Understanding the Heisenberg Effect of Spatial Interaction: A Selection Induced Error for Spatially Tracked Input Devices

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ABSTRACT
Virtual and augmented reality head-mounted displays (HMDs) are currently heavily relying on spatially tracked input devices (STID) for interaction. These STIDs are all prone to the phenomenon that a discrete input (e.g., button press) will disturb the position of the tracker, resulting in a different selection point during ray-cast interaction (Heisenberg Effect of Spatial Interaction). Besides the knowledge of its existence, there is currently a lack of a deeper understanding of its severity, structure and impact on throughput and angular error during a selection task. In this work, we present a formal evaluation of the Heisenberg effect and the impact of body posture, arm position and STID degrees of freedom on its severity. In a Fitt's law inspired user study (N=16), we found that the Heisenberg effect is responsible for 30.45% of the overall errors occurring during a pointing task, but can be reduced by 25.4% using a correction function.

Author Keywords
VR, virtual reality, pointing, Heisenberg effect

CCS Concepts
•**Human-centered computing** → **Empirical studies in HCI;** *Pointing devices;*

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INTRODUCTION AND MOTIVATION
Augmented and Virtual Reality head-mounted displays (HMDs) use the physical space around a user to superimpose information or fully immerse the user and can be classified as spatial computing devices [24]. Most spatial computing devices rely on spatially tracked input devices (STIDs) which allow the user to point at and select virtual content. All these STIDs are prone to the phenomenon that a discrete input such as a button press will disturb the position of the tracker and result in a different selection point (Heisenberg Effect of Spatial Interaction [3]).

Despite this phenomenon being observed by several researchers [4, 10], it is mostly ignored or compensated for by moving the selection to the non-pointing hand. This solution works inside a lab study but is difficult to apply for current consumer devices. Therefore, there is a current lack of understanding of the nature of the phenomenon (e.g., How much percentage of selection errors can be attributed to the Heisenberg effect? Does the Heisenberg effect follow certain characteristics? How can the effect be mitigated?).

To gain an understanding of the severity and characteristics of the Heisenberg effect, we conducted an ISO9241-9 inspired pointing task (N=16) using an HTC VIVE and measuring the Heisenberg effect and its impact on accuracy and throughput during selections in VR. To disentangle the spatial disturbance during discrete selections from ballistic movement during pointing, we collected both, stationary and ballistic data for each target. Additionally, we used body posture (standing, sitting), arm posture (stretched, bent) and degrees of freedom of the STID (3DoF, 6DoF) as independent variables.

We found that during ballistic selections the Heisenberg effect accounts for 30.45% of the selection errors. We also found that the Heisenberg effect is a systematic upwards shift. We hypothesize that this is related to the positioning of the trigger button of the HTC Vive. Our results further indicate that angular error increases with larger targets and longer click duration. Finally, we present a set of compensation techniques that can be applied to reduce the error down to 8.8%. We argue that with the progress of display quality and the ability to see and point at small targets further away, the Heisenberg effect will become more relevant but can be easily compensated for in software.

The main contributions of this work are

1. An in-depth analysis of the impact of the Heisenberg effect of spatial interaction on selection throughput and error rate.
2. An analysis of the unique characteristics of the Heisenberg effect and its systematic behavior during selection.
3. Compensation strategies for the Heisenberg effect during selection.

RELATED WORK

Selection in 2D and 3D

A widely used HCI technique for interacting with distant targets in 2D and 3D is via pointing. The current pointing position of a hand or STID is usually defined via ray-casting by extending the selecting hand or STID and calculating the intersection point with objects and planes along the ray [22]. Visualization techniques for the current pointing position include cursors [9, 11, 14, 18] and virtual hands [5, 23]. Depending on the STID used, pointing suffers from jitter and latency which can affect user performance with latency largely being more detrimental to selection performance [19]. STIDs for 3D selection such as VR controllers have been shown to suffer from additional positional [26] and rotational jitter [2]. These types of jitter do not affect selection precision significantly if target size is kept above a viable value. Teather et al. further concluded that similar to 2D input, latency in 3D selection is affecting human performance more than low spatial jitter [26].

In addition to tracking-induced jitter and inherent hand jitter of users, Bowman et al. observed the so called "Heisenberg Effect of Interaction", a spatial disturbance that occurs during discrete selections on an STID [3]. While some researchers reverted to STID positions measured before the actual selection in order to avoid this effect [4, 10, 28] or asked participants "to click with the non-dominant hand on the button of a remote control" [15], we are motivated to formally evaluate this phenomenon in order to gain a deeper understanding of its severity and impact on selection precision and throughput.

Fitts' Law

The Fitts' law models the expected movement time in respect to the index of difficulty of a target via

$$MT = a + b \times ID_e, \tag{1}$$

where a and b are factors that are determined empirically via linear regression. While this relationship is of predictive nature, we are more interested in deriving the performance metric of throughput. As throughput can be affected by user performance, McKenzie et al. introduced an approach to correct the throughput for input errors by calculating the effective throughput (TP_e) [13]. According to the ISO 9241-9 pointing task, effective throughput can be modeled via

$$TP_e = ID_e / MT \tag{2}$$

where ID_e is the effective index of difficulty of the target and MT the mean movement time. According to the Shannon formulation of Fitts' law [13], ID_e is defined as

$$ID_e = \log_2\left(\frac{D_e}{W_e} + 1\right), \tag{3}$$

where D_e is the effective distance between targets (i.e., standard deviation of over- and undershoots from the intended target center projected on the optimal path), and W_e is the effective width of the target (i.e., 4.133 standard deviations of the end-point positions) calculated as proposed by Soukoreff and MacKenzie [25]. Considering the end-point distribution, the effective width is a more precise estimate for the actual target width that the users were selecting. This model allows us to recalculate effective throughput for corrected end-point positions and thus compare the efficiency of compensation strategies.

