashed) session. Curved trajectories at the start of each session indicate that sensorimotor adaptation from the prior day was retained in 2–9).

Abstract—Redirected walking (RDW) alters the relationship between physical locomotion and visual feedback to guide users along virtual paths that vary from their real-world trajectories. Over time these changes can lead to adaptation of the user and produce novel sensorimotor settings that users might retain across sessions and apply directly once they enter virtual reality (VR). Although short-term adaptation to altered sensorimotor contingencies is well established, it remains unclear whether such adaptation is retained across multiple days. We investigated long-term retention of RDW adaptation by repeatedly exposing ten participants to a fixed rightward curvature gain of $\pi/30$ across nine sessions over two weeks. Each session consisted of 200 walking repetitions with gain applied. Adaptation was assessed before and after each session using blind walking and a pointing task. Moreover, perceptual detection thresholds for curvature gains were measured before the first session (Baseline), a day after the ninth session (Final), and once in-between before the 5th adaptation session. Results showed clear retention of adapted locomotor behavior: during blind walking at the beginning of the sessions, when instructed to walk straight, participants consistently exhibited curved trajectories, which indicates that newly acquired sensorimotor contingencies can be retained over days and are immediately available upon re-entering VR. At the same time, pointing accuracy remained stable throughout the experiment and detection thresholds showed no consistent changes across sessions. In summary, our study provides evidence that adaptation to altered sensorimotor contingencies in VR can be retained across multiple sessions and days and can be available as soon as the user enters VR. This may be useful for many scenarios in which users repeatedly use VR tools over a long period of time. The complete data set, all supplemental materials and the preprint of the manuscript are available at https://osf.io/z973w.

Index Terms—Virtual Reality, Locomotion, Long-term Adaptation, Path perception, Redirected Walking, Curvature Gains

1 Introduction

Human perception and motor control are highly adaptable to changes in the relationship between actions and sensory feedback. A well-studied example of this adaptability is prism adaptation, in which optical distortions systematically shift the visual field and initially impair basic motor performance. With continued exposure however, individuals adapt to the altered sensorimotor contingency, therefore regain accurate performance [35]. After removal of the distortion, robust aftereffects are observed which indicates a re-calibration of the underlying visuomotor mapping. Evidence from long-term prism

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adaptation studies and optical aids such as reading glasses suggests that prolonged exposure can lead to the coexistence of multiple sensorimotor mappings, and rapid switching between distorted and undistorted visual context [11, 27, 40, 53]. Thus, sensorimotor adaptation is not limited to short-term re-calibration.

Long-term use of virtual reality (VR) most likely produces similar adaptation to the visual and sensorimotor specifics of the virtual environment (VE) and most likely also the optics of the head-mounted display (HMD). As VR use with HMDs became more popular and more prevalent it is of critical importance to know whether multiple visuomotor mappings also exist between virtual space and real space, how they depend on the sensorimotor contingencies applied in different VEs and if the development of such states can be facilitated, if wanted, or suppressed, if needed.

For the manipulation of curvature gain in redirected walking (RDW), previous work has shown that the relationship between physical movement in real space and perceived movement in virtual space can be adapted such that users learn to accept an altered visual gain between physical and virtual walking as their new normal already in a single VR session [3]. In the present study we investigate whether and how this adaptation is retained or enhanced over repeated exposures as users enter the same virtual environment over multiple days. To investigate this, we repeatedly measure motor and perceptual adaptation at different points in time during the study. For our main question, retention across days, these measures are taken immediately after a user enters VR on that day, i.e., before starting any renewed adaptation. Any adaptation effects at that time must stem from retention of adaption form previous sessions. To reassure on the presence of adaptation within a session, some measurements were repeated at the end of the respective adaptation session.

To evaluate the adaptation effects, we measured performance on various tasks in the VE: During the *Walk & Point* task, participants are instructed to walk blindly in a straight line, stop when prompted by a head-fixed visual signal, turn around, and point back to their starting position. If adaptation to curvature gain is retained, we expect them to walk in a curve instead of a straight line. Furthermore, if they do not perceive that they are redirected they should not be able to correctly indicate their orientation at the end of the walk p by pointing. Both measures were collected on each day before (retention) and after each *Adaptation* phase. Third, we measured the threshold for the perception of curvature gains at three times over the course of the experiment: before the first adaptation session (Baseline), a day after the last adaptation session (Final) and once in-between. To measured the threshold, we used an adaptive psychometric method. If long-term effects of adaptation accumulate over time the perception threshold should shift towards the gain used in the *Adaptation* phase.

2 Background and Related work

2.1 Redirected Walking

RDW is a method to overcome the physical spatial limitations of tracking environments and was first introduced by Razzaque et al. [34]. For this purpose, the mapping between physical and virtual movement is manipulated, directing users onto physical paths that deviate from their virtual trajectories. Systematic manipulation that keeps users away from the physical limitations of the available tracking area throughout can optimise its use. Four primary gain types have been described: translation, rotation, curvature and bending gains [32, 46, 54]. Translation gains scales physical movements into larger or smaller virtual movements, while rotation gains accelerate or decelerate visual scene rotations relative to head turns [43, 44]. Curvature gains, which are central to the present work, redirect straight walking in VR into curved physical paths by rotating the scene in proportion to forward movements [44]. In bending gains, already curved physical paths are bent even further [23, 38].

Psychophysical studies show that manipulations can remain imperceptible within certain ranges. For example, Steinicke et al. [44] reported curvature gain detection thresholds corresponding to radii of approximately 22 m ($\approx 2.6°$/m). Later works suggest that thresholds depend on factors such as walking speed, environmental layout, wearing comfortable knee supports, or individual visual dependence [14, 24, 30, 31, 33], and can decrease to radii below 10 m in some conditions [16]. Beyond curvature, translation gains up to $+26\%$ or -14% and rotation gains up to $+49\%$ can remain unnoticed [47, 54]. Recent work has further shown that auditory cues can modulate curvature gain detection [1, 9, 15]. Gerritse et al. [15] demonstrated that adding spatial audio alters users' sensitivity to redirection, highlighting that multisensory integration plays a role in establishing perceptual thresholds. Such findings have been complemented by work exploiting perceptual "blind spots," such as saccades, blinks, or change blindness, to introduce additional scene manipulations [4, 48]. Collectively, this body of work establishes RDW as a powerful yet constrained method: effective within detection thresholds, but consciously noticed when exceeded.

