Cognitive Integration of Delays: Anticipated System Delays Slow Down User Actions

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Abstract

There are inevitably delays between user actions and system responses, which can increase task completion times. However, it remains unclear whether this is solely due to waiting times and compensation strategies, or whether users further slow down their actions because these delays become integrated into their cognitive action structures, as suggested by cognitive psychological theories. To explore this, we examined the effects of repeated exposure to delays during point-and-click tasks. Our findings demonstrate that longer system response delays significantly slow down users' actions, even before they experience the delayed feedback from the current input. This suggests that the user's cognitive system anticipates delays based on previous interactions and adjusts actions accordingly. These results emphasize the importance of minimizing systematic delays to maintain optimal user performance and highlight the potential for system properties to become embedded in users' cognitive action structures.

CCS Concepts

• **Human-centered computing → Empirical studies in HCI**; **Empirical studies in interaction design**.

Keywords

System Delays, Latency, Anticipatory Action Planning, Behavioral Adaptation, Ideomotor Theory

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1 Introduction

Humans primarily act to produce effects in their environment [25, 26, 51, 56]. For example, we press a door handle to open a door or flip a light switch to illuminate a room. Similarly, when using interactive systems, our actions are aimed at achieving specific effects. We click on icons to open applications, type on a keyboard to enter specific letters into a text editor, scroll with the mouse wheel to navigate to different parts of a web page, or use the arrow keys to control an avatar in a video game. In all these cases, actions must be chosen to produce the desired effect. Most of the time, this happens very quickly, without us having to consciously think about the necessary steps to achieve the desired effect. For example, when typing, it often feels as if the thought of a particular letter (e.g., "T") automatically causes certain fingers to land on the corresponding keys on the keyboard (little finger on "Shift," index finger on "T") [53].

In our daily interaction with computerized devices, the expected effects rarely follow our actions immediately. When we turn on a computer, we have to wait for it to boot. When we want to print a document, there is a delay between clicking on the print input element on the GUI and the actual printing process. Similarly, when loading web pages or opening applications, there is a time lag between our click and the completion of the action initiated by our input. Despite advances in computer technology, delays in human-computer interaction (HCI), also referred to as latency, remain relevant. Modern processors, networks, and software are designed for high-speed operation, yet delays persist in user interface responsiveness, data processing, and network communication. Increasing software complexity demands more computing resources, while cloud computing and reliance on remote servers introduce network delays. Even with advanced hardware, issues like memory bottlenecks and input/output constraints still affect performance. Moreover, heightened user expectations make even small delays more disruptive, keeping research into the effects of delays crucial.

The study of user interactions with delays in HCI has received considerable attention because delays can strongly affect both user experience and performance. Delays lead to frustration [36, 49, 64], reduced user satisfaction [1, 34], and decreased performance, such as longer task completion times [2, 8, 11]. However, it is unclear whether extended task completion times are caused solely by the additional waiting time and increased difficulty of precise navigation, or whether delays also introduce an additional behavioral slowdown of user actions.

We hypothesize a behavioral slowdown of user actions because of the anticipatory nature of human action planning. Psychological research, based on ideomotor theory [26, 56], shows that repeatedly

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experiencing the effects of a particular action leads to individuals developing bidirectional associations between these effects and the corresponding actions [15, 30]. Because of these associations, anticipating the effect automatically activates the associated action. Returning to our typing example: When someone first tries to type a capital "T" on a computer keyboard, they initially have to consciously look at the keys and move the little finger to the Shift key and the index finger to the "T" key. However, after many repetitions, simply thinking of a capital "T" will cause the fingers to automatically move to the relevant keys on the keyboard without conscious reflection [53]. This works because, through learned associations, the anticipated effect of the action, along with the corresponding motor programs, is stored in action plans. When the effect is anticipated, the entire action plan, including all its components (such as the motor actions of the fingers and the expected visual outcomes), is automatically retrieved [15, 25, 51].

Cognitive psychology research has shown that not only the visual or auditory appearance of effects is integrated into such action plans, but also the temporal aspects of these effects. For example, when participants repeatedly experience long effect durations in simple stimulus-response experiments, they initiate the actions that trigger these long effect durations more slowly [31]. The same has been shown for the repeated experience of effect delays. Actions whose effects repeatedly occur with a certain delay are initiated more slowly [13]. Applying the results of these studies to HCI suggests that the repeated experience of system delays leads to actions that trigger the delayed system response being performed more slowly over time. An input element (e.g., the print icon) that is associated with a delayed effect should, therefore, be clicked more slowly than an input element (e.g., the bold button) that leads to an effect with less delay. System behavior should thus be integrated into action plans and result in additional behavioral delays.

In the present paper, we investigated whether the repeated experience of delayed system responses leads to a slowdown in user actions that initiate these responses. Specifically, we hypothesized that users would take longer to click on GUI/input elements associated with delayed system responses compared to those with immediate responses. We also posited that this slowdown effect would become more pronounced with repeated exposure to the delayed system response. To test these hypotheses, we conducted a study involving a total of 50 participants who performed a game-like point-and-click task. Specifically, participants engaged in an aim trainer task where they had to shoot at targets as quickly and accurately as possible. One target disappeared immediately upon being hit, while the other target disappeared after a delay of 0.6 s. Our findings confirm the presence of a systematic slowdown effect. As the experiment progressed, the difference between the response times for the target with the delayed effect and the target with the immediate effect increased. By the final rounds of the game, the response time for the target with the delayed effect was 80 ms slower than for the target with the immediate effect.

These findings suggest that system delays do not simply result in longer task completion times due to waiting, but also to a deeper, more systematic behavioral adaptation. Our study makes an important contribution by showing that users integrate these delays into their cognitive action structures, resulting in slower action initiation even before the current delay is encountered. This anticipatory adaptation highlights a previously underexplored mechanism in HCI, where temporal features in system responses are not just tolerated, but actively incorporated into users' cognitive action structures. By shedding light on this cognitive integration, our study provides critical insights for the design of interactive systems that must account for these anticipatory behaviors in order to optimize user performance and experience.

2 Background and Related Work

In this section, we present a review of relevant literature on the effects of delay in HCI and the integration of these delays into user action planning. First, we discuss the direct effects of delays in HCI, focusing on how these delays affect user experience and performance. Then, we look at the concept of anticipatory action control, rooted in ideomotor theory, which provides a framework for understanding how the repeated experience of delays can be integrated into users' cognitive-motor processes. We then review related research in psychological stimulus-response experiments that shed light on how temporal aspects of action effects, including delays, might influence action initiation. Finally, we identify gaps in current research, particularly regarding how repeated exposure to system delays becomes embedded in users' cognitive structures, and how this might affect action initiation and performance, setting the stage for our experimental investigation.

2.1 Delays in Human-Computer Interaction

In HCI, delay or latency refer to a temporal separation between an action performed by a human and the corresponding system response [57]. These delays can occur in various forms, such as slow loading times, delayed responses to clicks or touches, or waiting times for data transmission over networks.

Delays in HCI can have a range of effects on users. For example, delays can have a significant impact on user experience. Systems with noticeable delays are often perceived as being of lower quality than those with little or no delay [1, 34]. In addition, delays can lead to negative emotional effects such as frustration and stress [36, 64], especially when users do not receive feedback on the progress of their actions [49]. In virtual environments, delays can affect the sense of presence [43] and immersion [55]. The effect of delays on user engagement has also been observed [37].

Delays also have a measurable impact on user performance. It has been shown that the delay between sampling of the input device and the updates displayed on the screen reduces accuracy in interaction tasks. This applies, for example, to tracking a target with a mouse [47, 48] or dragging a target in touch-based systems [12, 27]. Such delays also lead to longer movement times, defined as the time it takes for the user to move from one target to another and click on it [58] or the time it takes for a user to complete a path-steering task [63]. Delays are particularly problematic in interaction environments that require precise timing and quick reactions, such as video games. Consequently, much of the evidence on the negative effects of delay on performance is derived from game research. For example, delays cause players to become less efficient [2, 11], take longer to achieve game goals [8], and reduce the overall gaming experience [19, 21, 35]. Specifically, studies in which delays were added to user input like mouse movements, clicks or keystrokes, have shown that this leads to increased selection times and decreased accuracy of target selection [9, 34–36]. The negative effects of delays are so familiar to players that even the mere announcement of a delay alters the gaming experience and performance, although the actual delay remains constant [20].