THE HEISENBERG EFFECT

The Heisenberg Effect was originally observed by Bowman et al. as a side effect when using STIDs [3]. The authors gave a beautiful description of the effect that they observed during a user study:

"[..]a user wants to select an object using ray casting. She orients the ray so that it intersects the object, but when she presses the button, the force of the button press displaces the ray so that the object is not selected."

In Figure 1, we show an abstract depiction of the Heisenberg Effect that we created based on the insights gathered in our user studies. We present this model early in the paper to give the reader a visual understanding of the effect and its interplay with hand jitter, target size and direction.

The angular offset between selection start and selection end is in the following referred to as *Heisenberg Magnitude*. Selections that started within a target but were displaced due to the Heisenberg Effect and thus led to a miss are called *Heisenberg Errors*. Therefore, developers and researchers that want to avoid *Heisenberg Errors* at all cost, need to design targets with a radius larger than the *Heisenberg Magnitude*. In section 6, we will explain why this approach is not always desirable and present further correction mechanisms. Additionally, we found a systematic shift to the top left during our study. We partially explain this with the location of the physical trigger button on the controller.

EXPERIMENT

To explore the impact of the Heisenberg Effect on selection performance and quantify the influence of input parameters, we conducted a user study consisting of two pointing tasks. The first one was an ISO 9241-9 pointing task (in the following referred to as *ballistic*). The second task removed the ballistic motion from the selection to allow us to quantify the "pure" Heisenberg Effect (in the following referred to as *stationary*).

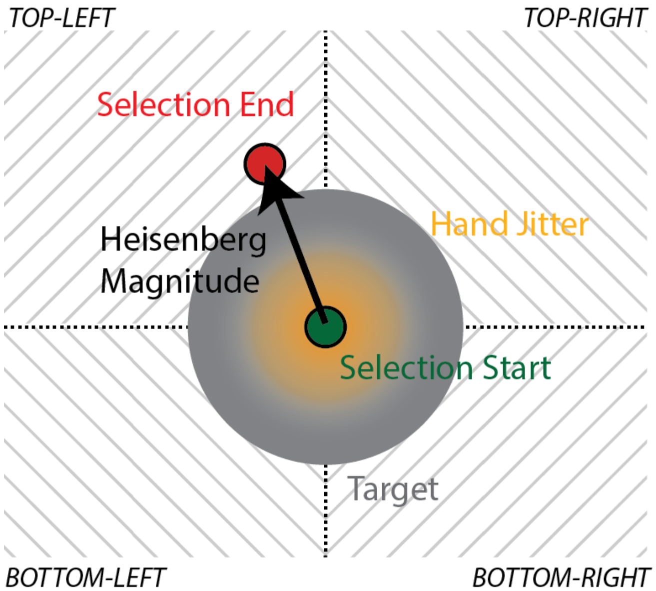

Figure 1: A theoretical model of the Heisenberg Effect for spatial interaction, showing the systematic shift to the top left, the relationship to hand jitter and the definition of a Heisenberg Error: Starting a selection inside the target but ending outside due to a disturbance of the input device.

Apparatus

We implemented the selection task inside a simple VR scene using Unity3D and an HTC Vive HMD (V 1.0) connected to a computer equipped with an i5-6600k (stock) processor and an Nvidia GTX 1080 graphics card. We used the trigger button of the HTC Vive controller as the selection button (as it is commonly used). The trigger button gives values about the trigger state of the button (starting from 0 for no contact and going linearly up to 1.0 depending on how far the user pushed the button in) and additionally fires a selection event when the trigger is completely pushed through.

To establish a baseline for the angular offset during a pointing task with a VR controller, the spatial jitter for the controller and HMD device was measured in a resting position lying on the floor. The Vive base stations (V 1.0) were 2.5 meters apart with the currently measured device being in the center of the tracking space. Angular data was recorded in a time frame of 120 seconds and resulted in a positional jitter of $0.025° - 0.085°$ mean-to-peak for the controller and $0.0094° - 0.059°$ mean-to-peak for the HMD.

Through a combination of optical tracking and inertial sensors the update rate of a Vive controller (V 1.0) is reported to be between 250 Hz and 1000 Hz. The update rate accessible via the API is significantly lower and depends on the performance of the computer used. To measure the temporal jitter, i.e. the change of latency over time, the time difference between consecutive frames during several pointing tasks was analyzed. A histogram of these values revealed that over 96.5% of all updates happened in an interval of 9-11 ms and all remaining updates in an interval of 6-8 ms. Temporal and spatial jitter are therefore not considered an issue for the experiment.