Beyond the study of detection thresholds and gain manipulations, recent work has focused on steering algorithms that dynamically control user trajectories in the physical space. These approaches aim to optimise redirection of one or multiple users online by making assumptions about future paths, considering obstacles, and therefore minimising the number of resets [12, 25]. Recent advances include predictive RDW methods that combine clothoid-based trajectory planning with artificial potential fields for non-convex and dynamic environments [18], as well as curvature-based steering strategies designed to avoid collisions while maintaining immersion [55]. In addition, studies explored the extent to which predictions of user locomotion based on machine learning can contribute to more effective use of RDW manipulation [5, 20, 42]. Overall, steering-based RDW illustrates a shift toward more adaptive and context-aware approaches, complementing threshold-oriented investigations and pointing towards future integration of perceptual limits with algorithmic control.

2.2 Sensorimotor Adaptation & Redirected Walking

Sensorimotor adaptation is the ability to gradually adapt our motor skills to changes in our body or the environment. For example, we get used to the visual distortions of new glasses or adapt our movements as we become weaker with age. Adaptation to manipulated sensorimotor input is a well-known phenomenon in perception and movement research. Studies using prism glasses have shown that even small visual displacements can lead to systematic motor errors which are gradually reduced with repeated exposure, reflecting re-calibration of motor commands and shifts in perceptual reference frames [17, 36, 37]. Comparable effects have been demonstrated in locomotion, where visual offsets between physical and virtual heading cause participants to follow curved paths until partial compensation is achieved [8, 39]. Interestingly, these locomotor adjustments mirror the aftereffects known from prism and inversion-goggle experiments [36, 45], where both motor performance and the perceived straight-ahead direction are altered after adaptation.

This ability to re-calibrate could also form an essential basis for understanding users' reactions to manipulations in RDW: Here, too, users are exposed to a consistent discrepancy between physical and virtual movement, which over time should lead to an adjustment of both motor control and spatial perception. The parallels become particularly clear when analysing locomotion: The curved paths caused by wearing prism glasses resemble the trajectories caused by curvature gains [3, 29, 39], or when being exposed to constant offsets between physical and virtual heading until partial compensation is achieved through repeated exposure [7, 8]. Such parallels suggest that RDW builds upon well-established mechanisms of sensorimotor adaptation. Beyond within-session adjustments, adaptation studies indicate that sensorimotor adaptations can be retained, suggesting longer-term recalibration rather than transient error correction [22, 26]. Maintaining such an adapted mapping, in which both motor responses and perceptual judgements can be transferred from one session to the next, would be relevant for many VR applications.

While detection thresholds determine the immediate imperceptibility of gains, a growing body of research suggests that repeated exposure can lead to sensorimotor adaptation. The similarity between prism aftereffects and RDW trajectories has motivated investigations into whether

VR users re-calibrate their locomotor system under sustained curvature manipulations [29, 39]: Bölling et al. [3] provided evidence for both perceptual and motor adaptation to curvature gains across three days of exposure. Participants not only adjusted their walking trajectories during training but also displayed aftereffects during blind walking, where curved paths persisted in the absence of visual manipulation. Indeed, these aftereffects imply a re-calibration of internal spatial mapping rather than a purely online correction. Interestingly, Steinicke et al. [44] further showed that explicit awareness is not necessary for adaptation: detection performance did not differ across naïve, informed, or expert groups. Comparable findings from prism studies likewise indicate that aftereffects can occur even when manipulations remain unnoticed [19, 28]. All of these effects highlight the plasticity of the visuomotor system: with sufficient exposure, humans can establish new mappings between vision and action that can persist beyond the manipulation itself, even if they are not aware of them.

Although retention of sensorimotor adaptations has been demonstrated in other domains, relatively little is known about whether RDW-induced adaptations persist across multiple days. Most prior RDW studies have examined short-term adjustments within a session, leaving open the question of whether re-calibrated sensorimotor contingencies are retained and re-applied when users return to VR. Moreover, while both motor and perceptual aftereffects have been demonstrated, their parallel development under repeated exposure has not been systematically investigated.

An established way to measure the current state of adaptation is through psychophysical threshold measurements [3, 44]. However, such a measurement inevitably involves testing different amplifications of RDW manipulations, which could lead to inconsistent assignments across many trials and thus interfere with an ongoing adaptation process. Therefore, our work examines how repeated exposure to a fixed curvature gain influences both motor and perceptual adaptation across sessions. Finally, we investigate whether possible adaptation effects on perception thresholds are retained across days of training.

3 Method

3.1 Participants

Eleven participants (8 female, 3 male; age range: 20–26 years, M = 22.6, SD = 2.0) were recruited from the university community. All participants reported normal or corrected-to-normal vision and no history of vestibular or neurological disorders that could affect locomotion. Participants gave informed written consent and the experimental procedures were approved by the Ethics Committee of the Department of Psychology and Sports Science of the University of Münster. One participnat withdrew after the first session and did not complete the study. Participants received either monetary compensation or course credit for their participation.

3.2 Setup

The experiment took place in the VR laboratory of the Institute for Psychology at the University of Münster. The recorded space was 10.5 m long and 6 m wide. The VE was displayed using an HTC Vive Pro Eye with a nominal field of view of 110° on a dual OLED display with a diagonal of 3.5" and a resolution of 1440 × 1600 pixels per eye at 90 Hz. interpupillary and lens distance were adjusted for each participant after the eye-tracking calibration procedure. During the experiment, we tracked the positions of the HMD and HTC Vive trackers attached to the chest, waist and feet. In addition, HTC Vive controllers were used to track the participants' hands and inputs. Tracking was performed using six HTC Base Stations 2.0, which were positioned in the corners of the room and halfway along the 10.5 m long side. The HMD was also equipped with the HTC Vive Wireless Adapter, allowing participants to move freely within the tracked area. The VE was streamed from a computer with an Nvidia RTX 4090 graphics card, an AMD Ryzen 9 7900 X3D 12-Core processor and 32 GB RAM using Unity 2022.3.50f1, running on Windows 11.