The central question for our study is why we slow down when exposed to delays. An obvious reason lies in the waiting time for the system's response. When the system responds with a delay, we inevitably have to wait before we can proceed with the next action. This leads to an immediate slowdown in overall performance. Furthermore, in the case of local delays in input devices, additional time is required for corrections. For example, delays in mouse movements can cause the cursor to move too far or not far enough, necessitating an additional corrective movement [46]. There is also a time-accuracy tradeoff: the more difficult it becomes to act precisely, the slower movements are executed to avoid errors [62]. However, these factors might not fully explain why this slowdown occurs. Another relevant mechanism could be the integration of anticipated delays into one's actions (see next section). This hypothesis is supported by a study highly relevant to our research topic by Olguin Munoz et al. [45], which investigated the effects of delayed system responses in the context of wearable cognitive assistance systems. The study showed that longer system delays led to users completing their tasks significantly more slowly, even after the system's responsiveness had improved. Particularly relevant to our research was the evidence for the so-called "pacing effect." Olguin Munoz et al. found that users took longer to complete tasks not only because they had to wait for the system's response, but also because their reactions to new instructions from the system were delayed. This slowdown in reaction times constituted an additional source of significant slowing, which intensified with the decrease in system responsiveness. Remarkably, this effect persisted even when the system's performance improved. The authors also noted that the slowdown was not caused by resource depletion or emotional arousal but by impaired cognitive planning. These findings can be well explained by the anticipatory nature of action planning and thus support our hypothesis that delays in system response are systematically integrated into users' action plans, leading to a sustained slowdown in user responses.

2.2 Anticipatory Action Control (The Ideomotor Theory)

When we perform actions, we do not necessarily have to think about all the required motor actions needed to achieve a goal. Instead, we tend to anticipate the intended effect (e.g., "Copy") and automatically execute the necessary actions (e.g., "pressing Ctrl and C"). This fast response is made possible by anticipatory action planning. To carry out an action, we rely on stored motor programs shaped by past experiences and the anticipated effects [25, 51, 56]. These programs include not only the movement sequences but also the sensory consequences of the action. Evidence for this joint storage of sensory effects and the actions that trigger them can be found in studies showing that the presentation of action effects leads to the motor activation of the actions that produced them. For example, in experienced typists, the mere thought of a letter activates the associated typing action [53] Another example is pianists, whose motor system is activated just by hearing tones [14].

Research on anticipatory action planning has its roots in the ideomotor hypothesis (for an overview, see [56]). The ideomotor hypothesis is a psychological concept that suggests actions and their effects are linked in our memory. This theory originated in the 19th century [23, 26, 50] and was later developed further in more recent psychological frameworks on action planning [25, 51]. According to the ideomotor theory, the perception or anticipation of an effect automatically activates the corresponding action through an associative link stored in memory. When a person repeatedly performs an action that leads to a specific effect, this connection is strengthened. Later, when the effect is perceived, the associated action is reactivated, facilitating the selection and execution of the action. Thus, merely thinking about a goal (the "idea" of an action) can lead to the execution of the associated action.

Although the origins of ideomotor theory date back to the late 19th century, experimental testing of this theory only occurred much later. Elsner and Hommel [15] had participants repeatedly press left and right keys that were associated with different auditory feedback. In a subsequent test phase, the tones previously used as feedback were presented as stimuli, and participants were asked to respond to them with either the left or right key. Participants responded faster when using the key that had previously produced the specific stimulus tone than when using the key associated with the other tone. This suggests that participants formed action-effect associations, leading to faster execution of the corresponding action when the tone was perceived [15]. Additional evidence for anticipatory action planning comes from studies using action-effect compatibility paradigms [30, 31]. In an experiment by Kunde [30], participants were asked to press a key either gently or forcefully, which produced either a loud or soft tone. The conditions were designed so that the intensities of the action and effect were either compatible (softly and quiet, forceful and loud) or incompatible (softly and loud, forceful and quiet). The results showed that reactions in the compatible condition were significantly faster and more accurate than in the incompatible condition, suggesting that participants were better able to perform actions whose effects matched the properties of the action. This effect was also demonstrated for the duration of actions and their effects by Kunde [31]. In his study, participants were asked to press a key either briefly or for an extended period, which produced a long or short tone. Again, participants were faster and more accurate when the effect duration was compatible with the duration of the action (both short or both long) compared to incompatible pairings (short-long or long-short). These findings suggest that our motor actions are stored together with their sensory consequences in action plans. Most importantly, they show that the anticipation or expectation of an action effect can influence the action even before the effect actually occurs.

2.3 Anticipatory Action Control and Delays

A delay occurs when there is a temporal gap between the user's action and the intended effect. Delays, therefore, are temporal components of action effects. So, what happens when one repeatedly experiences that certain actions lead to delayed effects, as is often the case when interacting with interactive systems? In the study by Kunde [31] on action-effect compatibilities discussed in the previous section, an effect related to the duration of the effect was observed, independent of the compatibility effects. The participants' reaction times were generally longer when they performed actions associated with a long effect duration (a long tone) compared to actions associated with a short effect duration (a short tone). Longer effects thus led to a delay in the execution of the action, indicating that the participants anticipated the duration of the effect, which, in the case of a long anticipated duration, slowed down the execution of the action. These results were extended by Dignath and colleagues [13] to the duration of the intervals between action and effect. In one of their experiments (Experiment 3b), Dignath et al. [13] demonstrated that not only the duration of the effect but also the temporal delay between the action and the effect had a significant impact on reaction times. Participants were instructed to respond as quickly as possible to the presentation of a colored asterisk by pressing a key (left or right). Each key press was associated with an auditory effect that occurred either after a short delay (50 ms) for one key or after a long delay (2000 ms) for the other key. Participants completed five blocks of 40 trials each. The results showed that responses were initiated more slowly when the reaction was associated with a long delay of the effect compared to a short delay of the effect. This indicates that temporal delays between action and effect are integrated into the cognitive structure of the action plan and are automatically retrieved during action selection, significantly influencing the efficiency of action execution.

2.4 Summary

The study of delays in HCI has been critical in understanding how system performance impacts user experience and behavior. Delays, which refer to the temporal gap between a user's input and the system's response, have been shown to negatively affect user experience and overall performance. Previous research has largely focused on the immediate consequences of these delays, such as frustration [36, 49, 64], reduced user satisfaction [1, 34], and decreased performance, such as longer task completion times [2, 8, 11]. These studies provide valuable insights into the disruptive effects of even brief delays, particularly in contexts that require precise timing, such as video games and other time-sensitive tasks.

It is clear that delays slow down user performance because users have to wait for the system's response or must use compensatory strategies. However, it is less certain whether users also slow down their actions independently of these factors. Psychological research based on ideomotor theory [56] suggests that delayed action effects can also become embedded in users' cognitive-motor processes, leading them to anticipate these delayed effects and adjust their actions accordingly [13, 31]. This raises an open question: Do users, after repeated exposure to delays, systematically alter their behavior by slowing down their actions in anticipation of delays, even before encountering the current delayed feedback? Further research is needed to explore this potential cognitive-motor adaptation and determine the extent to which delays become embedded in users' action plans independently of direct compensatory strategies or waiting times.

Our study addresses this question by examining whether repeated exposure to system delays leads users to slow down their actions, not merely as a response to the delay itself but as a result of incorporating these delays into their cognitive action structures.

3 Method

In this section, we describe the method of our study that investigates whether delays in system response are integrated into user action plans. Specifically, we explore whether repeated exposure to delayed system feedback causes users to gradually initiate actions more slowly. To investigate this, we designed a game-like point-and-click task where participants had to shoot at targets as quickly as possible. One target disappeared immediately upon being clicked, while the other target disappeared after a short delay. This setup allowed us to measure how repeated exposure to these different system response times affected user performance, specifically whether the delay led to a gradual slowing of response times for the target with delayed disappearance.