Variables

Independent Variables: Our experimental design consisted of five independent variables (*BodyPosition*, *ArmPosition*, *DoF*, *Width* and *Distance*). Since the Heisenberg effect is a disturbance in the pointing accuracy resulting from the press of a physical button, we hypothesized that the stability of the pointing arm is a relevant factor that should probably influence the magnitude of the Heisenberg Effect. Therefore, we were choosing variable postures that all result in a different level of stability (e.g. extending an arm is less stable than applying it and similarly sitting is less stable than standing [27]). Inspired by previous work, the *BodyPosition* had two levels (*Sitting*, e.g., Barrera and Stuerzlinger [1] and *Standing*, e.g., Kopper et al. [12]). The *ArmPosition* had also two levels in which users either *Extended* their arm during pointing (e.g., Grossman and Balakrishnan [7] or Miller et al. [16]) or *Applied* it (elbow at 90 degrees, pressed against body, e.g., Gielen et al. [6]). The *DoF* of the STIDs were either *Three* degrees (only rotational) or *Six* degrees (rotation and translation). We selected *DoF* as a variable, since we were interested if the Heisenberg Effect would be stronger for 3DoF STIDs which are currently widely used for mobile VR HMDs (e.g. Oculus Go). The last two independent variables were contributed by the pointing task: *Width* of the targets (*15, 30, 50* cm) and *Distance* between the targets (*150, 350* cm). We want to emphasize that this distance refers to the distance between targets and not between user and target. In our study the user was always at a fixed distance to the selection targets (8m).

Dependent Variables: To be able to calculate what percentage of the overall pointing errors occurred due to the Heisenberg Effect and to quantify the severity of the Heisenberg Effect we measured *EffectiveThroughput*, *OverallError*, *HeisenbergError* and *HeisenbergMagnitude*.

The *EffectiveThroughput* was measured as proposed by Soukoreff and MacKenzie [25] and helped us to quantify how performance can be improved by compensating the Heisenberg Effect. The *OverallError* was measured as the overall percentage of missed targets. The *HeisenbergError* was measured as the percentage of targets in which the selection (start of button press) started inside the target but ended outside of the target (end of button press[2]). The *HeisenbergMagnitude* was measured as the distance in angular degrees between the start of the selection (button trigger value >0) and the end of the selection (button completely pushed through).

To be able to quantify the characteristics of the Heisenberg Effect, we recorded *FalsePresses*, *Left*, *Top* and *ClickDuration*. *FalsePresses* were defined as the amount of button presses with values higher than zero that were not completely pushed through. This is a good indicator of how often users accidentally started a selection without finishing it. To further quantify a systematic directional offset of the Heisenberg Effect, we

[2]As the end of the button press we used the event which is normally used as a selection event. With the HTC Vive controller this happens after the trigger is completely pushed through.

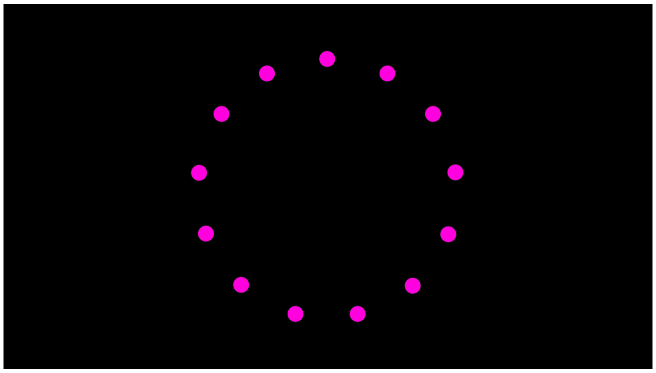

Figure 2: Participant view of the target plane in the study environment. Only one target at a time was shown during the pointing task.

counted the amount of target selections which ended up being above the target (*Top*) and the amount of target selections which ended up being left of the target (*Left*). Finally, we measured the time a fully executed selection (i.e., trigger value >0 leading to a trigger press) took from start (trigger value >0) to finish (trigger press) as *ClickDuration*.

Procedure

The study was executed inside a quite room at our institution. After an informed consent and demographics, participants were introduced to the experiment and asked to follow the instructions on the interface presented in the VR environment. The users saw a set of circular flat targets floating 8 meters in front of them and could select them using a ray cast metaphor with the HTC Vive controller.

The *ballistic* task was the ISO 9241-9 pointing task where flat circular targets with a given width (*Width*) are arranged on a circle with a given diameter (*Distance*, see Figure 2). For each *Width* x *Distance* combination, participants had to select 13 disks.

To be able to measure the "pure" Heisenberg Effect (i.e., the offset induced by a button press from a stationary position while a regular selection error consists of the disturbance using the button and the overshooting from a ballistic motion) and hand jitter without ballistic over- or undershoot, we added a second pointing task. After each ballistic selection, participants had time to position themselves above the target (hence removing the ballistic motion). Once above the target, the pointer had to stay within the target for a duration of 500 ms while a visual indicator was filling up in a red color to display the remaining time (see Figure 3 left). After 500 ms the indicator turned green and participants had to perform a selection (press the trigger from value 0 to 1.0, see Figure 3 right). Participants were instructed to aim for the center of the target. Afterwards, the next ballistic target was activated. This separation into *ballistic* and *stationary* allowed us to be certain about the user's intended selection position in the *stationary* condition (i.e., the center of the target). In the following analysis the center of the target was always used as the intended start of the selection.

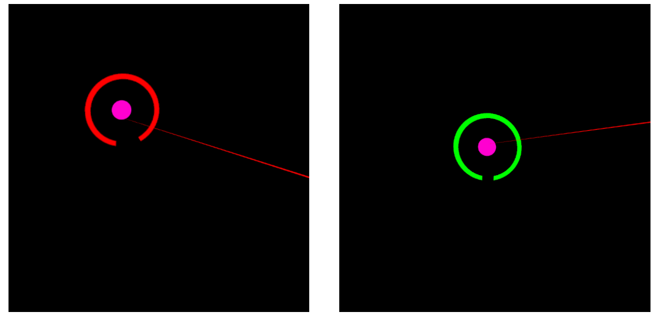

Figure 3: Participant view during the *stationary* selection. Left: A red visual indicator displays the remaining time before the participant has to click. Right: A green indicator symbolizes that the participant should perform a click.