3.3 Session Planning and Timeline

We employed a longitudinal repeated-measures design to examine whether repeated adaptation to curvature gains in RDW leads to retention of adapted sensorimotor contingencies across several days (see Table 1). Participants first completed a Baseline session, followed by nine adaptation sessions distributed across two weeks. The Baseline session provided initial measurements of detection thresholds, motor and perceptual adaptation. Each adaptation session exposed participants to curvature gain manipulations during natural walking, while motor and perceptual adaptation were assessed before and after exposure. The experiment began with a Baseline session on a Friday, during which the reference values for *Walk & Point* and *Threshold* were measured. Over the following two weeks, participants completed a total of nine adjustment sessions, one on each weekday except for the last Friday. In the Final session on that last Friday the *Walk & Point* and *Threshold* measurements were taken once more after all adaptation session had been concluded. Each adaptation session consisted of 200 natural walking repetitions with a constant curvature gain of $\pi/30$. Before and after each adaptation session, participants' motor adaptation (blind walking) and perceptual adaptation (pointing) were measured by a single trial each. An in-between *Threshold* measurements for curvature gains, similar to the Baseline and Final sessions was taken on the Friday of the first week before the 5th adaptation session.

3.4 Experimental Procedure

At the start of each session, participants were fitted with five motion trackers: pelvis, knees, and feet. They then completed two calibration procedures. First, the display was adjusted to the pupil distance and the Vive Pro Eyes eye tracking system was calibrated to ensure accurate tracking. This was followed by a body joint calibration, during which participants performed a series of poses to align tracker positions with anatomical joints, guided by the experimenter. Before starting the walking tasks, participants also completed a well-being questionnaire.

Depending on the trial type, participants completed one of three experimental phases in VE consisting of a desert landscape and a visible white walking path (see Figure 2).

In the *Walk & Point* phase, the instructor guided the participant to the physical location where each trial began. A short beep signalled the correct starting position. During each trial a white path appeared, which participants were asked to memorise before pressing the trigger button on the controller to make it disappear. The participants then walked along the memorised path without visual guidance, stopped at a red hand signal that appeared when they had reached a predefined distance of 5.75 m, turned around on the spot and aligned a virtual pillar to mark their starting position (pointing task). After each attempt, the virtual scene turned black and the instructor guided the participant back to the starting point.

In the *Adaptation* phase, participants followed a visible white path to a tree, with a fixed rightward curvature gain of $\pi/30$ applied to subtly redirect their physical walking trajectory. Upon reaching an invisible pillar near the tree, the scene briefly disappeared before the next trial began. To enhance immersion, participants heard ambient background sounds throughout this phase.

In the *Threshold* phase, participants followed a visible path to a tree and then estimated whether they had turned left or right in the physical laboratory. Participants then used the thumb pad on the controller to select a user interface button for left or right. They then confirmed their selection by clicking on the thumb pad, whereupon an acoustic signal signalled confirmation of the selection (Figure 2B). For a visual demonstration of the experimental phases described in this section, please refer to the provided video.

To minimise the number of trials and estimate perception thresholds, we used the QUEST+ algorithm [51, 52] which is a Bayesian adaptive psychometric procedure, that we re-implemented in C#, based on Watson's QUEST+ algorithm for Matlab. At each trial, QUEST+ selects a stimulus based on its expected information yield, incorporating posterior information from previous responses of the participant and a cumulative gaussian function with sigmoidal shape. In this experiment the perception threshold (μ) was estimated within a range from -$\pi/15$

Table 1: Schedule of experimental sessions. For sessions 1–9, *Walk & Point* was measured before and after *Adaptation*. Session 5 started with a *Threshold* measurement, then *Walk & Point* was measured before and after *Adaptation*. Baseline and Final include a *Threshold* and a single *Walk & Point* block.

Session	Day	Threshold	Walk & Point (Pre)	Adaptation	Walk & Point (Post)
Baseline	Fri	Threshold	Walk & Point		
1	Mon		Walk & Point	Adaptation	Walk & Point
2	Tue		Walk & Point	Adaptation	Walk & Point
3	Wed		Walk & Point	Adaptation	Walk & Point
4	Thu		Walk & Point	Adaptation	Walk & Point
5	Fri	Threshold	Walk & Point	Adaptation	Walk & Point
6	Mon		Walk & Point	Adaptation	Walk & Point
7	Tue		Walk & Point	Adaptation	Walk & Point
8	Wed		Walk & Point	Adaptation	Walk & Point
9	Thu		Walk & Point	Adaptation	Walk & Point
Final	Fri	Threshold	Walk & Point		

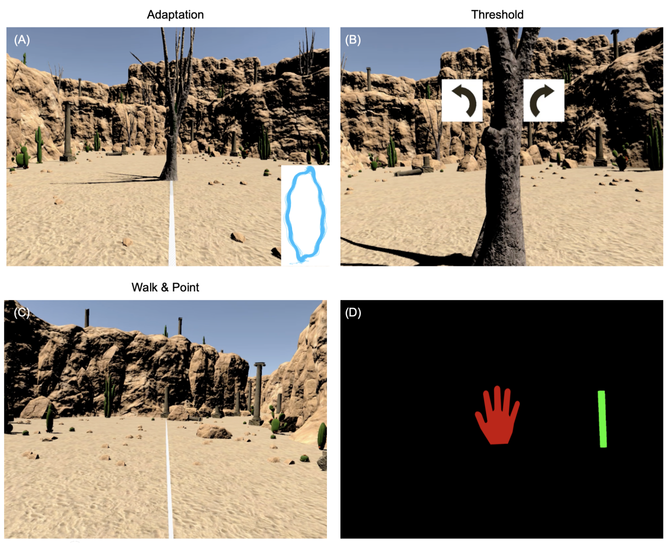

Fig. 2: Experimental scenes presented in the VR environment. (A) *Adaptation*: Participants walked through the virtual desert between two trees while exposed to redirected walking manipulations. (B) *Threshold*: After each walk between two trees, participants judged the turning direction using arrow cues. (C) *Walk & Point*: Participants viewed a path that they had to memorize, then walked blindfolded in VR. (D) *Walk & Point task*: Upon encountering a stop signal (red hand), participants turned on the spot and indicated the perceived start location by positioning a green pillar.

to $\pi/15$ based on the participants feedback. The width of the psychometric function was fixed to 0.3. Lapse and guess rate were fixed to 0.05. After 30 trials, the algorithm returned the final estimate of μ. To make consecutive trials independent from each other and reduce the risk of convergence to local minima, two parallel instances of QUEST+ were run, each updated every second trial. In total, participants completed 60 trials in each *Threshold* phase. For every completed trial, current parameter estimates, the selected stimulus, and the participant's response were recorded.