Our task design reflects a deliberate effort to balance ecological validity with experimental control. To explore the cognitive and behavioral effects of system-induced delays in a context that mirrors real-world HCI scenarios, we drew inspiration from related studies in cognitive psychology [13, 31], which have demonstrated behavioral changes caused by delays in controlled environments. Translating their task structures into a HCI setting allowed us to explore how such effects manifest in interactive systems. The game-like nature of the point-and-click task was chosen to maintain participant engagement and motivation over a high number of trials (480 per participant), ensuring robust data collection without inducing fatigue. This approach was essential for capturing the hypothesized slowdown effect, which relies on participants repeatedly experiencing delays to form associations between their actions, input elements, and the corresponding delayed effects.

All analysis scripts and associated raw data are available via the Open Science Foundation (OSF, project link: https://osf.io/e2mc9)

3.1 Participants

We recruited 50 participants (22 self-identified as female, 27 as male, one participant did not disclose gender information and none self-identified as non-binary) from our institution and the local community who participated voluntarily or for course credits. The participants had a mean age of 23.4 years (SD = 4.1; min = 17; max = 37) and were predominantly right-handed (48 right-handed, 2 left-handed), as assessed via self-report. Most participants, 40 of 50, reported they do not play first-person shooter games at all or for a maximum of three hours per week. Four participants reported playing first-person shooter games for 3 to 5 hours per week, four reported 5 to 10 hours per week, and one reported more than 15 hours per week. Regarding their general experience with working on a computer, 29 participants indicated using their computer for more than 15 hours per week, ten participants reported 10 to 15 hours per week, two participants reported 5 to 10 hours per week, and five participants reported 3 to 5 hours per week. Four participants indicated using their computer not at all or for less than 3

Figure 1: Study setup. The images show a participant sitting in front of the study setup and playing the game-like point-and-click task. The screen in the left image shows our custom game interface. It shows the player's virtual weapon and a lateral target. At the top of the screen is a counter showing the number of targets remaining in the round and the score. The screen on the right shows the performance feedback that was presented after each round. Feedback was given on accuracy and average reaction time. Arrows indicate whether performance (accuracy and response time) was better or worse than in the previous round.

hours per week. When asked about their preferred input device, 25 participants stated they primarily use a mouse. 15 participants stated to primarily use a touch pad, and ten participants reported to use both equally. Before starting the game, all participants provided informed, written consent.

3.2 Apparatus

We developed a custom version of Aimlabs [32] with Unity3D (version 2020.3.14f1). We installed our game-like task on a stationary workstation in our laboratory (see Figure 1). The workstation (Intel i7, Nvidia GT970, 16 GB RAM) was attached to a monitor (24" FullHD @60Hz), a computer mouse (Logitech M10), and a headset. The game ran in full-screen mode. The laboratory was quiet and free of external disturbances.

To determine end-to-end latency of our setup, we used a high-speed camera (GoPro 7) recording monitor and mouse at 240 frames per second (4.167 ms/frame). We took 60 measurements during gameplay. Each measurement was manually reviewed from the recorded data. Measurement started with a mouse click to fire the virtual weapon and ended with the first visible particle effects of the shot rendered on the display. The results of our measurements show that the end-to-end latency of our setup is 13.8 frames (SD = 2.34 frames), corresponding to 57.51 ms (SD = 9.73 ms). This baseline end-to-end latency of our systems is reported separately to increase comparability with other study settings. All further delay and latency values in this paper are reported without the measured baseline end-to-end latency.

3.3 Game mechanics and game procedure

The game's goal was to shoot targets (red balls) as quickly as possible. Players were rewarded with points for successful hits, and no points for missing the target. The targets appeared in three locations: left, middle, or right. Only one target was visible at any given time. The avatar was stationary and could not be moved in the game world. The movement of the avatar's weapon was controlled by moving the mouse. Players could fire their virtual weapon by pressing the left mouse button. The trial procedure is illustrated in Figure 2. In each trial, participants had to shoot two targets, one central target and one lateral target. Every trial started with spawning a target at the middle position to ensure a central orientation of the participant's attention and the mouse cursor. After shooting the middle target, it was destroyed, and after 0.4 s, a lateral target (left or right) appeared. A distinct hit sound was generated after successfully shooting the lateral target, and the target was destroyed. If the player missed the lateral target, it disappeared without a hit sound. Each shot was accompanied by a shooting sound. In all trials, the lateral targets had a fixed size of 62 pixels (diameter) and were placed at a consistent distance of 262 pixels from the location of the central target (center to center). These constant parameters were chosen to minimize variability and ensure sufficient statistical power for detecting the hypothesized effects.

Our experimental manipulation was applied to the lateral targets. For half of the participants, the left target had a delayed effect. This means that when the lateral target appeared on the left side, the hit sound and the destruction of the target occurred with a delay of 0.6 seconds. Conversely, when the lateral target appeared on the right side, the hit sound and destruction occurred immediately after successfully shooting the target (see Figure 2). For the other half of the participants, the delay assignment was reversed. For each trial, we measured the *response time (RT)*, defined as the time from the appearance of the target to shooting the target.

The game started with a short warm-up round (ten trials) to familiarize the players with the setting and the game itself. Following the warm-up round, participants played eight rounds, each consisting of 60 trials (30 trials with a delayed effect of the lateral target and 30 trials with an immediate effect of the lateral target,

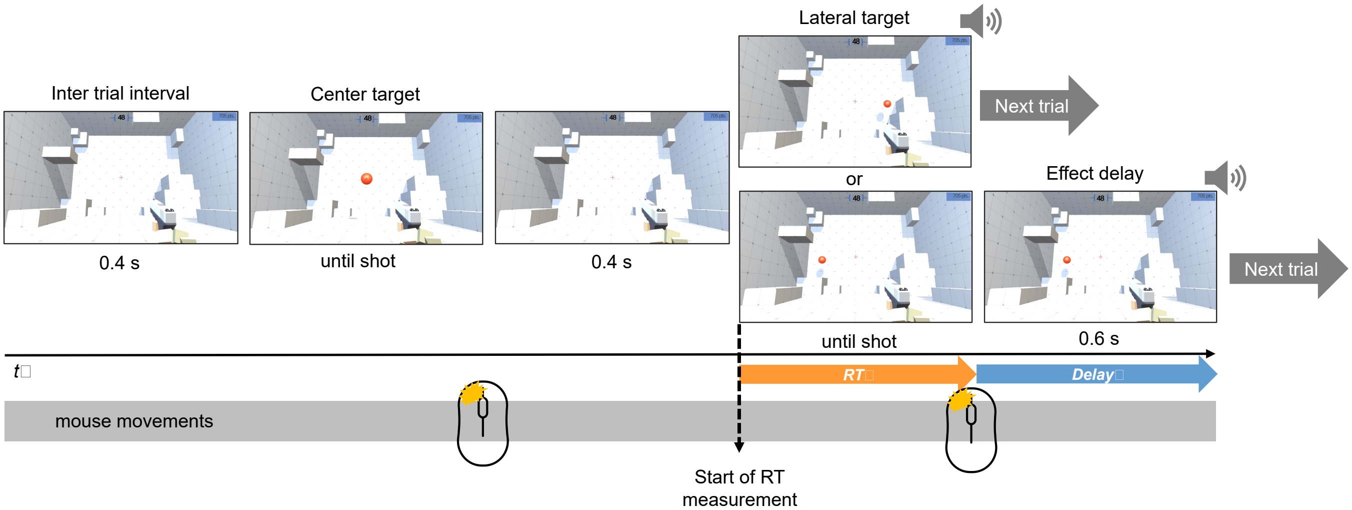

Figure 2: Experimental trial procedure of the game-like point-and-click task. In each trial, participants had to shoot two targets, the central target and one lateral target. A trial started with an inter-trial interval of 0.4 s followed by the center target. After the central target was shot, either the left or the right lateral target spawned after 0.4 s. For half of the participants, the left target had a delayed effect. This means that when the lateral target appeared on the left side, the hit sound and the destruction of the target occurred with a delay of 0.6 seconds. Conversely, when the lateral target appeared on the right side, the hit sound and destruction occurred immediately after successfully shooting the target. For the other half of the participants, the delay assignment was reversed. After the lateral target had disappeared, the next trial started. *RT* is defined as the time to successfully hit the lateral target after its appearance and is denoted by an orange arrow. The blue arrow indicates the inserted system delay.

presented in randomized order). After each round, an in-game performance overview showcasing accuracy and mean response time of the previous round was presented to the participants (see Figure 1). Furthermore, the performance overview showed how the performance changed compared to the previous round, thus, motivating participants to enhance accuracy and response time. This feedback remained for at least 30 seconds to give the participants the opportunity to briefly recover themselves and their hands. After 30 seconds, participants could start the next round by clicking on a start button. In total, each participant completed 480 experimental trials: 240 trials with a lateral target with a delayed effect and 240 trials with a lateral target with an immediate effect. For half of the participants, the target with a delayed effect was always the right target, while for the other half, the target with a delayed effect was always the left target.

