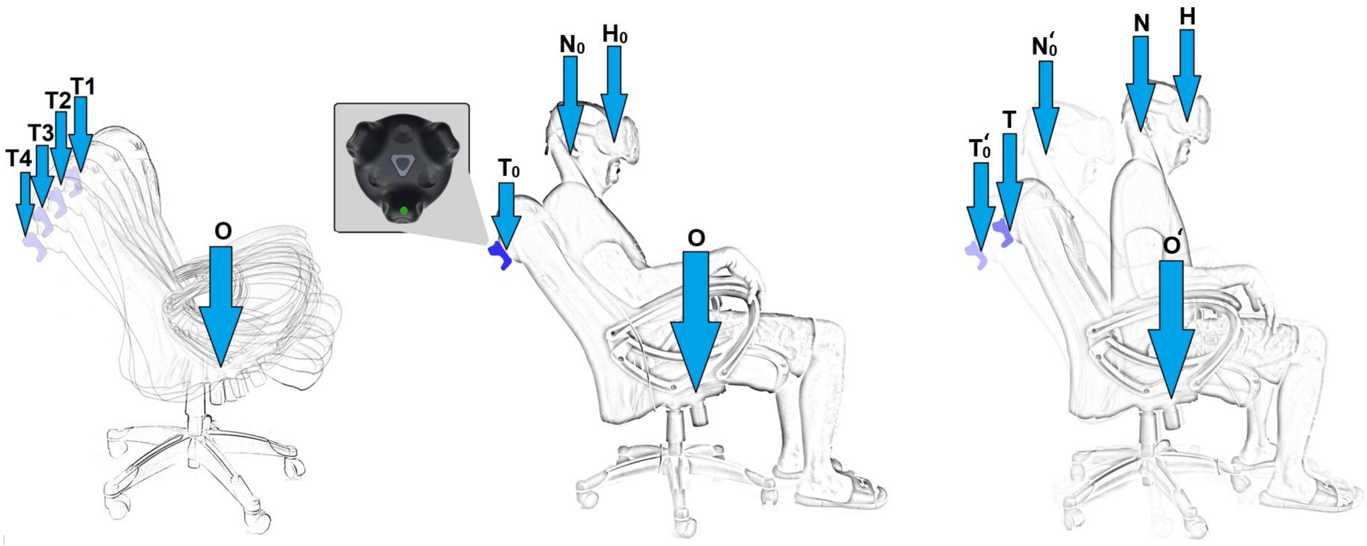

Fig. 1. HeadJoystick motion model: (Left) Tracker calibration process, (Middle) Setting zero-point when starting flight, (Right) Flight motion model. Position of Tracker (T), HMD (H), above the head rotation center in the neck (N), Center of chair backrest pitch rotation (O) are annotated in the figure, where T_0, N_0, and H_0 indicates the initial positions of tracker, head rotation center, and HMD when the flight starts. O', T_0', and N_0' are the estimated position for the backrest rotation center, initial position of the tracker, and head rotation center during flight.

1 Appendix

1.1 Motion Control Model

LeaningTranslation interface does not use a swivel chair, and thus has a *static* zero-point (initial head position) when the flight begins. However, because the HeadJoystick has a *dynamic* zero-point, it uses a tracker to track the backrest movements of a swivel chair including its yaw or pitch rotations, to update the zero-point relative to the center of the chair backrest pitch rotations. We call this the *chair center*, indicated as O in Figure 1. Tracking the chair center requires a tracker to be attached to the chair, and a calibration process is needed to calculate the chair center relative to the tracker position and orientation. Our calculations use orientation as $(pitch, yaw, roll)$ and the position in both Cartesian (x, y, z) and spherical (r, θ, ϕ) coordinates to make the equations easier to understand.