Participants

16 participants (8 male, 7 female, 1 non-binary) were recruited via convenience sampling. Participants were aged between 20 and 30 (M = 24.5, SD = 2.85). 15 participants were right-handed and 7 had corrected-to-normal vision. All but three participants had prior VR experience and 8 participants reported to play VR games where pointing was the main task (e.g., shooting or selecting).

RESULTS

A total of 19968 selections were recorded and analyzed using a repeated measures ANOVA with Greenhouse-Geisser correction where sphericity was violated. Pairwise comparisons are reported with Bonferronni adjusted p-values. For the sake of readability, all statistical results are presented in Table 1 and Table 2. In the following result section, we will only highlight briefly a subset of significant results.

Characteristics of the Heisenberg Effect

Hand jitter was measured during a time frame of 500 ms during stationary selections. Departure from normal distribution for all three angular offset distributions caused by hand jitter during the *Width* conditions was tested with D'Agostino and Pearson's test and was found to be not significant [20] (p>.05). Therefore, a normal distribution was assumed for hand jitter during all selections.

Irrelevant of the target position, the Heisenberg Effect expressed a systematic upwards shift (see Figure 4 top). Aggregated selection offsets over target width can be found in (Figure 4 bottom). For smaller targets, a higher percentage of selections ended outside of the target, leading to a higher *HeisenbergError*.

Sampling over the angular offsets during a button press (sampling rate: click duration/10), resulted in a nearly linear relationship between button press value and angular offset: $\rho = .737, p < .001$ (see Figure 5).

Impacting Factors

ArmPosition: During both selection tasks, *ClickDuration* was significantly higher in the applied *ArmPosition* condition (stationary: M=308.303 ms, SE=58.858 ms; ballistic:

			OverallError			HeisenbergError			HeisenbergMagnitude			TP_e		
		df	*F*	*p*	η^2	*F*	*p*	η^2	*F*	*p*	η^2	*F*	*p*	η^2
BodyPosition	stationary	1,15	.10	ns	.007	.42	ns	.027	.39	ns	.025	–	–	–
	ballistic	1,15	.46	ns	.029	.01	ns	.001	0.43	ns	.028	.45	ns	.029
ArmPosition	stationary	1,15	1.16	ns	.072	3.33	ns	.182	.16	ns	.010	–	–	–
	ballistic	1,15	.16	ns	.011	.17	ns	.011	2.37	ns	.136	.01	ns	.000
DoF	stationary	1,15	1.44	ns	.088	2.70	ns	.153	.28	ns	.018	–	–	–
	ballistic	1,15	1.83	ns	.108	6.63	$*$	.307	4.19	.059	.218	18.19	$**$	.548
Width	stationary	2,30	158.90	$***$	.914	115.18 ($\varepsilon = .658$)	$***$	.885	16.03 ($\varepsilon = .564$)	$**$	.517	–	–	–
	ballistic	2,30	592.43	$***$	.975	13.76	$***$	.479	1.39	$*$	.266	16.51	$***$	.524
Distance	stationary	1,15	.25	ns	.016	.04	ns	.003	6.34	$*$	.297	–	–	–
	ballistic	1,15	25.58	$***$	.630	2.52	ns	.144	5.44	$*$	.266	117.91	$***$	.887

Table 1: Results for dependent variables split by stationary and ballistic task. Significant results are marked with $*$ (p<.05), $**$ (p<.001) and $***$ (p<.0001). Greenhouse-Geisser-corrected F-values are reported with ε-values.

			FalsePresses			Top			Left			ClickDuration		
		df	*F*	*p*	η^2	*F*	*p*	η^2	*F*	*p*	η^2	*F*	*p*	η^2
BodyPosition	stationary	1,15	.63	ns	.040	.68	ns	.043	2.10	ns	.123	.57	ns	.036
	ballistic	1,15	.28	ns	.018	.08	ns	.005	0.2	ns	.001	1.56	ns	.094
ArmPosition	stationary	1,15	4.31	.055	.223	2.81	ns	.158	.10	ns	.007	6.40	$*$	.299
	ballistic	1,15	2.76	ns	.155	.26	ns	.017	5.02	$*$	.251	6.63	$*$	.306
DoF	stationary	1,15	.65	ns	.041	1.61	ns	.097	.02	ns	.001	.25	ns	.016
	ballistic	1,15	2.75	ns	.155	1.21	ns	.075	2.89	ns	.161	.82	ns	.052
Width	stationary	2,30	.28	ns	.019	.34	ns	.022	.42	ns	.027	15.61 ($\varepsilon = .509$)	$**$	.510
	ballistic	2,30	.29	ns	.019	1.07	ns	.067	4.56	$*$	.233	15.73 ($\varepsilon = .507$)	$**$	.512
Distance	stationary	1,15	.07	ns	.005	.88	ns	.055	3.76	.072	.20	3.16	ns	.174
	ballistic	1,15	11.80	$*$	.440	2.76	ns	.156	7.33	$*$	.328	12.36	$*$	.452

Table 2: Results for Heisenberg characteristics split by stationary and ballistic task. Significant results are marked with $*$ (p<.05), $**$ (p<.001) and $***$ (p<.0001). Greenhouse-Geisser-corrected F-values are reported with ε-values.