The Baseline session consisted of *Threshold* and *Walk & Point* tasks. Each of the nine adaptation session included 200 walking repetitions of the adaptation phase with the fixed gain, preceded and followed by *Walk & Point* measurements. Before sessions 5 and in the Final session, *Threshold* measurements were administered. Blindfolded walking tasks were incorporated into the *Walk & Point* phase, allowing assessment of motor adaptation without visual feedback. Breaks were provided upon request, and at the conclusion of the final session. In each session, participants filled out the simulator sickness questionnaire [21] as well as the Slater-Usoh-Steed presence questionnaire [49].

4 Results

Of the eleven participants recruited, one participant withdrew after the second session and was therefore excluded. The final data set includes in total 110 sessions from 10 participants. The adaptation sessions 1, 2, 3, 4, 6, 7, 8 and 9) lasted approximately 60 minutes, while the Baseline and Fin<l sessions were completed in 40 to 50 minutes. Session 5 was the longest session, lasting approximately 80 minutes.

The trajectories of all *Walk & Point* trials were manually reviewed and 11 trials (including 8 trials from the start of the session) were excluded from further analysis due to tracking issues or data loss during the trial.

For all comparisons across sessions, the assumptions for the use of dependent t-tests were checked using Shapiro-Wilk and a Breusch-Pagan tests [6,41]. In addition, the distribution of the residuals, qqplots, and Cook's distance [10] were manually inspected for each linear model. P-values were adjusted using the Benjamini-Hochberg correction [2]. All statistics were done in R (Version 4.5.1). As the questionnaire results did not contain any relevant findings for the purpose of this study, they are not presented further in this manuscript. For the sake of completeness and for possible evaluation in meta-analyses, they are included in the data set provided.

4.1 Walk & Point

We calculated two metrics to measure possible retention of adaptation during the blindfolded walking (Figure 3). The first is the lateral shift, i.e., the deviation from the straight walking direction that occurred between start (first frame of the walking phase) and end of each walk (final frame, before participants reached a virtual collider). The second was the change of HMD orientation (α), which was defined as the signed difference between the yaw angle at the start and at the end of the walk, wrapped to the range -180° to 180°. Both measures were taken at the start of the session, i.e., before the adaptation, to measure retention across days and again after the adaptation to estimate the amount of adaptation within the session (Table 1).

4.1.1 Shifts

Figure 1 illustrates the walking paths of one participant taken in the different sessions after adaptation and their retention on the next day. To illustrate retention across participants, Figure 4 shows the shifts in the initial blindfolded walks in each session, thus representing the retention effects resulting from the previous day's *Adaptation* phases (Note that an overview of all shifts across all sessions, including the within-session adaptations can be seen in supplementary Figure 1).

During the Baseline session, several participants exhibited a small leftward walking bias. In Session 1, prior to any adaptation exposure, walking trajectories were largely straight, with lateral shifts close to zero. Across most following sessions, participants showed strong retention effects, exhibiting rightward shifts of approximately 1 m on average. However, in sessions in which the *Walk & Point* task was

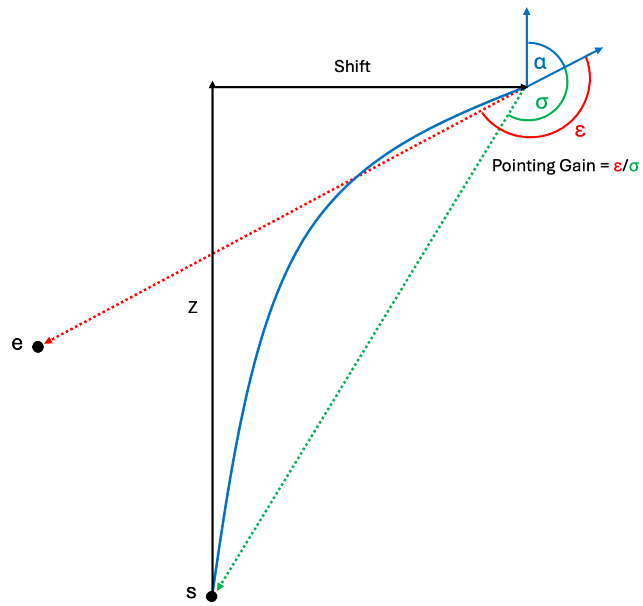

Fig. 3: Schematic of the measures used to quantify retention during *Walk & Point* trials. Shifts are the lateral movement from the start to the end of each walk. α describes how much participants rotate during the blindfolded walk. σ is the pointing angle from the end position back to the start (s) and therefore describes the most accurate pointing angle possible. ε is the pointing angle to the estimated start position (e).

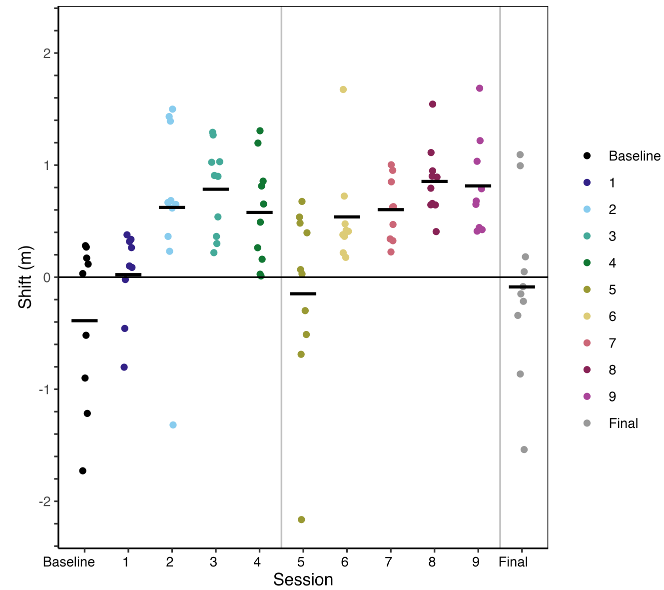

Fig. 4: Walking shifts from initial *Walk & Point* from each session. Each dot represents the lateral shift of a single trial from one participant; black horizontal lines indicate the mean per session. The horizontal reference line at 0 m denotes no lateral shift. Vertical gray lines mark sessions 5 and Final, in which perceptual thresholds were measured.

Table 2: Blindfolded walking shifts. One-sided dependent t-tests comparing the lateral shift in the first trial of each session to the initial blindfolded walk in the Baseline session (df = 77).