Tracker Calibration: The tracker has to be calibrated after the tracker is attached to the chair and before the flight starts. The user does not need to repeat the calibration process as long as the tracker remains attached to the chair and does not move with respect to the chair. As shown in Figure 1-left, the calibration process requires the user to lean back to change the backrest pitch. We recorded four different positions of the tracker - called T_1, T_2, T_3, T_4, with at least $2.5°$ pitch differences to calculate the chair pitch rotation center (O). Considering the tracker (T) has a constant distance from the chair center, we used the W.H. Beyer approach, which finds the center of an sphere using any four points on it by solving the below equation [1]:

$$\det \begin{vmatrix} (x_O^2 + y_O^2 + z_O^2) & x_O & y_O & z_O & 1 \\ (x_{T_1}^2 + y_{T_1}^2 + z_{T_1}^2) & x_{T_1} & y_{T_1} & z_{T_1} & 1 \\ (x_{T_2}^2 + y_{T_2}^2 + z_{T_2}^2) & x_{T_2} & y_{T_2} & z_{T_2} & 1 \\ (x_{T_3}^2 + y_{T_3}^2 + z_{T_3}^2) & x_{T_3} & y_{T_3} & z_{T_3} & 1 \\ (x_{T_4}^2 + y_{T_4}^2 + z_{T_4}^2) & x_{T_4} & y_{T_4} & z_{T_4} & 1 \end{vmatrix} = 0$$

Set Zero-Point: To start the flight, we asked users to sit comfortably and centered on the chair. Then we asked them to gently lean backwards until they touch the backrest, without pushing it backwards, after which they press a button to set the zero-point before starting the flight. This way, the user gets physical feedback for their zero-point when their back touches the backrest during flight. Pilot studies showed that this makes it easier than using visual cues to stop the flight. To ensure that users can rotate their head freely without initiating a virtual translation, we did not use the initial position of the HMD (H_0) as the zero-point, but instead calculated through pilot testing the approximate rotation center of the head (N_0) as indicate in Figure 1-middle. This allows the user to rotate their head left/right or up/down to view the VE without affecting their flight direction or speed. Our pilot tests showed that Vive HMD has an average of 0.13m horizontal distance with the typical head rotation center, for adults i.e., $\overrightarrow{H_0N_0}$. We also calculated the head rotation center distance from tracker (T_0), so we could later update the head rotation center position based on the tracker movements:

$$\begin{aligned} \overrightarrow{H_0N_0}(r, \theta, \phi) &= (0.13m, yaw_{H_0}, pitch_{H_0}) \\ N_0 &= H_0 + \overrightarrow{H_0N_0} \\ \overrightarrow{T_0N_0} &= N_0 - T_0 \\ \overrightarrow{OT_0} &= T_0 - O \end{aligned}$$

Flight Motion: As depicted in Figure 1-right, we measured the position of the tracker (T) during flight, to estimate the position of the chair center (O'), the initial position of the tracker (T_0'), and the initial user's head rotation center position (N'_0):

$$\begin{aligned} \Delta pitch &= pitch_T - pitch_{T_0} \\ \overrightarrow{\mathrm{O'T}}(r,\theta,\phi) &= (r_{\overrightarrow{OT_0}}, \theta_{\overrightarrow{OT_0}}, \phi_{\overrightarrow{OT_0}} + \Delta pitch) \\ O' &= T - \overrightarrow{\mathrm{O'T}} \\ T'_O &= O' + \overrightarrow{OT_0} \\ N'_0 &= T'_0 + \overrightarrow{T_0 N_0} \end{aligned}$$

As the next step, we predicted the head rotation center position (N) using the HMD position (H), yaw (yaw_H) and pitch ($pitch_H$). Then we found the head rotation center displacement (D) using its initial position (N'_0) and the current position (N). To calculate the speed, we then multiplied the displacement to a sensitivity coefficient of α, which we determined as 8 in our pilot testings. Moreover, because users usually have lower range for their vertical head movement compared to their horizontal head movement, we multiplied the vertical sensitivity to a higher sensitivity coefficient (β) determined as 3 based on our pilot testings. This makes the overall vertical sensitivity coefficient as 24 ($3 * 8$).

$$\begin{aligned} \overrightarrow{\mathrm{HN}}(r,\theta,\phi) &= (0.13m, yaw_H, pitch_H) \\ N &= H + \overrightarrow{\mathrm{HN}} \\ \vec{D} &= N - N'_0 \\ \vec{D} &= \vec{D} * \alpha \\ y_{\vec{D}} &= y_{\vec{D}} * \beta \end{aligned}$$

Then, we calculated the user's simulated speed ($\vec{S}$) using an exponential transfer function. Pilot testing showed us that using 1.53 as the exponential factor makes it easier for the user to find the zero-point and control their movements accurately in lower speeds. Finally, we apply the speed limit (v_{max}), because our pilot testings showed that high speeds could make the user dizzy. We used ($\vec{S}$) as the speed of moving the user's view-point in study 1.