M=272.426 ms, SE=46.555 ms) than in the stretched *ArmPosition* condition (stationary: M=250.870, SE=60.403; ballistic: M=231.754, SE=50.021). Furthermore, significantly more selections were shifted to the left during ballistic selections with an applied *ArmPosition* (M=0.512, SE=0.020) than with a stretched *ArmPosition* (M=0.548, SE=0.023).

DoF: *HeisenbergError* for a *DoF* of *SIX* (M=0.112, SE=0.016) was significantly lower than for a *DoF* of *THREE* (M=0.124, SE=0.018). Furthermore, *EffectiveThroughput* for a *DoF* of *SIX* (M=1.793, SE=0.105) was significantly higher than for a *DoF* of *THREE* (M=1.656, SE=0.082). This was a rather surprising insight for us as we expected that more degrees of freedom would lead to a higher *HeisenbergError* (due to higher probabilities of disturbing the input via rotation and translation). However, this indicates that the Heisenberg Effect is less influenced by a translational disturbance but more by a rotational.

There were no significant differences between the *BodyPosition* conditions.

Target Width and Distance: We found that the *OverallError*, *HeisenbergError* and *ClickDuration* all increased for smaller targets while the *HeisenbergMagnitude* decreased (see Figure 6). This means that smaller targets lead to a higher *HeisenbergError* while having a smaller *HeisenbergMagnitude*. This further indicates that the *HeisenbergMagnitude* is also influenced by the visual representation of the targets.

In the *stationary* condition, we found that *HeisenbergMagnitude* for a *Distance* of 150 cm $(M = 0.652°, SE = 0.043°)$ is significantly lower than for a *Distance* of 350 cm $(M = 0.680°, SE = 0.036°)$; p=0.024. Similar results were found in the *ballistic* condition. *HeisenbergMagnitude* for a *Distance* of 150 $(M = 2.536°, SE = 0.695°)$ is significantly lower than for a *Distance* of 350 cm $(M = 4.538°, SE = 1.54°)$; p=.034. Unsurprisingly, *Overall Error* for a *Distance* of 150 (M=0.351, SE=0.029) was significantly lower than for a *Distance* of 350 (M=0.423, SE=0.026, p<.001) in the ballistic condition which can be attributed to the inertia of ballistic movements.

Correlation of Dependent Variables

There was a significant correlation between *ClickDuration* and *HeisenbergMagnitude* $(p < .001, \rho = 0.327)$, *ClickDuration* and *HeisenbergError* $(p < .001, r = -0.04)$, *ClickDuration* and *FalsePresses* $(p < .001, \rho = -0.599)$, *ClickDuration* and *Top* $(p < .001, r = -0.126)$, and *ClickDuration* and *Left* $(p < .001, r = 0.075)$.

Discussion

Characteristics of the Heisenberg Effect

Our results indicate that the Heisenberg Effect is responsible for 81.98% of the errors during stationary and 30.49% during ballistic selections. The low percentage of Heisenberg Errors in the ballistic condition can be explained by the low number of selections that started in a target (43.3%). For these selections, the Heisenberg Error value for the ballistic condition was