3.4 Procedure

After being welcomed by the experimenter in the laboratory, participants were informed about the study procedure and gave informed consent and agreement to data collection. Participants were not informed about the exact purpose of the study (investigating integration of system delay in motor action) but were told to test a novel game. Afterward, each participant played the game. After completing the ninth round (one practice round and eight experimental rounds), the game automatically ended and a post-experience questionnaire was displayed. The questionnaire was used to collect demographic information from the participants, such as their identified gender, age, need for vision correction, employment status or course of study, information about their experience with video games, and general experience with working on a computer. Participants rated their experience with video games and computers on a scale based on hours spent per week (0-3 hours, 3-5 hours, 5-10 hours, 10-15 hours, and more than 15 hours). They also provided information about their preferred input devices. The study ended with a debriefing session in which participants were asked about the temporal pattern of the game and whether they noticed any temporal regularities. First, the experimenter asked whether the participant noticed any regularities in the game. If the participant stated that they did not notice any regularities, the participant was informed about the purpose of the study and the debriefing was finished. If, on the other hand, the participant indicated that they had noticed regularities in the game, the experimenter asked what these noticed regularities were. The experimenter then asked if the participant noticed any temporal regularities and if they could specify what these temporal regularities were. After these three additional questions, the participant was informed about the purpose of the study and the debriefing ended. The experimenter recorded all responses on a pre-printed form. The study took approximately one hour. This study was conducted in accordance with the ethics and privacy regulations of our institution and, thus, following the policies of our country and funding body. Throughout the user study, participants did not face any immediate risks or dangers. The study did not involve vulnerable groups, and no intense emotions or physical stress were induced. All participants were informed about the study's purpose and explicitly informed that they can withdraw from the voluntary participation at any time. The data of all participants were anonymized in all data sets. All authors were dedicated to the highest ethical standard and adhered to the institution's code of conduct.

3.5 Experimental Design and Hypotheses

For our investigation, we used a 4 x 2 design with Block (*1-2*, *3-4*, *5-6* and *7-8*) and Effect delay (*no delay* and *delay)* as within-subject factors. To obtain reliable mean estimates for each phase of the experiment, each Block level comprised two game rounds with a total of 120 trials (60 delay trials and 60 non-delay trials). To measure the potential effect of learned action-effect-delay associations, we assessed *RT* as the time to successfully hitting the lateral target after its appearance (orange arrow in Figure 2). If the effect delay is integrated in motor action, towards the end of the game, we should observe higher *RTs* when shooting the target with a delayed effect than when shooting the target without a delayed effect. Therefore, we address the following research question (RQ) and hypotheses (H1 and H2):

RQ: Are temporal system properties, such as the delayed disappearance of a shot target, integrated into action plans, resulting in a slowdown in player performance?

H1: Users will take longer (higher *RT*) to shoot targets that disappear with a delay compared to targets that disappear immediately (main effect of Effect Delay).

H2: The *RT* difference between shooting targets with a delayed effect and those with an immediate effect will increase as the experiment progresses (interaction between Block and Effect Delay).

3.6 Statistical Analyses

Analysis scripts and associated raw data can be found at https://osf.io/e2mc9. Data was preprocessed and analysed in R (version 4.4.2, [52]) using within-subject ANOVAs and *t*-tests. Effects with violations of sphericity were Greenhouse-Geisser-corrected and are reported with corresponding ε estimates. We used the *tidyverse* R package bundle (version 2.0.0; [61]) for preprocessing and the R package *rstatix* for statistical analyses (R package *rstatix* version 0.7.2; [28]).

We used parametric tests to analyze our data since our sample size of 50 participants ensured, according to the central limit theorem, that the sampling distribution was approximately normally distributed [5, 16] and the methods employed are known to be relatively robust to violations of the normality assumption at this sample size [40]. To minimize potential distortions caused by extreme values, we conducted an outlier analysis, excluding response times exceeding 4000 ms as well as reaction times deviating more than 3 standard deviations from the cell mean. To confirm the robustness of our results, we performed additional non-parametric analyses which supported our original parametric findings. Furthermore, analyses conducted with and without outlier removal did not differ substantially. All additional analyses are available in the OSF repository (https://osf.io/e2mc9).

4 Results

4.1 Response Times

*RT*s indicate how much time has elapsed between the appearance of the target and the shooting by the participant (see orange arrow in Figure 2). For the analysis of *RT*, we excluded the first trial of each round and trials in which participants failed to hit the lateral target (12 % of all trials). We then excluded trials with *RT*s higher than 4000 ms (0.02 % of all trials) as an extremely high *RT* may indicate that the participant was distracted. According to established outlier detection standards [6], we then excluded all trials with *RT*s that deviated more than three standard deviations from the individual condition mean (0.7 % of all trials). In sum, 86 % of all experimental trials were included for *RT* analysis.

Figure 3A shows mean *RT* values as a function of Block x Effect Delay. A 4 (Block: *1-2*, *3-4*, *5-6* and *7-8*) x 2 (Effect Delay: *delay* and *no delay*) ANOVA with repeated measures on both factors on *RT* revealed a significant main effect of Block, $F(2.02,98.89)$ = 48.3, p < .001, η_p^2 = 0.50, ε = 0.673. Not surprisingly, participants performed better in later blocks than in earlier blocks, indicating a general practice effect ($Mean_{1\text{-}2}$: 1096 ms, $Mean_{3\text{-}4}$: 997 ms, $Mean_{5\text{-}6}$: 950 ms, $Mean_{7\text{-}8}$: 944 ms; see Figure 3A). All blocks, with exception of the last two blocks, differed significantly from each other (all *p*s < .001, Block 5-6 vs. Block 7-8: p = .567). Importantly, there was a significant main effect of Effect delay, $F(1,49)$ = 18.0 p < 0.001, η_p^2 = 0.27. Participants shot slower at targets with a delayed effect, than at targets with an immediate effect (975 ms vs. 1019 ms, Figure 3A). Most importantly, there was a significant interaction effect of Block x Effect delay, $F(2.29, 112.28)$ = 5.7, p = .003, η_p^2 = 0.10, ε = 0.764. Comparisons of the two Effect Delay conditions for each Block condition separately are listed in Table 1. As hypothesized, the difference in *RT*s between trials with delay and trials without delay was greater in the last blocks than in the earlier blocks, with the lowest mean difference of 19.4 ms (*SD* = 102) in the first rounds (1-2) and the greatest difference of 81 ms (*SD* = 121 ms) in the last rounds (7-8, see Figure 3B).

4.2 Error Rate

*ER*s indicate the ratio of failed shots on the lateral targets and is specified in percent. For the analysis of *ER*, we only excluded the first trial of each round. In sum 98 % of all experimental trials were included for *ER* analysis.

Figure 3C shows mean *ER* values as a function of Block x Effect delay. A 4 (Block: *1-2*, *3-4*, *5-6* and *7-8*) x 2 (Effect Delay: *no delay* and *delay*) ANOVA with repeated measures on both factors on *ER* did not reveal any significant effects for Block, $F(2.58, 126.57)$ = 1.7, p = 0.185, η_p^2 = 0.03, ε = 0.86, Effect delay, $F(1,49)$ = 1.9 p = 0.170, η_p^2 = 0.04, or the interaction of Block x Effect delay, $F(2.46, 120.54)$ = 0.7, p = 0.524, η_p^2 = 0.01, ε = 0.82. Figure 3D shows that the ER differences between the two Effect Delay conditions converge to zero for each individual Block condition. The non-significant comparisons of the two Effect Delay conditions for each Block condition separately are listed in Table 2.