$$\vec{S}(r,\theta,\phi) = (\min(r_{\vec{D}}^{1.53}, v_{max}), \theta_{\vec{D}}, \phi_{\vec{D}})$$

Smooth Acceleration: To prevent abrupt speed changes and reduce the motion sickness, we smoothly applied the simulated speed ($\vec{S}$) to the current simulated speed of the user ($\vec{K}$) using SmoothStep function in Unity with an acceleration smoothness factor (δ) determined as 0.12 based on our pilot testings.

$$\begin{aligned} x_{\vec{K}} &= Mathf.SmoothStep(x_{\vec{K}}, x_{\vec{S}}, \delta) \\ y_{\vec{K}} &= Mathf.SmoothStep(y_{\vec{K}}, y_{\vec{S}}, \delta) \\ z_{\vec{K}} &= Mathf.SmoothStep(z_{\vec{K}}, z_{\vec{S}}, \delta) \end{aligned}$$

References

[1] W. H. Beyer, *CRC Standard Mathematical Tables*, 28th ed. CRC Press, 1987.

[2] D. A. Bowman, E. T. Davis, L. F. Hodges, and A. N. Badre, "Maintaining Spatial Orientation during Travel in an Immersive Virtual Environment," *Presence: Teleoperators and Virtual Environments*, vol. 8, no. 6, pp. 618–631, Dec. 1999.

TABLE 1
2D (ground-based) leaning-based interfaces with full 360° physical rotation and their significant differences compared to handheld interfaces such as gamepad and touchpad. The last row shows the current study and its results to facilitate direct comparison.

Body Posture	Interface Name	Translation Input	Task	Compared with	Significant Advantages	Significant Disadvantages
Standing	*Wii-Leaning [2]*	Weight Shifting	Pointing	Joystick	Lower latency, turning error	
				WIP		Higher turning error and latency
Standing	*LAS-WIP [58]*	Torso Leaning angle	Follow-the-path	WIP	Higher Preference	
Standing	*Joyman [4]*	Torso Leaning angle	Reach-the-target	Joystick	Higher fun, presence, and rotation realism	Lower speed, accuracy, intuitiveness, and higher fatigue
Standing	*Naviboard [3]*	HMD position	Navigational search	Controller	Higher search speed, lower taskload, travelled distance, and motion sickness	
Seated	*NaviChair [3]*	HMD Position	Navigational search	Controller	Higher search speed, with lower travelled distance	
Seated	*NaviChair [7]*	Weight Shifting	Follow-the-avatar	Real-Rotation		higher distance error, lower precision
				Joystick		higher distance error, lower precision, comfort, long-term use, usability, higher usability problems
Seated	*Swivel-Chair [7]*	Chair Backrest Tilt and HMD Position	Follow-the-avatar	Joystick		Lower precise control
Seated	*Leaning [13]*	HMD position	Reach-the-taregt	Joystick	Higher speed, lower finger & arm fatigue	Higher spine fatigue
				Teleport		Lower speed, usability, comfort, ease of use, higher motion sickness
Seated	*Head Joystick [Current Study]*	Position of the head rotation center	Reach-the-target, Follow-the-path, and racing	Real-Rotation	Lower motion sickness and higher speed, accuracy, precision, throughput, enjoyment, preference, vection intensity, immersion, usability, ease of use, ease of learning, presence, long-term use, daily use, and lower task-load	

TABLE 2
Overview of our suggested factors to evaluate a locomotion interface, including suggested DVs and how to measure them. Factors that go beyond Bowman's effectiveness factors [2] are highlighted in green. "I" stands for introspective measures and "B" for behavioral measures.