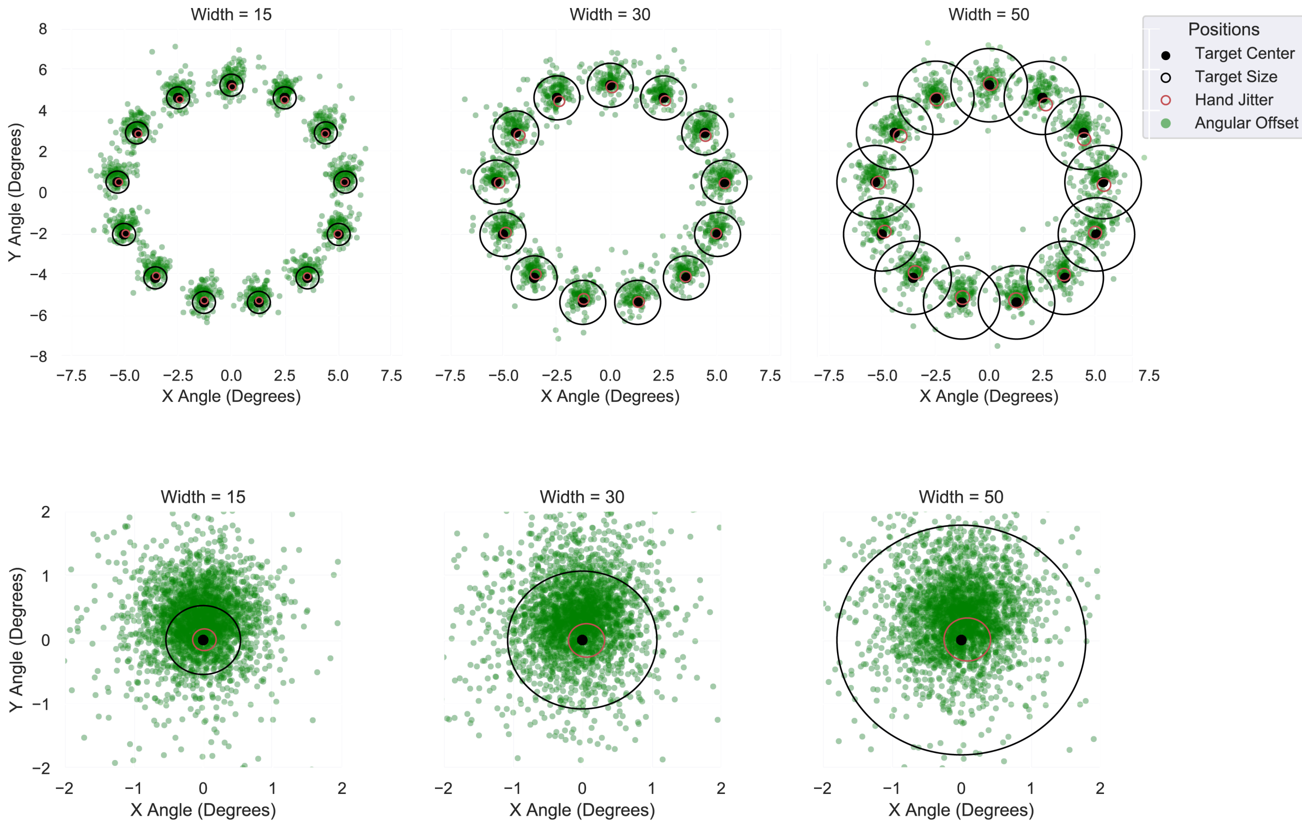

Figure 4: Heisenberg Magnitude in angles (degrees) by target width, aggregated over target distance (top) and distance and position (bottom). The green dots (Angular Offset) outside the target boundaries show the selections which where disturbed by the Heisenberg Effect of spatial interaction.

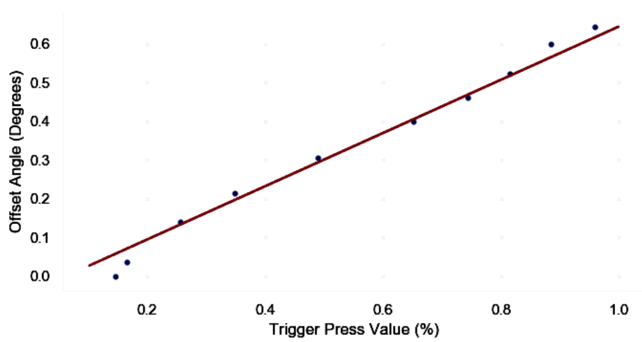

Figure 5: Relationship between trigger press value and angular offset during a selection.

26.6% which is more consistent with the stationary condition (23.2%).

We found an upward shift for 77.8% of all selections in the stationary and 64% in the ballistic selection. This systematic shift can be mostly attributed to the Heisenberg Effect since 89.75% of all Heisenberg Errors had an upward shift in the stationary and 86.65% in the ballistic condition. We hypothesize that this directional shift is related to the position of the trigger button on an HTC Vive controller. Further tests are necessary to evaluate the directional shift for other button types and positions. Additionally, we found a horizontal shift to the left in the ballistic condition while stationary selections showed only vertical shifts with a tendency to the top. This again supports our finding of a systematic upward shift due to the Heisenberg Effect.

Angular error increased with target width from 0.587° for the smallest to 0.745° for the largest target. This is also consistent with hand jitter that increased from 0.169° to 0.335°. A possible explanation could lie in the model of anticipatory postural adjustments that leads to a varying muscle tension and arm posture depending on the perceived target size [17]. This is also reflected in an increasing click duration for smaller targets.

Impact on the Heisenberg Effect

No significant differences could be found for the body position probably due to no impact on the pointing arm. Arm position, however, seems to influence click duration with a stretched arm posture leading to a shorter click duration. This might be explained by the more stable arm position and increased tension in the lower arm and fingers [21].

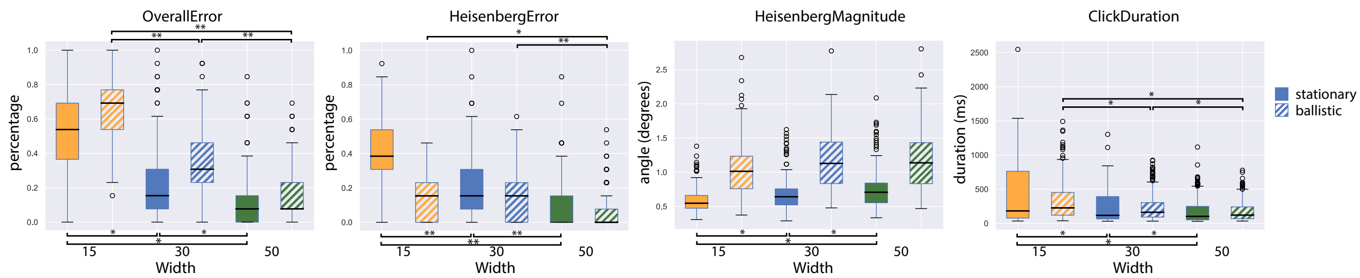

Figure 6: Results of pairwise comparisons for target width. Significant differences are marked with $*$ (p<.05) and $**$ (p<.001).

Angular error increased with target distance. This could be explained be the steeper arm angle required to select targets further from the center. While targets in the small distance condition were positioned at an angle of 5.4° from the the participant, targets in the large distance condition were positioned at 12.6°.

Degrees-of-freedom showed no significant differences in the stationary condition which suggests no correlation with the Heisenberg Effect. In the ballistic condition, six DoF led to a significantly higher Heisenberg Error, shorter movement time between selections and a higher effective throughput. We hypothesize that participants did not change their selection behavior in the three DoF condition and continued to move their whole arm instead of rotating the wrist. Since the pointer origin was fixed during the three DoF condition, it would require a wider arm movement to move the pointer by the same amount of degrees as in the six DoF condition.