4.3 Qualitative Feedback/Debriefing

In the brief interview conducted at the end of the experiment, participants shared their impressions about potential anomalies they encountered during the game. They speculated about delays, the position and size of the targets, and the presence or absence of rhythm. Notably, 84% of participants suspected there were delays on either the left or right side, depending on the version of the game they played (i.e. version with a delayed effect for the left lateral

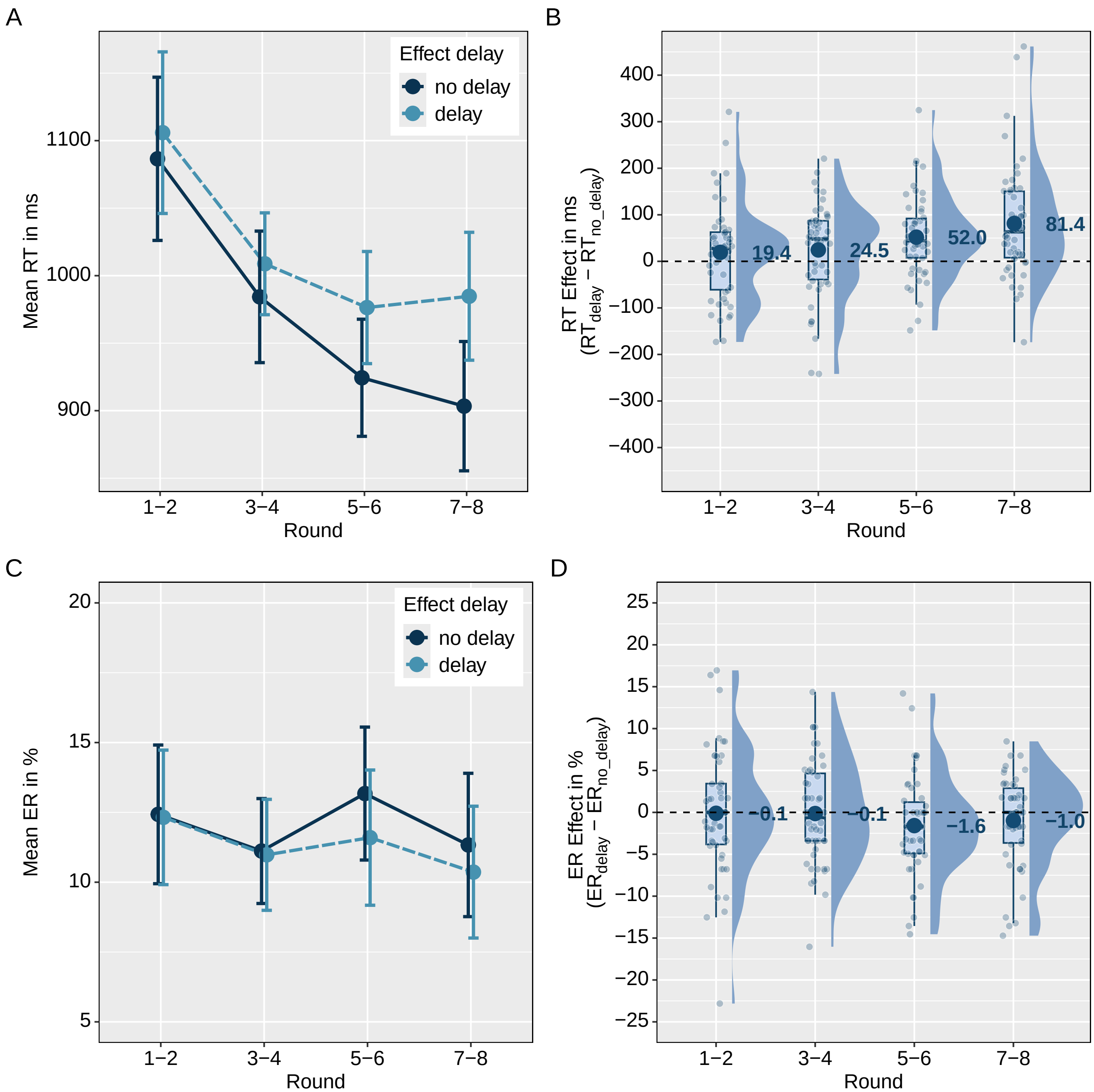

Figure 3: Results. Upper panel: (A) Mean response times (*RT*) of successful shots on a lateral target as a function of Effect delay: no delay (dark blue solid lines) vs. delay (light blue dashed lines) and Block. (B) Mean *RT* effect, calculated as the difference between mean *RT* for targets with delay and mean *RT* for targets without delay for each block. Lower panel: (C) Mean error rates (*ER*) as a function of Effect delay and Block. (D) Mean *ER* effect, calculated as the difference between mean *ER* for targets with delay and mean *ER* for targets without delay for each block. Error bars represent standard errors.

Block	No Delay		Delay		Difference	*t*(49)	*p*	*Cohen's d*
	M	*SD*	*M*	*SD*				
1-2	1087	213	1106	211	19	1.333	.756	0.188
3-4	984	171	1009	133	24	1.705	.378	0.241
5-6	924	153	976	146	52	4.136	< .001	0.585
7-8	903	169	985	167	81	4.760	< .001	0.673

Table 1: Means (*M*) and standard deviations (*SD*) of *RT*s in ms for each condition and comparisons of the two Effect Delay conditions for each Block condition separately. *p*-values are Bonferroni corrected for multiple comparisons.

Block	No Delay		Delay		Difference	*t*(49)	*p*	*Cohen's d*
	M	*SD*	*M*	*SD*				
1-2	12.4	8.7	12.3	8.47	-0.1	0.103	1.000	0.014
3-4	11.1	6.6	11.0	6.99	-0.1	0.157	1.000	0.022
5-6	13.2	8.4	11.6	8.52	-1.6	1.892	.257	0.268
7-8	11.3	9.0	10.4	8.30	-1.0	1.258	.856	0.178

Table 2: Means (*M*) and standard deviations (*SD*) of *ER*s in % for each condition and comparisons of the two Effect Delay conditions for each Block condition separately. *p*-values are Bonferroni corrected for multiple comparisons.

target or version with a delayed effect for the right lateral target). However, in some cases, participants identified the delays either late or incorrectly. Additionally, 16% of participants did not mention any delays at all. Some participants felt that the delays might have affected their performance, with a few expressing uncertainty about whether they had successfully hit the target, which led them to fire multiple shots. This created a sense of unease for some. Furthermore, 10% of participants believed there was a rhythmic pattern in the appearance of the targets or that one side appeared more frequently.

5 Discussion

In this study, we investigated whether delays in system responses are integrated into users' cognitive-motor processes and contribute to a slowing of user actions. Specifically, we examined whether the repeated experience of delayed system responses causes users to initiate their actions more slowly over time. In our study, participants performed an aim trainer task in which targets were shot, and either disappeared immediately or with a delay (after 0.6 seconds). The results of our study provide compelling evidence that delays in system responses are integrated into users' cognitive-motor action plans. Specifically, participants showed a significant slowing down of their response times when shooting at targets that disappeared with a delay compared to shooting at those that disappeared immediately (confirming H1). This effect became more pronounced as the experiment progressed, with the slowdown reaching 80 ms by the end of the experimental game (confirming H2).

The results of our study provide important insights into how delays affect user behavior. In the following sections, we discuss the meaning and underlying cognitive mechanisms of our findings, as well as the implications for designing more efficient interactive systems that take into account users' adaptations to temporal system properties.

5.1 Integration of System Delays into Users' Cognitive Action Structures

The results of the present study show that system delays are not only disruptive due to the waiting time they cause, but are also integrated into users' cognitive action structures, leading to longer-term behavioral adjustments. Actions associated with a delayed system response were executed more slowly than those associated with an immediate response. Thus, we demonstrate that the repeated experience of delayed system responses leads to slowed down user behavior and, consequently, an increase in task completion time, even before the delay in the current interaction occurs.