Comparison	Mean diff.	SE	t-value	p-value
1 – Baseline	0.30	0.15	1.99	0.05
2 – Baseline	1.04***	0.15	6.73	< 0.001
3 – Baseline	1.09***	0.15	7.47	< 0.001
4 – Baseline	0.88***	0.15	6.05	< 0.001
5 – Baseline	0.39*	0.15	2.63	0.01
6 – Baseline	0.79***	0.16	5.09	< 0.001
7 – Baseline	0.87***	0.15	5.80	< 0.001
8 – Baseline	1.16***	0.15	7.95	< 0.001
9 – Baseline	1.09***	0.15	7.28	< 0.001
Final – Baseline	0.44**	0.16	2.75	0.01

Table 3: Blindfolded walking orientation change (α). One-sided dependent t-tests comparing the rotation in the first trial of each session to the initial blindfolded walk in the Baseline session (df = 80).

Comparison	Mean diff.	SE	t-value	p-value
1 – Baseline	5.62	3.07	1.83	0.07
2 – Baseline	16.64***	3.07	5.42	< 0.001
3 – Baseline	16.91***	3.01	5.63	< 0.001
4 – Baseline	13.52***	3.01	4.50	< 0.001
5 – Baseline	7.51*	3.09	2.43	0.03
6 – Baseline	15.42***	3.09	4.99	< 0.001
7 – Baseline	12.66***	3.15	4.02	< 0.001
8 – Baseline	18.59***	3.01	6.18	< 0.001
9 – Baseline	19.91***	3.09	6.44	< 0.001
Final – Baseline	8.15*	3.09	2.63	0.03

preceded by a *Threshold* measurement (Sessions 5 and Final), no lateral shifts were observed.

To meet the assumption of normally distributed residuals, 8 trials were excluded from the comparison across sessions based on Cook's distance using a cutoff threshold of $4/n$. The remaining 97 shift-values were used to test if shifts significantly differed to the Baseline in later sessions (see Table 2 for an overview of all tests).

One-sided dependent t-tests comparing the lateral shift in the first trial of each session to the initial blindfolded walk in the Baseline session revealed that shifts were significantly higher than in the Baseline in all sessions. Additional one-sided pairwise post-hoc t-tests between session 4 and 5 (M = 0.49, df = 77, $p < 0.001$) and session 9 and Final (M = 0.65, df = 77, $p < 0.001$) confirmed that in both cases shifts were significantly smaller after the *Threshold* measurement.

4.1.2 α-Orientations

To meet the assumption of normally distributed residuals, five trials were excluded from the comparison across sessions based on Cook's distance using a cutoff threshold of $4/n$. The remaining 100 α-orientations were used to test if participants rotated significantly further in comparison to the Baseline in later sessions (see Table 3 for an overview of all tests).

During the Baseline session, several participants exhibited a leftward rotation during blindfolded walking. In Session 1, prior to any adaptation exposure, walking orientation remained close to zero, indicating little to no systematic rotation. Across most subsequent sessions, participants showed strong retention effects, rotating to the right while attempting to walk straight without visual input. In sessions in which the *Walk & Point* task was preceded by a *Threshold* measurement (Sessions 5 and Final), no rotations were observed. (see Figure 5 for an overview of all values).

One-sided dependent t-tests comparing α in the first trial of each session to the initial blindfolded walk in the Baseline session revealed that α-values were significantly higher than in the Baseline in all sessions (see Table 3. Post-hoc one-sided pairwise t-tests between session 4 and 5 (M = 6.01, df = 77, p = 0.021) and session 9 and Final (M = 11.76, df = 77, $p < 0.001$) confirmed that in both cases shifts were significantly smaller after the *Threshold* measurement.

4.1.3 Pointing Gains

To examine whether adaptation to curvature gains also influenced spatial updating, we included a pointing task after each blind walking trial. This task required participants to estimate their starting position

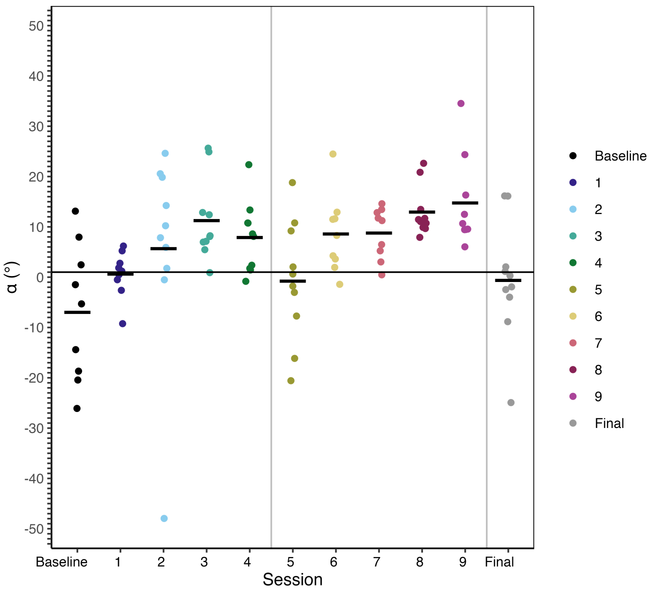

Fig. 5: Rotation during walking from initial *Walk & Point* from each session. Each dot represents the orientation change during a single trial (α) for one participant; black horizontal lines indicate the mean per session. The horizontal reference line at 0° denotes no rotation. Vertical gray lines mark sessions 5 and Final, in which perceptual thresholds were measured.

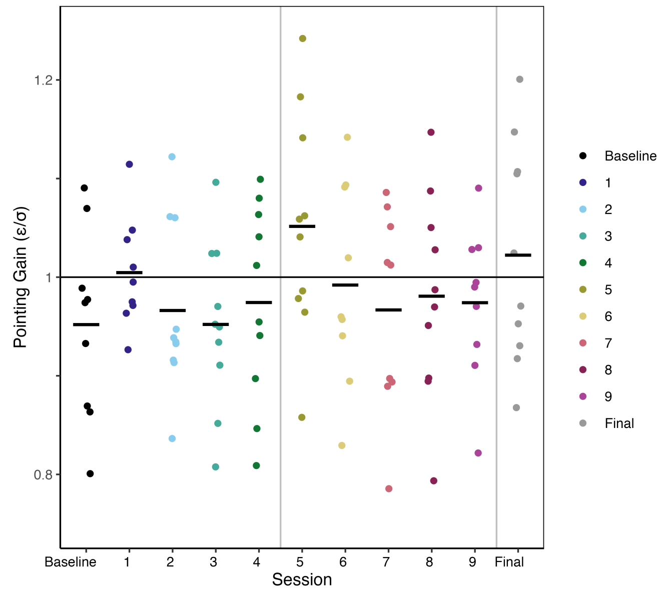

Fig. 6: Pointing gain of initial *Walk & Point* data from each session. Each dot represents the pointing gain of one participant; black horizontal ticks indicate the mean per session. The solid horizontal reference line at 1 denotes perfectly accurate pointing, with values below 1 indicating under-rotation and values above 1 indicating over-rotation.

within the VE, turn around point towards it with a controller and place a visible pillar on their estimated starting position. In case they walked on a straight trajectory without rotating their head, they would need to reach a combined rotation of pointing and turning of 180° to point exactly to their initial starting position. In case participants were redirected to a shifted position (as depicted in Figure 3), they would need to incorporate the rotation during their walk to reduce the necessary combined turning and pointing angle to 180-α. At the same time , to incorporate their shifted position after walking, it would be necessary to increase the combined turning and pointing angle accordingly.