DEALING WITH THE HEISENBERG EFFECT

Our results have clearly shown that the Heisenberg Effect is always present during selections with a trigger button. We argue that this will be the case for other hardware buttons as well, as long as force has to be applied to the input device in order to confirm a selection. This chapter will now present and discuss mitigation and compensation strategies.

Time Shift to Initial Press

Since discrete input via a physical button is the cause of the spatial disturbance and thus the Heisenberg Effect, a naive assumption could be to shift back in time to the initial position where the user started pressing the button. However, an analysis of the initial press positions revealed that on average 7% occurred outside of the target in the stationary and 55.7% in the ballistic condition ($F_{1,15} = 87.613, p < .001, \eta^2 = 0.854$). As can be seen in Table 3, the percentage of initial presses that happened outside of the target in the ballistic condition differs significantly between the target distance conditions ($F_{1,15} = 55.314, p < .001, \eta^2 = 787$) and width conditions ($F_{1.385,20.774} = 97.991, p < .001, \eta^2 = 0.867$). A naive time shift to the initial press position in a ballistic condition would therefore induce an error of 37.4% for the largest target width tested which is higher than the raw Heisenberg Error of 26.6% and almost as high as the Overall Error of 38.7%. Only the stationary condition shows an improvement for all target distance and width conditions compared to the raw Heisenberg Error of 24.9% and the Overall Error of 28.3%.

		Stationary	Ballistic
Distance	150	6%	50.4%
	350	7.9%	61%
Width	15	14.3%	75.4%
	30	4.7%	54.3%
	50	1.9%	37.4%

Table 3: Percentage of trigger presses outside of the target.

Time Shift to Position Before Click

As presented in the subsection *Correlation of Dependent Variables*, the duration of a full click correlates with the magnitude of the Heisenberg Effect and the probability to make a Heisenberg Error. Thus, a logical assumption could be to shorten the click duration by using a trigger press value lower than 1.0. However, for a total of 19968 selections, 17318 so called 'false trigger presses' were recorded, resulting in 0.87 false trigger presses for each valid selection, where participants pressed the trigger button and released it completely without fully clicking. The mean trigger press value at which the button was released over all conditions was as high as 0.55 (±0.22) with a trigger value of 1.0 being a full click. As can be seen in Figure 7, 95% of all false trigger press values lie below a trigger press value of approximately 0.83. Values below this threshold would increase the Type I error (accept a false trigger press as a click), while values above would reduce the benefit of the reduced click duration and thus increase the Heisenberg Magnitude and the Heisenberg Error. Accepting a click at a trigger press value of 0.83 would reduce the average Heisenberg Magnitude from 0.66° to 0.53° for stationary selection (see Figure 5).

Correction Function

As an alternative to the above mentioned naive strategies, we propose to distill a correction mechanism from the gathered data similar to touch-position correction in previous work [8]. To this end, the offset vectors of the Heisenberg Error for all stationary selections were collapsed globally (*Global*) and group-wise by the independent variables (*GroupWise*) to create correction vectors that can be subtracted from the selection

		Effective Throughput			Heisenberg Error			Overall Error		
		c_{none}	c_g	c_{gw}	c_{none}	c_g	c_{gw}	c_{none}	c_g	c_{gw}
BodyPosition	SITTING	2.908	2.948	2.988	0.117	0.095	0.089	0.392	0.362	0.348
	STANDING	2.911	2.976	3.016	0.118	0.095	0.087	0.383	0.349	0.334
ArmPosition	APPLIED	2.953	3.015	3.058	0.116	0.091	0.083	0.390	0.348	0.338
	STRETCHED	2.866	2.908	2.946	0.120	0.099	0.092	0.384	0.363	0.344
DoF	SIX	3.010	3.064	3.102	0.112	0.088	0.083	0.379	0.349	0.339
	THREE	2.809	2.859	2.902	0.124	0.102	0.092	0.396	0.362	0.343
OVERALL		2.909	2.962	3.002	0.118	0.095	0.088	0.387	0.356	0.341

Table 4: Impact of Heiseberg effect compensation on effective throughput, *HeisenbergError* and *OverallError* by independent variable. Correction strategies are none (c_{none}), global correction (c_g), and group-wise correction (c_{gw}).

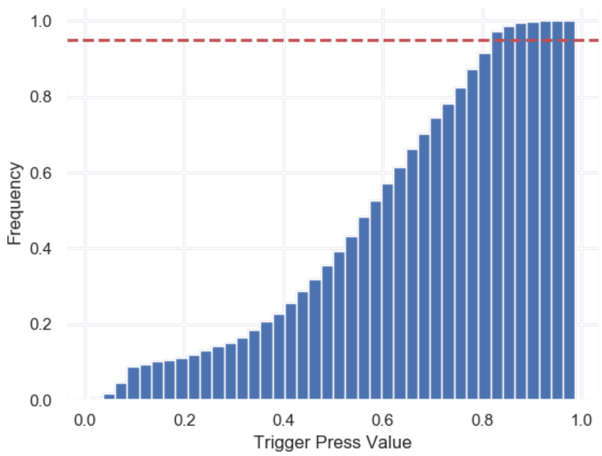

Figure 7: Cumulative histogram of false trigger presses by trigger value. 95% of all false trigger presses lie below a trigger press value of approximately 0.83.

position. Results on the benefit of the correction mechanisms on effective throughput, *HeisenbergError* and *OverallError* against uncorrected values (*Raw*) can be found below and are summarized in Table 4.