Our findings extend previous results from cognitive psychology to the context of HCI. Results from simple stimulus-response experiments have suggested that temporal properties of action effects can influence the actions that trigger them. A study by Kunde [31] showed that actions producing longer effect durations are initiated more slowly than those producing shorter effect durations. Even more relevant to our study are the results of Dignath et al. [13], which demonstrated that delays in action effects can also induce a slowdown. However, our study shows that these findings are not limited to reduced stimulus-response paradigms but are also applicable to real-world HCI scenarios. Whereas previous studies employed simple stimulus-response tasks, we demonstrated this slowing effect in an applied, time-sensitive HCI scenario: a game-like task in which participants were motivated to shoot targets as quickly as possible. Furthermore, while Dignath et al.[13] examined delays of two seconds, which are typical for processes such as web page loading or data transmission, our results show that even shorter delays of 0.6 seconds can lead to a significant slowing of user responses.

The delay-induced slowing effect demonstrated in our study can be explained by the ideomotor theory [26, 56]. The basis of goal-directed action control lies in the close associations between actions and their effects in our memory. When an action (navigating and clicking on a target) consistently produces a particular effect (target disappears), the association between the specific action and the effect is strengthened. As a result, anticipating the desired effect (target disappearing) automatically activates the associated action (navigating and clicking on the target). As proposed by Dignath and colleagues [13], temporal information such as a delay between an action and its effect also becomes part of such action-effect associations in users' memories. This means that when a participant anticipated the disappearance of the target, they also anticipated the previously experienced delay of this disappearance. Because anticipating a longer time interval requires more time than anticipating a short time interval [13, 31], actions associated with longer effect delays were initiated more slowly than those with no delays.

Overall, our findings underscore the importance of considering not only the immediate, observable impacts of system delays, but also how users in HCI environments implicitly adapt their behavior in anticipation of these delays. This highlights the fact that users integrate the temporal properties of system responses into their cognitive-motor processes, leading to a systematic slowdown in their interactions. Reducing delays is crucial, even if delays were not integrated into action plans, since there are obvious negative effects on UX and performance. However, with our work, we could argue that it is even more important than previously thought because delays are integrated in the users' cognitive models of the interaction.

5.2 Implications

The results of our study have implications for the design of interactive systems. Designers should be aware that delays can lead to systematic behavioral adjustments in users. Repeated delays are anticipated by users and integrated into their cognitive action structures, resulting in a measurable decrease in efficiency.

The most obvious implication is to minimize delays as much as possible to ensure optimal performance, particularly for time-sensitive tasks. This is especially crucial in the gaming domain, where fast user actions often play a decisive role. The repeated experience of system delays not only leads to immediate negative effects such as frustration and inefficient target acquisition but, according to the results of our study, also causes a slowing of player actions. This is particularly relevant for competitive games, where quick reactions can be the key to success. Game designers and developers should therefore prioritize reducing latency, for example by applying latency compensation techniques [38], to prevent players from experiencing long-term performance degradation due to repeated delays. Moreover, minimizing system delays is equally important in workplace settings, especially for technology-driven tasks. Companies should invest in high-performance, responsive systems and hardware to ensure efficient operation of digital tools and IT infrastructures. Delays in system responses can not only frustrate employees but, as the results of our study suggests, gradually lead to cognitive slowdowns in work performance, further compounding the delays caused by the system itself.

If delays are unavoidable due to system limitations, already established principles for avoiding user frustration could prevent the slowdown effect. In the case of unavoidable delays, it is recommended to provide users with immediate visual or auditory feedback that their actions have at least been successfully registered, for example in the form of wait cursors or progress bars [44]. While it remains to be investigated whether such feedback can actually prevent or reduce the slowing effect demonstrated in our study, it seems plausible from a cognitive-psychological perspective. Even if the system takes longer to display the intended effect, users still receive immediate feedback on their action. This may lead them to perceive the action itself as more complete, potentially weakening the association with the subsequent delay.

Our results might explain seemingly contradictory results for the effects of delay variations. Halbhuber et al. found that changes in system response delay [21] affect subjective feedback and performance. Schmid et al. [54], however, found no effects for rapid changes in system response delays. In the study by Halbhuber et al., participants had time to integrate the system response delay into their action plan, consequently resulting in slower RTs. Rapid changes in system response delays, however, prevented the integration of the delay into users' action plans resulting in no observable effects. Altogether the results might suggest that constantly varying system response delays improves performance and subjective perception compared to longer-term switches of constant amounts of delay.

Since our study suggests that users anticipate delays and integrate them into their action planning, developers and designers could strategically design mechanisms to take advantage of this anticipatory behavior. For example, they could deliberately associate certain waiting times with certain system effects, resulting in a more predictable and smoother interaction experience. This approach has already been explored in studies on time-based expectancy [59, 60]. In this framework, the duration of the delay provides the user with information about what to expect next. For instance, if a shorter delay consistently leads to one system effect and a longer delay to another, users can predict these effects based on the elapsed time and adjust their reactions accordingly. A recent study applied the concept of time-based expectancy to the gaming context [22]. In this study, delay-event associations were used to make target locations more predictable. The results showed that associating different delays with specific target locations improved player performance due to anticipatory mechanisms.

Moreover, our study highlights the applicability of psychological concepts such as ideomotor theory in the HCI context. Our findings were predicted and validated on the basis of ideomotor theory. We have demonstrated that properties of computers and computerized devices can become part of cognitive action structures, thereby influencing user behavior. Our study highlights that HCI researchers may benefit from engaging with the psychological foundations of perception and action control when designing and evaluating new interaction technologies [29]. There are already approaches to applying ideomotor principles in human-robot interaction [18] and in game design [7]). In cognitive psychology, there are further HCI-relevant concepts that examine the interaction between action and perception [17, 24], as well as the role of temporal factors in this relationship [3, 4]. Enhancing the bidirectional exchange between applied HCI research on user behavior and cognitive psychology could generate valuable synergies for the development of more intuitive, efficient, and user-centered interaction technologies.

5.3 Limitations and Future Work

While our study provides valuable insights into the integration of system delays into users' cognitive action plans, several questions remain unanswered, suggesting opportunities for future research.

An open question arising from our study is which specific component of the point-and-click-task is affected by the observed slowdown effect. The response time measure in our study encompasses several phases, including the recognition of the target's location, the planning phase before action initiation, the movement of the mouse cursor, and the execution of the click. While our study demonstrates the overall impact of anticipated delays on task completion times, isolating these individual phases would provide deeper insights into the specific mechanisms underlying the observed effects and would facilitate the integration of our findings into models of user interaction with system delays [10, 33, 39]. We hypothesize that the slowdown primarily occurs during the action planning phase, prior to the initiation of movement. This assumption is supported by previous studies, which showed that keypresses were initiated later when triggering effects with longer durations [31] or delayed effects [13]. Analogously, we propose that in our study, the observed slowdown may predominantly affect the initiation of actions. However, it cannot be excluded that the execution phase, including cursor movement and click time, may also be affected. While the results of the present study already have general implications for the design of interactive systems, future studies could aim to investigate the slowdown effect in experimental settings that allow for a more targeted analysis of the individual components of response time. Such studies could use analyses of mouse movements or standardized tasks like Fitts' Law tasks [41] to systematically investigate recognition, planning and execution dynamics to provide further clarity on how specific components contribute to the slowdown effect.