For our analysis we calculated a turning gain that compares the pointing angle of a participant in a trial ε with the ideal pointing angle σ. Pointing gains < 1 indicate that participants underestimated the necessary rotation, whereas pointing gains > 1 indicate that they turned too far.

$$\text{Pointing Gain} = \varepsilon / \sigma \quad (1)$$

Figure 6 gives an overview over all pointing gains across the different sessions. Overall, the data is spread widely and average pointing gain values are close to 1. During the Baseline session, the mean pointing gain was slightly below 1, indicating mild under-rotation. In Session 1, the average pointing gain was closest to veridical performance. Across the subsequent sessions, average pointing gain values again tended to be slightly below 1, with similar patterns observed in Sessions 7, 8, and 9. Following perceptual threshold measurements in Sessions 5 and Final, participants showed a small tendency to overestimate the required rotation, resulting in average pointing gain values slightly above 1.

No trials needed to be excluded to meet the assumption for testing, thus all gain-values were used to test if pointing significantly differed to the Baseline in later sessions. We found no significant differences between the Baseline and any other session (see Table 4 for an overview of all tests).

4.2 Perceptual Thresholds

In order to measure the possible retention of adaptation with regard to the perception threshold (μ) for curvature gains, these were recorded

Table 4: Pointing gains. Two-sided dependent t-tests comparing the first pointing response of each session to the initial pointing gain in the Baseline session (*df* = 85).

Comparison	Mean diff.	SE	t-value	p-value
1 – Baseline	0.05	0.03	1.56	0.41
2 – Baseline	0.01	0.03	0.29	0.92
3 – Baseline	0.00	0.03	-0.14	0.92
4 – Baseline	0.02	0.03	0.54	0.85
5 – Baseline	0.09	0.03	2.87	0.05
6 – Baseline	0.04	0.03	1.25	0.54
7 – Baseline	0.00	0.03	0.11	0.92
8 – Baseline	0.02	0.03	0.73	0.85
9 – Baseline	0.02	0.03	0.64	0.85
Final – Baseline	0.07	0.03	1.98	0.25

in the Final session and at the start of session 5 using the adaptive Quest+ procedure. Fitted μ-values from alternating Quest+ runs were averaged for each session. The resulting psychometric functions from each subject in each session can be seen in supplementary Figure 3. No trials needed to be excluded to meet the assumption for testing. We found no significant differences between the Baseline and any other *Threshold* measurement (see Table 5 and Section 7).

5 Discussion

We investigated long-term adaptation in VR. Specifically we asked whether retention of altered sensorimotor contingencies through curvature gains can be observed using behavioural and psychophysical measurements such as blind walking, pointing and perception threshold measurements.

5.1 Summary of Results

Our results confirmed a previous finding by Bölling et al [3]: Participants showed motoric adaptation effects in blind walking directly after being exposed to a consistent rightward curvature gain of π / 30. After the adaptation phase, participants shifted to the right and rotated rightwards when trying to walk in a straight line blindly. As a results they walked on a curved trajectory. This trajectory was clearly distin-

Table 5: Perception thresholds. One-sided dependent t-tests comparing the average perception threshold (μ) to the corresponding value in the Baseline session (df = 18).

Comparison	Mean diff.	SE	t-value	p-value
5 – Baseline	−0.04	0.03	−1.11	0.57
Final – Baseline	−0.01	0.03	−0.35	0.73

guishable from the blindfolded walking paths before any adaptation in Baseline and session 1). We are therefore confident that the manipulation in our experiment worked and that adaptation effects were induced.

Regarding retention of these effects, our analysis of lateral displacement and rotation during blindfolded walking showed that the maintenance of altered sensorimotor contingencies was retained one day later (sessions 2,3,4,7,8,9) or even three days later (session 6). However, shifts and rotations in session 5 and the Final session showed no retention but were similar to the values in session 1, i.e., before any adaptation.

In the Baseline session participants showed a small bias towards the left side, while trajectories in session 1 before adaptation were straight. We assume that the differences between session 1 and the Baseline were mainly driven by random shifts and rotations that occurred when participants performed the walking task for the first time.

Perception threshold estimations did not reveal any shifts of the perception threshold after participants were exposed to curvature gains for four (session 5) or nine days (Final). This seems in contrast to Bölling et al. [3], who described clear effects of adaptation on perceptual thresholds. However, their measurements were taken directly after the adaptation phase (i.e., within-session) while our focus was on retention. Our data, therefore, shows that any within-session effects of adaptation might not be as easily retained as motoric adaptation. Indeed, our results from blindfolded walking indicate that when measured directly after adaptation, effects tended to be stronger than the long-term retention effects that can be found on the next day, or three days later. The pointing data also showed no consistent change over sessions. Since the variance in this measure was quite high it might have prevented any observations of significant results with the statistical power available in this experiment. Therefore, based on our data, we cannot answer whether participants were aware of their persistent motor adaptation effects in terms of rotation and lateral displacement. Figure 2 in the supplementary material shows that immediately after exposure to manipulated motor-visual contingencies (where we would have expected the strongest effects due to the influence of such adaptation on walking (see Figure 1)), users pointed in similar directions as in the Baseline session.

5.2 General Discussion

Manipulations of the link between visual input and locomotion can lead to adaptation. Such adaptation effects have previously been shown with prism glasses, but also using curvature gains in VR. Based on measurements of the perception threshold using psychophysical method of constant stimuli, perception thresholds for curvature gains can change after participants are exposed to 20 minutes of locomotion with a constant curvature gain [3]. In addition, when attempting to walk straight ahead without visual landmarks afterwards, participants deviate from a straight path. Instead, they walk on a shifted trajectories that are curved in the same direction as the route they walked during the adaptation phase.