	Factor/Construct	Dependent Variable	Research Instrument/measure
Usability (I) and Performance (B)	Ease of learning / learning effects	*I: Rating for ease of learning*	*"How easy was it to learn using the interface for the first time?"*
		B: Performance improvements over time	Comparing the overall performance improvement of interfaces over repeated trials of using each interface based on the linear regression
	Ease of Use	*I: Taskload*	*NASA-Task load index questionnaire [73]*
		I: Rating for ease of use	*"How easy was it to use the interface?"*
	User Comfort	***I: Rated potential for long-term use***	***"I could imagine using the interface for longer time than the study task"***
		I: Rated potential for daily use	***"I could imagine using the interface in daily applications frequently"***
	Overall Usablity	***I: Rating for overall usability***	***"Overall usability of the interface"***
	Speed	B: Task completion Time	Average time to complete the task
	Accuracy	B: Proximity to the desired target or path	Average absolute disrance error from the desired target or the path
	Precision	**B: The ability of technique for fine movements [68]**	**Average number of missed targets or crashes to unwanted objects**
	Overall performance	**B: Performance Score**	**Defined per task to combine its different performance measures**
		B: Throughput [21], [22]	**Ratio of effective index of difficulty over movement time**
User Experience	Presence	*I: Spatial presence*	*SUS Questionnaire of spatial presence [74]*
		I: immersion	*"I felt immersed in the virtual scence (captivated by the task)"*
	Self-motion perception	***I: Vection intensity***	***"I had a strong sensation of self-motion with the interface"***
	Motrion sickness	*I: Motion Sickness*	*Simulator Sickness Questionnaire (SSQ) [75]*
	Overall user experience	***I: Enjoyment***	***"I enjoyed doing the task using this interface?"***
		I: Overall preference	***"Overall preference ratings"***

TABLE 3
Study 1: t-test results for all dependent variables: Significant effects $(p \leq 5\%)$ are highlighted in green, and were always in the direction of enhanced user experiences for HeadJoystick over Controller. The effect size *Cohen's d* indicates the magnitude of the effect i.e., the difference between two means expressed in standard deviations.

	t(23)	*p*	*Cohen's d*
Enjoyment	30.8	<.001	.572
Preference	26.9	<.001	.539
Immersion	11.6	.003	.335
Vection Intensity	15.4	<.001	.402
Long-Term Use	2.07	.163	.083
Daily Use	5.13	.03	.182
Overall Usability	24.7	<.001	.518
Presence (SUS)	35.2	<.001	.605
Ease of Use	38.6	<.001	.627
Ease of Learning	27.4	<.001	.543
NASA-TLX	21.9	<.001	.605
Post-Pre Motion Sickness	.285	.6	.012
Reach-the-Target Average Time	69.6	<.001	.865
Reach-the-Target Minmum Size	51.6	<.001	.802
Reach-the-Target Overall Score	56.8	<.001	.712
Reach-the-Target Error Rate	43.4	<.001	.653
Reach-the-Target Througput	54.7	<.001	.362
Follow-the-Path Average Velocity	66.2	<.001	.742
Follow-the-Path Distance Error	68.5	<.001	.944
Follow-the-Path Collisions	5.71	.030	.456
Follow-the-Path Overall Score	16.1	<.001	.411
Racing Average Overtaking Time	14.5	.001	.638
Racing Car Crashes	5.67	.030	.415
Racing Overall Score	29.5	<.001	.562

TABLE 4
Study 2: t-test results for all user experience and usability measures: Significant effects $(p \leq 5\%)$ are highlighted in green, and were always in the direction of enhanced user experiences for HeadJoystick over Controller. The effect size *Cohen's d* indicates the magnitude of effect i.e., the difference between two means expressed in standard deviations.

	t(17)	*p*	*Cohen's d*
Enjoyment	32.1	<.001	.654
Preference	18.5	<.001	.521
Immersion	13.8	.002	.448
Vection Intensity	132	<.001	.886
Long-Term Use	7.33	.015	.301
Daily Use	2.22	.155	.115
Overall Usability	27.2	<.001	.615
Presence (SUS)	41.0	<.001	.707
Ease of Use	18.8	<.001	.525
Ease of Learning	13.3	.002	.439
NASA-TLX	21.9	<.001	.452
Pre-Post Motion Sickness	8.90	.008	.334

TABLE 5
Study 3: Wilcoxon signed-ranked test results for user experience and usability measures. Significant effects $(p \leq 5\%)$ are highlighted in green, and were always in the direction of enhanced user experiences for HeadJoystick followed by HeadJoystick+brake and then Controller, as illustrated in Figure **??**