One aspect of our study design to consider is the absence of a time limit for responses or a time-based reward system. This may have encouraged participants to prioritize accuracy over speed, potentially influencing the observed results. While we interpret our findings in light of ideomotor theory—suggesting that system delays are integrated into users' cognitive-motor processes and subsequently lead to slower responses when shooting at targets with delayed effects — it could be argued that the observed slowdown effect is, at least in part, due to a speed-accuracy trade-off. Indeed, the descriptive data (see Figure 3) indicate slightly lower error rates for targets with delayed effects in blocks 5-6 (difference: 1.6%) and blocks 7-8 (difference: 1.0%). This pattern may reflect a potential adaptation strategy by participants: they may have slowed down their responses to improve accuracy, with this trade-off being more pronounced for targets with delayed feedback. A possible explanation for why this effect only occurred for delayed targets could be an increased uncertainty associated with their delayed disappearance, leading participants to adopt a more cautious and precise approach. However, error rates for targets with delayed feedback do not show a statistically significant difference compared to targets with immediate feedback (see Table 2). Furthermore, a comparison of the unstandardized and standardized effect sizes for differences in response times and error rates (see Table 1 and Table 2) shows that the estimated effect sizes for error rates are substantially smaller than those for response times. This suggests that a speed-accuracy trade-off cannot fully explain the slowdown effect. In addition, the performance feedback (see Figure 1) prominently displayed detailed information on both accuracy and response time, along with clear indications of improvement or deterioration in each metric. This dual focus was designed to reinforce the importance of both aspects equally, ensuring that participants were consistently motivated to balance speed and accuracy throughout the task. Nevertheless, this alternative explanation should be investigated or controlled more closely in future research. This could involve tasks with stricter time constraints, time-based reward structures, easier tasks or standardized tasks with measures independent of speed-accuracy trade-offs [42].

Another limitation of our study is that the effect of delay integration was observed over a relatively short number of interactions (240 interactions with delay and 240 interactions without a delay). It is unclear how this effect would evolve over longer periods. Would the difference between response times for targets with delay and targets without delay continue to grow, or would it reach an asymptote? If an asymptote is reached, how would this be related to the magnitude of the delay? Investigating these dynamics could reveal whether the behavioral adaptation to delays has limits or stabilizes over time.

In our study, we used a mixture of delay conditions (0 and 0.6 seconds) within the same experimental setup, allowing us to demonstrate the impact of input-element-specific delays (e.g., when the process triggered by one input element takes longer than the process triggered by another input element). However, delays often do not affect individual input elements alone; instead, delays within a given environment tend to be consistent with low variability around a fixed latency. Future studies should examine if users may adapt to a generally slow system by slowing their overall pace of interaction. Relatedly it would be interesting to examine how this adaptation influences their behavior when transitioning to a more responsive system. This aligns with the work of Olguin Munoz et al. [45], who demonstrated that users adapt to system delays in the context of wearable cognitive assistance systems. They found that even after the delays were removed, users continued to exhibit slower interactions. This suggests that prolonged exposure to system delays can lead to lasting changes in user behavior, which may persist even when the system becomes more responsive. Building on these insights, future studies could explore how extended exposure to delays across different systems or interfaces impacts user behavior when transitioning between environments with varying levels of responsiveness.

Other aspects of our task design, while contributing to the clarity of our findings, highlight opportunities for future research to extend their applicability. One such aspect to consider is the magnitude of the delays used in our study. We employed delays of 0.6 s, which allowed us to clearly observe the effects of delay integration on user behavior. In gaming contexts, for example, shorter delays have also been shown to be relevant and can lead to performance declines. While our study provides valuable insights into how delays influence user actions, future research should investigate whether slowdown effects can be observed across a wider range of latencies to further clarify the generalizability of our findings. Another aspect to reflect on is the 0.4-second interval between the disappearance of the central target and the appearance of the lateral target. This interval was implemented to allow participants to refocus their attention across the entire screen and ensure readiness for the task. However, this interval may have allowed for potential anticipatory cursor movements prior to the target's appearance. Such anticipatory behavior could have contributed to increased variability in user behavior, potentially reducing the statistical power of our study. Nevertheless, because the identity of the lateral target (with delayed effect or with immediate effect) was randomized and therefore unpredictable, any anticipatory movements would not constitute a confounding factor. Still, to better control for such anticipatory behavior, future studies could record cursor trajectories or at least the mouse cursor position at the moment of target appearance. Furthermore, our study employed a fixed target size and distance across all trials. This decision ensured consistency and sufficient statistical power to detect the hypothesized slowdown effect and was aligned with our goal of isolating the impact of effect delays on user behavior in a controlled experimental HCI setting. However, this simplification may limit the applicability of the findings to real-world HCI scenarios, where distances and target sizes are often variable. Incorporating such variations in future experiments could extend the scope of these results and provide deeper insights into whether the observed slowdown effects generalize to more complex and dynamic interaction settings.

Finally, the game-like nature of our task (shooting targets in an aim trainer) might also limit the generalizability of our findings to other HCI contexts. This task was chosen because we expected participants to be more motivated compared to performing more repetitive everyday GUI tasks (such as clicking the print button), allowing us to conduct a larger number of trials (480 trials). Additionally, we used this task to ensure that the anticipated effect would manifest in a scenario where users are motivated to act as quickly and accurately as possible. However, it would be important to examine whether similar slowdown effects occur in more diverse and practical scenarios, such as office tasks or real-time collaborative environments. To build on these findings and extend their applicability to a broader range of interactions, future work could involve developing a classification system for different types of interactions and sequences of interactions where this phenomenon is likely to be observed. Such a classification could help identify which specific tasks, systems, or environments are more susceptible to the integration of delays into users' cognitive-motor processes, providing a more targeted approach to mitigating the negative effects of system delays in various HCI contexts.

6 Conclusion

In this paper, we examined the effects of repeated exposure to system delays during point-and-click tasks. We found that delays lead to longer task completion times not only due to waiting periods but also because of a delay-induced slowdown in user actions. Our results show that participants became progressively slower when performing actions associated with delayed system responses compared to actions with immediate feedback. This suggests that repeated exposure to delays causes these delays to become integrated into users' cognitive action structures, leading to measurable behavioral changes.

An important insight from our findings is that system properties—such as delays—are not just temporary obstacles but can become embedded in users' cognitive planning processes. Whether delays, visual feedback, or other system behaviors, these characteristics can influence how users anticipate and execute actions, resulting in behavioral adaptations that may persist over time. Designers need to be aware that consistent system properties can shape user behavior over time, potentially leading to long-term adaptations. Therefore, it is crucial to design interfaces that mitigate such unintended behavioral consequences and support more intuitive and efficient user interactions.

References

[1] Rahul Amin, France Jackson, Juan E. Gilbert, Jim Martin, and Terry Shaw. 2013. Assessing the Impact of Latency and Jitter on the Perceived Quality of Call of Duty Modern Warfare 2. In *Human-Computer Interaction. Users and Contexts of Use*, Masaaki Kurosu (Ed.). Springer Berlin Heidelberg, Berlin, Heidelberg, 97–106. doi:10.1007/978-3-642-39265-8_11

[2] Tom Beigbeder, Rory Coughlan, Corey Lusher, John Plunkett, Emmanuel Agu, and Mark Claypool. 2004. The Effects of Loss and Latency on User Performance in Unreal Tournament 2003 r. In *Proceedings of 3rd ACM SIGCOMM Workshop on Network and System Support for Games* (Portland, Oregon, USA) *(NetGames '04)*. Association for Computing Machinery, New York, NY, USA, 144–151. doi:10.1145/1016540.1016556

[3] Johanna Bogon, Katrin Köllnberger, Roland Thomaschke, and Roland Pfister. 2023. Binding and Retrieval of Temporal Action Features: Probing the Precision Level of Feature Representations in Action Planning. *Journal of Experimental Psychology: Human Perception and Performance* 49, 7 (July 2023), 989–998. doi:10.1037/xhp0001136

[4] Johanna Bogon, Roland Thomaschke, and Gesine Dreisbach. 2017. Binding Time: Evidence for Integration of Temporal Stimulus Features. *Attention, Perception, & Psychophysics* 79 (2017), 1290–1296. doi:10.3758/s13414-017-1330-9

[5] Jürgen Bortz and Christof Schuster. 2010. *Statistik Für Human-und Sozialwissenschaftler [Statistics for human and social scientists]*. Springer-Verlag, Gießen. doi:10.1007/978-3-642-12770-0

[6] Lauren K. Bush, Ursula Hess, and George Wolford. 1993. Transformations for within-subject designs: a Monte Carlo investigation. *Psychological Bulletin* 113, 3 (1993), 566. doi:10.1037/0033-2909.113.3.566