A repeated measures ANOVA revealed significant differences in the *EffectiveThroughput* for the *Correction* strategies; $F_{2,30} = 10.139, p < .001, \eta^2 = 0.403$. Pairwise comparisons with Bonferroni correction revealed that *EffectiveThroughput* for the *GroupWise* condition (M=3.002, SE=0.125) is significantly higher than for the *Raw* condition (M=2.909, SE=0.132, p=.001).

A repeated measures ANOVA with Greenhouse-Geisser correction revealed significant differences in the *HeisenbergError* for the *Correction* strategies; $F_{1.260,18.902} = 13.438, p = .001, \eta^2 = 0.473,\ \varepsilon = 0.630$. Pairwise comparisons with Bonferroni correction revealed that *HeisenbergError* for the *GroupWise* condition (M=0.088, SE=0.011) is significantly lower than for the *Raw* condition (M=0.118, SE=0.017, p=.006). Furthermore, the *HeisebergError* for the *Global* condition (M=0.095, SE=0.014) is significantly lower than for the *Raw* condition (p=.005).

A repeated measures ANOVA revealed significant differences in the *OverallError* for the *Correction* strategies; $F_{2,30} = 11.702, p < .001, \eta^2 = 0.438$. Pairwise comparisons with Bonferroni correction revealed that *OverallError* for the *GroupWise* condition (M=0.341, SE=0.020) is significantly lower than for the *Raw* condition (M=0.387, SE=0.027, p=.004). Furthermore, the *OverallError* for the *Global* condition (M=0.356, SE=0.023) is significantly lower than for the *Raw* condition (p=.022).

As can be seen in Table 4, the *Global* correction, a mechanism that can be easily implemented, reduces the Heisenberg Error and Overall Error. With additional information on the current body position, arm position and DoF, a further improvement in accuracy and throughput can be achieved via *GroupWise* correction. We argue that this information can be easily inferred from the HMD position (*BodyPosition*), controller distance to the HMD (*ArmPosition*) and hardware platform used (*DoF*).

Minimum Viable Heisenberg Compensated Target Size

Since the Heisenberg Effect is unconscious and is likely to vary with the hardware button built into the controller, a minimum target size can be calculated to reduce the Heisenberg Error to a desired percentage. Since *HeisenbergMagnitude* showed significant differences for the *Width* conditions (see subsection 5.2), a separate analysis for each target width tested was performed (see Figure 8). As can be seen in the cumulative histograms, 95% of Heisenberg Errors have an angle of at least 1.7° for the largest target width. Assuming that a user is pointing at the exact center of the target, the minimum target width necessary is therefore:

$$distance\_controller\_to\_target \times \sin(1.7°) \times 2 \qquad (4)$$

Some example values for a given controller to target distance can be found in Table 5. Since this naive calculation assumes that the pointer is perfectly centered at the target and the overall Heisenberg Magnitude does not further increase for a larger target, the required minimum target width should be higher rendering this compensation strategy less viable in a real-world deployment.

LIMITATIONS

Although we could show a systematic upwards shift for the Heisenberg Effect, it remains to be evaluated whether this directional shift and its severity is tied to a certain button position and type (i.e., force of resistance). Only one type of controller was evaluated. Other controller types would be tracked by different hardware (e.g., IMU) and would therefore

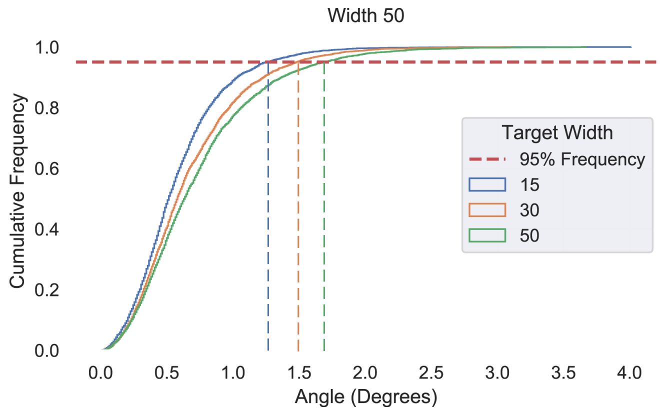

Figure 8: Cumulative histogram of Heisenberg Magnitude in degrees during the stationary condition by target width.

	Distance to Target (m)						
	1	2	3	4	5	6	7
Width (cm)	5.9	11.9	17.8	23.7	29.7	35.6	41.5

Table 5: Minimum target distance required (in cm) for a given controller to target distance (in m) to compensate approximately 95% of the Heisenberg Error.

yield different results due to inherent system jitter and varying tracking resolution.

CONCLUSION

In this work, we presented an evaluation of the Heisenberg Effect of spatial interaction and its impact on selection error and throughput. To measure the influence of body posture, arm posture and degrees-of-freedom, we performed a Fitts' law inspired user study (N=16). We could show that the angular offset has a systematic upwards shift and is relatively large in comparison to hand jitter. Surprisingly, body and arm posture had no impact on the Heisenberg Effect while degrees-of-freedom affected the effective throughput. Furthermore, target width and target distance had a significant impact on the Heisenberg Effect, with smaller targets leading to a higher Heisenberg Error. This implicates that with HMDs increasing in resolution, smaller targets will be possible which in turn would increase the impact of the Heisenberg Effect. To compensate for its impact on selection error and throughput in future experiments, we presented compensation strategies.

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