In the present study, we investigated potential long-term adaptation effects that could be relevant for the use of RDW in VR. We were able to replicate the effects of adaptation on walking blindly. In addition, our results suggests that about half of the adaptation is retained on the next day. Interestingly, the retention was of a similar magnitude even after two days over the weekend, showing that that this adaptation effect does not vanish even after two days without using VR. This suggests that the visual-motor system is able to learn and recall context-specific associations between visual input and locomotion. Similar to putting on a pair of glasses, to which one first had to get used to, participants seemed to fall back on the adapted pattern when they returned to the same VE, wearing the same HMD.

In Sessions 5 and Final we attempted to measure retention of changes to perceptual thresholds for gain manipulation. These measurements did not reveal any change in thresholds. At the same time, motoric adaptation effects on walking, that were prominently retained in all other sessions, were not observed in these two sessions. We believe that the *Threshold* measurements might have interfered with the retention of adaptation effects. Specifically, our *Threshold* measurements were done with a Quest+ staircase method that used adaptive sampling to concentrate stimuli near the perceptual threshold. Nevertheless, the measurement procedure necessarily had to include different sets of gains, including ones that were far away from the gain used in the *Adaptation* phase (e.g., leftward curves). We suspect that the confrontation with many different curvature gains during the *Threshold* measurement triggered motoric de-adaptation. The fact that this interference only occurred when confronted with varying gains is supported by the following two observations: Firstly, de-adaptation is visible twice in our data immediately after a threshold measurement (after session 4 and session 9). Second, further adaptation after session 5 restored the previously observed adaptation effects on walking.

The retention of the lateral shift that we found in blindfolded walking needs to be distinguished from an aftereffect that typically occurs when an adaptation protocol is ended. For example, in adaptation experiments with prism glasses, users also learn a new constant relationship between self-motion and visual input. When subsequently tested without prism glasses, users typically deviate in the opposite direction to the direction of adaptation. This aftereffect occurs because the manipulation is suddenly taken away. However, in retention the donning of the HMD serves as a contextual cue to reinstate the formerly learned behavior, i.e., produce a trajectory shift towards the same side as in the adapted case.

In summary, we showed that motoric adaptation effects, such as those described by Bölling et al. [3] can be retained for several days and reinstated upon entering the VR. Secondly, based on our data, we suspect that we de-adapt as soon as we are exposed to motor-visual contingencies that are far away from our expectations, such as consistent motor-visual mapping to which we have previously adapted. This seems to be for example the case when the gain direction changes. In such cases, our visuomotor system appears to trigger a relearning effect. This fits well with the recent findings that adaptation effects of redirected hand movements in VR can restore normal levels after a brief exposure to unchanged hand interactions [13]. Since we seem to be particularly susceptible to motion sickness caused by independent visual stimuli when walking [50], such phases of de-adaptation could be an important factor for motion sickness in VR in general. It may therefore be useful to develop future RDW controllers that take these considerations into account and minimise such relearning phases based on the predicted movement of the user.

6 Limitations

In currently used RDW systems gains are usually applied dynamically and gain magnitude often ramps up from zero to a maximally undetectable level that is dampened as users are redirected, and may change direction over time depending on the physical limitations of the room. As a result, users are exposed to a wide range of gains rather than a single, consistent transformation. One might expect that little adaptation would occur in this situation because exposure to variable gains interfered with the motoric adaptation in our study. Yet, this would need to be tested in future work. If true, it is reassuring in terms of the safety of using RDW, but it also means that the direct applicability of adaptation effects in current controllers is limited.

Although we were able to demonstrate significant motor adaptation effects, the sample size of our experiment limited the analysis of the pointing task. Furthermore, our sample exhibited a gender imbalance and limited demographic diversity, which potentially limits the validity of our findings. Thus, future studies should examine whether the observed motor retention effects generalise to larger and more diverse participant groups and also to different types of locomotor manipulations.

7 Conclusions and Future work

This study demonstrates that sensorimotor adaptation to curvature gains in RDW can be retained across sessions and reactivated when participants return to VR. Blind walking revealed persistent deviations consistent with prior adaptation, indicating that the visuomotor system recalls altered mappings even after days without exposure to a manipulated VE. However, perceptual thresholds did not shift over time and appeared to reset when participants were confronted with varying curvature gains during the *Threshold* measurements.

In summary, we draw three conclusions: 1) Adaptation to motor-visual contingencies after RDW exposure can be maintained for several days. Even though participants were exposed to their natural environment between daily sessions, we were able to demonstrate clearly visible motor adaptation effects when walking in VR without visual feedback. 2) For our perception systems, confrontation with motor-visual contingencies that are far removed from our (previously learned) expectations appears to be a special case that triggers learning or de-adaptation. 3) In order to utilise these adaptation effects for RDW, it could be advantageous to redirect users to only similar gains (e.g. only using curvature gains to one side): In current RDW controllers users are usually exposed to varying motor-visual contingencies. Making applied gains more consistent might allow using higher gains over time, while users continuously stay below the detection threshold and navigate the VE intuitively while being redirected.

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All authors conceived the experiment, N.H. programmed the stimuli, T.A. conducted the experiments, N.H. and T.A. analysed the results, N.H., T.A. and M.L. wrote the manuscript, all authors reviewed the manuscript.

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Supplemental Materials

All data will be made available on OSF at https://osf.io/z973w. Quest+ C# package is available on github at https://github.com/4bgt/QuestPlus

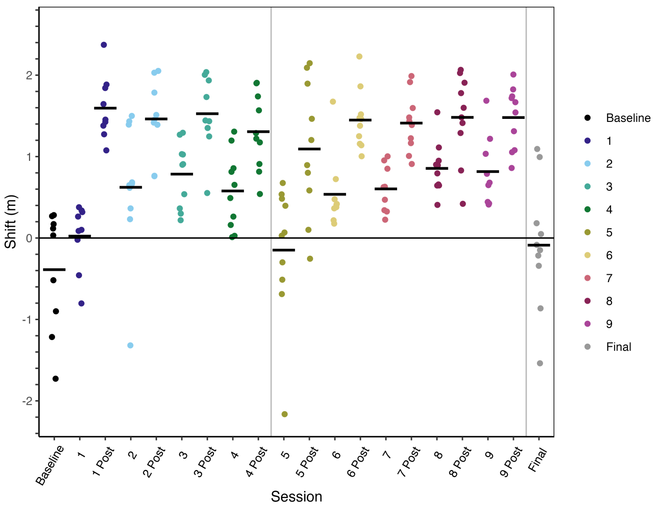

Fig. 1: Walking shift within sessions. Each dot represents a lateral shift during a trial of one participant, black horizontal lines show the mean per condition. The horizontal line at 0 m indicates no shift. Vertical grey lines mark sessions 5 and Final in which threshold perception was measured. In the Baseline session, some participants initially shifted to the left. In the post blocks of Sessions 1–4, strong adaptation effects emerged, with participants consistently shifting to the right by about 1m compared to Baseline. After the first *Threshold* measurement in Session 5, post-trial shifts were again close to 0m, resembling Baseline performance. In the post blocks of Sessions 6–9, lateral shifts reappeared at around 1m. Following the final *Threshold* measurement, post-trial shifts again dropped close to 0m, indicating that the threshold task disrupted the adapted state.