Measures	Controller vs HeadJoystick		HeadJoystick+Brake vs HeadJoystick		Controller vs HeadJoystick+Brake	
	Z	*p*	Z	*p*	Z	*p*
Enjoyment (%)	100	0.003	48.0	0.030	92.0	0.013
Preference (%)	97.5	0.005	84.5	0.043	99.0	0.025
Immersion (%)	78.0	0.002	36.0	0.011	36.0	0.011
SUS Presence (%)	120	0.001	88.0	0.003	114	0.002
Long-Term Use (%)	63.5	0.489	58.5	0.360	40.5	0.906
Overall Usability (%)	61.0	0.130	48.0	0.320	65.5	0.161
Ease of Use (%)	89.0	0.021	37.5	0.073	74.5	0.166
Ease of Learning (%)	44.5	0.336	67.0	0.132	59.0	0.683
Motion Sickness (%)	20.0	0.779	34.0	0.929	41.0	0.477
Task Difficulty (%)	4.50	<0.001	31.0	0.177	3.00	<0.001
Missed-Targets (#)	1.00	<0.001	12.0	0.002	7.00	0.001
Error Rate (%)	1.00	<0.001	6.00	0.001	5.00	<0.001

TABLE 6
Study 2 Statistical analysis for per-trial data, with significant effects shown in green. Significant main effects of interface and interface-trial interactions were always in the direction of enhanced user experience and performance for HeadJoystick versus Controller.

Measures	HeadJoystick		Controller		Interface			Trial			Interface * Trial		
	M	SD	M	SD	F(1,17)	p	η_p^2	F(1,17)	p	η_p^2	F(1,17)	p	η_p^2
Motion Sickness (%)	5.63	7.48	14.8	15.5	7.13	0.016	0.005	39.9	<0.001	0.243	14.3	0.002	0.103
Task Difficulty (%)	29.2	13.6	49.6	14.2	64.3	<0.001	0.201	670	<0.001	0.241	2.68	0.018	0.039
Time to reach a target (s)	4.30	1.52	5.59	1.94	99.0	<0.001	0.187	61.2	<0.001	0.187	0.736	0.372	0.038
Minimum Target Size (cm)	2.61	1.80	4.03	2.26	101	<0.001	0.110	80.3	<0.001	0.173	1.83	0.087	0.041
Overall Score (K)	7.45	4.48	4.08	2.21	86.2	<0.001	0.108	109	<0.001	0.214	10.8	0.004	0.082
Reached Targets (#)	15.0	3.79	11.7	3.12	18.2	<0.001	0.118	45.1	<0.001	0.241	14.6	0.002	0.093
Missed targets (#)	1.65	1.56	7.57	4.43	36.0	<0.001	0.202	22.0	<0.001	0.134	8.04	0.005	0.054
Error Rate (%)	9.06	7.14	35.6	14.1	241	<0.001	0.250	80.3	<0.001	0.058	2.60	0.016	0.064
Throughput	1.96	1.01	1.48	0.795	20.0	<0.001	0.002	80.3	<0.001	0.029	2.57	0.017	0.064

TABLE 7
Study 3 Statistical analysis for per-trial data, with significant effects shown in green. Significant main effects of interface and interface-trial interactions were always in the direction of enhanced user experience and performance for HeadJoystick followed by HeadJoystick+Brake and then Controller, and performance improvement over the course of the three trials per interface, as illustrated in Figure **??**.

Measures	HeadJoystick		HeadJoystick+Brake		Controller		Interface			Trial			Interface * Trial		
	M	SD	M	SD	M	SD	F(1,17)	p	η_p^2	F(1,17)	p	η_p^2	F(1,17)	p	η_p^2
Overall Score (K)	10.4	2.37	8.30	2.59	5.15	2.05	40.4	<0.001	0.704	82.5	<0.001	0.829	5.25	0.001	0.236
Reached Targets (#)	18.6	3.31	15.6	3.70	11.1	2.89	41.2	<0.001	0.708	80.7	<0.001	0.826	5.92	<0.001	0.258
Average Time (s)	6.76	1.25	8.57	1.98	12.0	3.34	31.3	<0.001	0.648	42.6	<0.001	0.715	4.61	0.008	0.213
Throughput	1.03	0.22	0.805	0.210	0.532	0.159	78.8	<0.001	0.822	49.8	<0.001	0.746	1.88	0.125	0.099