Table 1: Average fitted μ-values for each participant from each *Threshold* measurements. μ represents the lateral shift of the psychometric function.

Subject	Baseline	5	Final
1	-0.14	-0.07	-0.09
2	0.05	0.02	-0.05
3	-0.21	-0.09	-0.12
4	0.07	-0.05	0.12
5	0.05	-0.02	0.00
6	-0.14	-0.21	-0.21
7	-0.05	-0.14	-0.16
8	0.09	-0.12	0.21
9	-0.07	0.02	-0.12
10	0.00	-0.07	-0.05
M	-0.03	-0.07	-0.05
SD	0.12	0.10	0.13

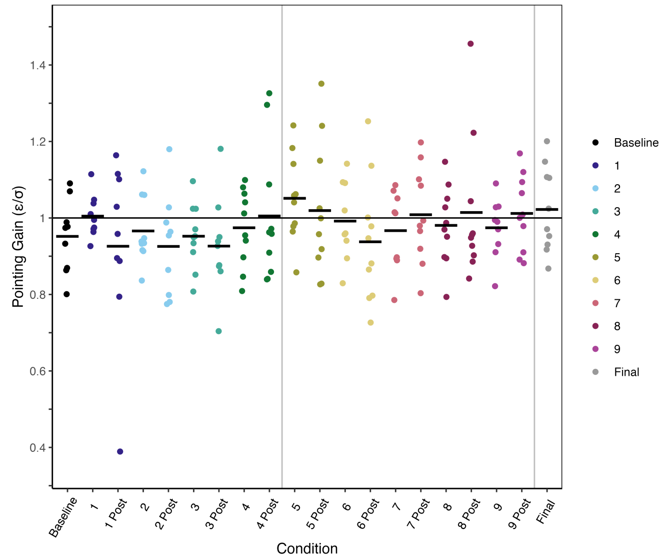

Fig. 2: Pointing gain within sessions. Each dot represents one participant, and black horizontal ticks indicate the condition mean. The solid horizontal line at 1 marks perfectly accurate pointing, with values < 1 indicating under-rotation and > 1 indicating over-rotation. In the Baseline session, average pointing gain was slightly below 1. In Session 1, before adaptation, pointing was closest to accurate (≈ 1). In the post blocks of Sessions 2–4, average gains remained slightly below 1. After the *Threshold* measurement in Session 5, post-trial gains shifted above 1, reflecting over-rotation. In the post blocks of Sessions 6–9, pointing gains again returned to values slightly below 1, but after the final *Threshold* measurement, post-trial gains were again slightly above 1.

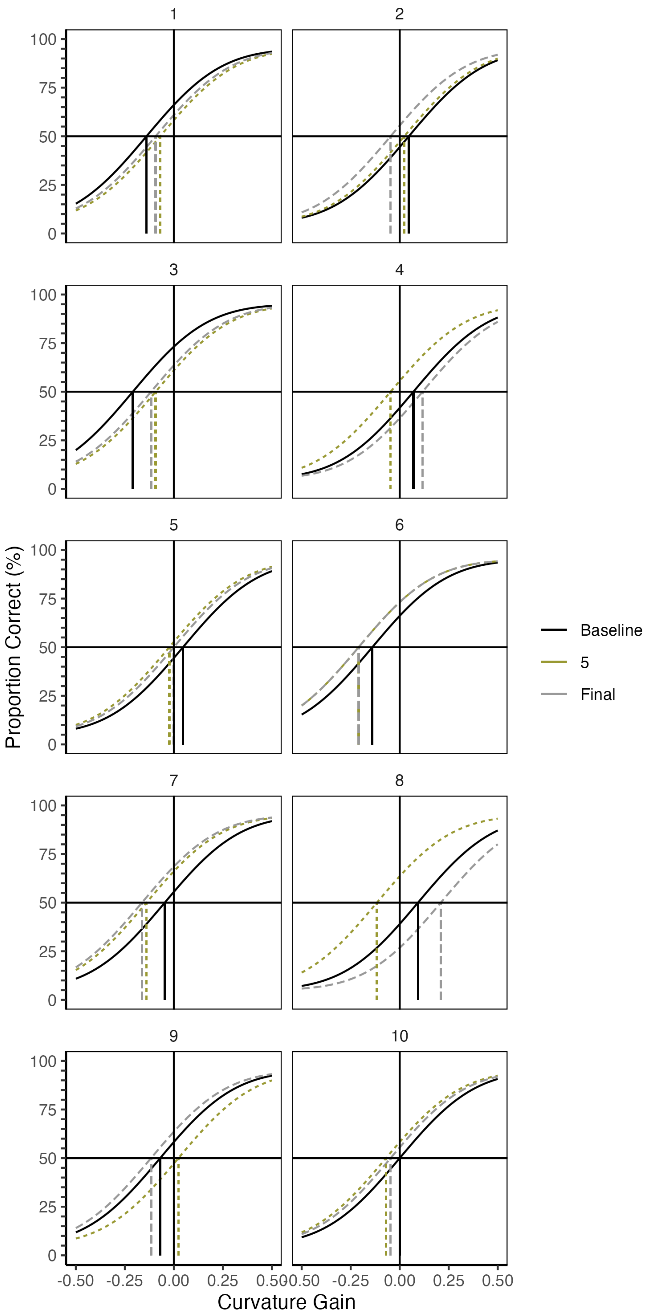

Fig. 3: Psychometric functions based on the fitted μ values based on the two alternating Quest+ adaptive measurements. Across all participants psychometric functions are spread around a μ-value of approximately 0. No systematic differences between sessions are visible. Thus, there seems to be no retention of altered sensorimotor contingencies through adaptation to curvature gains from the previous sessions that could be measured using this method.