[7] Sanjay Chandrasekharan, Alexandra Mazalek, Michael Nitsche, Yanfeng Chen, and Apara Ranjan. 2010. Ideomotor Design: Using Common Coding Theory to Derive Novel Video Game Interactions. *Pragmatics & Cognition* 18, 2 (Aug. 2010), 313–339. doi:10.1075/pc.18.2.04cha

[8] Mark Claypool and Kajal Claypool. 2006. Latency and Player Actions in Online Games. *Commun. ACM* 49, 11 (2006), 40–45. doi:10.1145/1167838.1167860

[9] Mark Claypool, Andy Cockburn, and Carl Gutwin. 2020. The Impact of Motion and Delay on Selecting Game Targets with a Mouse. *ACM Transactions on Multimedia Computing, Communications, and Applications* 16, 2s (April 2020), 1–24. doi:10.1145/3390464

[10] Mark Claypool, Ragnhild Eg, and Kjetil Raaen. 2017. Modeling User Performance for Moving Target Selection with a Delayed Mouse. In *International Conference on Multimedia Modeling*. Springer, Cham, 226–237. doi:10.1007/978-3-319-51811-4_19

[11] Mark Claypool and David Finkel. 2014. The Effects of Latency on Player Performance in Cloud-Based Games. In *2014 13th Annual Workshop on Network and Systems Support for Games*. IEEE, Nagoya, Japan, 1–6. doi:10.1109/NetGames.2014.7008964

[12] Jonathan Deber, Ricardo Jota, Clifton Forlines, and Daniel Wigdor. 2015. How Much Faster Is Fast Enough? User Perception of Latency & Latency Improvements in Direct and Indirect Touch. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. Association for Computing Machinery, New York, NY, USA, 1827–1836. doi:10.1145/2702123.2702300

[13] David Dignath, Roland Pfister, Andreas B. Eder, Andrea Kiesel, and Wilfried Kunde. 2014. Representing the Hyphen in Action-Effect Associations: Automatic Acquisition and Bidirectional Retrieval of Action-Effect Intervals. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 40, 6 (Nov. 2014), 1701–12. doi:10.1037/xlm0000022

[14] Ulrich C. Drost, Martina Rieger, Marcel Brass, Thomas C. Gunter, and Wolfgang Prinz. 2005. When Hearing Turns into Playing: Movement Induction by Auditory Stimuli in Pianists. *The Quarterly Journal of Experimental Psychology Section A* 58, 8 (Nov. 2005), 1376–1389. doi:10.1080/02724980443000610

[15] Birgit Elsner and Bernhard Hommel. 2001. Effect Anticipation and Action Control. *Journal of Experimental Psychology: Human Perception and Performance* 27, 1 (2001), 229–240. doi:10.1037/0096-1523.27.1.229

[16] Andy Field. 2018. *Discovering Statistics Using IBM SPSS Statistics*. Sage Publications Limited, London.

[17] Christian Frings, Bernhard Hommel, Iring Koch, Klaus Rothermund, David Dignath, Carina Giesen, Andrea Kiesel, Wilfried Kunde, Susanne Mayr, Birte Moeller, Malte Möller, Roland Pfister, and Andrea Philipp. 2020. Binding and Retrieval in Action Control (BRAC). *Trends in Cognitive Sciences* 5, 24 (2020), 375–387. doi:10.1016/j.tics.2020.02.004

[18] Lena Guinot. 2022. Ideomotor Principle as a Human-Robot Communication Method during Collaborative Work. In *CHI Conference on Human Factors in Computing Systems Extended Abstracts*. Association for Computing Machinery, New Orleans LA USA, 1–4. doi:10.1145/3491101.3516812

[19] David Halbhuber, Niels Henze, and Valentin Schwind. 2021. Increasing Player Performance and Game Experience in High Latency Systems. *Proceedings of the ACM on Human-Computer Interaction* 5, CHI PLAY (2021), 1–20. doi:10.1145/3474710

[20] David Halbhuber, Maximilian Schlenczek, Johanna Bogon, and Niels Henze. 2022. Better Be Quiet about It! The Effects of Phantom Latency on Experienced First-Person Shooter Players. In *Proceedings of the 21st International Conference on Mobile and Ubiquitous Multimedia* (Lisbon, Portugal) *(MUM '22)*. Association for Computing Machinery, New York, NY, USA, 172–181. doi:10.1145/3568444.3568448

[21] David Halbhuber, Valentin Schwind, and Niels Henze. 2022. Don't Break my Flow: Effects of Switching Latency in Shooting Video Games. *Proceedings of the ACM on Human-Computer Interaction* 6, CHI PLAY (Oct. 2022), 229:1–229:20. doi:10.1145/3549492

[22] David Halbhuber, Roland Thomaschke, Niels Henze, Christian Wolff, Kilian Probst, and Johanna Bogon. 2023. Play with My Expectations: Players Implicitly Anticipate Game Events Based on In-Game Time-Event Correlations. In *Proceedings of the 22nd International Conference on Mobile and Ubiquitous Multimedia*. Association for Computing Machinery, Vienna Austria, 386–397. doi:10.1145/3626705.3627970

[23] Emil Harleß. 1861. Der Apparat des Willens [The Apparatus of Will]. *Zeitschrift für Philosophie und philosophische Kritik* 38, 2 (1861), 50–73.

[24] Bernhard Hommel. 2004. Event Files: Feature Binding in and across Perception and Action. *Trends in Cognitive Sciences* 8, 11 (Nov. 2004), 494–500. doi:10.1016/j.tics.2004.08.007

[25] Bernhard Hommel, Jochen Müsseler, Gisa Aschersleben, and Wolfgang Prinz. 2001. The Theory of Event Coding (TEC): A Framework for Perception and Action Planning. *Behavioral and Brain Sciences* 24, 5 (2001), 849–78; discussion 878–937. doi:10.1017/S0140525X01000103

[26] William James. 1890. *The Principles of Psychology*. Henry Holt and Company, NY, US. vi, 704 pages. doi:10.1037/11059-000

[27] Ricardo Jota, Albert Ng, Paul Dietz, and Daniel Wigdor. 2013. How Fast Is Fast Enough? A Study of the Effects of Latency in Direct-Touch Pointing Tasks. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13)*. Association for Computing Machinery, New York, NY, USA, 2291–2300. doi:10.1145/2470654.2481317

[28] Alboukadel Kassambara. 2023. *rstatix: Pipe-friendly Framework for Basic Statistical Tests.* https://CRAN.R-project.org/package=rstatix R package version 0.7.2.

[29] Roberta L. Klatzky and Mahadev Satyanarayanan. 2023. Psychological Science Meets Wearable Cognitive Assistance. *Current Directions in Psychological Science* 32, 6 (Dec. 2023), 446–453. doi:10.1177/09637214231187912

[30] Wilfried Kunde. 2001. Response-Effect Compatibility in Manual Choice Reaction Tasks. *Journal of Experimental Psychology: Human Perception and Performance* 27, 2 (April 2001), 387–394. doi:10.1037//0096-1523.27.2.387

[31] Wilfried Kunde. 2003. Temporal Response-Effect Compatibility. *Psychological Research* 67 (2003), 153–159. doi:10.1007/s00426-002-0114-5

[32] State Space Lans. 2024. Aimlabs. https://store.steampowered.com/app/714010/Aimlabs/.

[33] Shengmei Liu and Mark Claypool. 2021. Game Input with Delay – A Model of the Time Distribution for Selecting a Moving Target with a Mouse. In *MultiMedia Modeling*, Jakub Lokoč, Tomáš Skopal, Klaus Schoeffmann, Vasileios Mezaris, Xirong Li, Stefanos Vrochidis, and Ioannis Patras (Eds.). Lecture Notes in Computer Science, Vol. 12572. Springer International Publishing, Cham, 506–518. doi:10.1007/978-3-030-67832-6_41

[34] Shengmei Liu and Mark Claypool. 2023. The Impact of Latency on Target Selection in First-Person Shooter Games. In *Proceedings of the 14th ACM Multimedia Systems Conference*. Association for Computing Machinery, Vancouver BC Canada, 51–61. doi:10.1145/3587819.3590977

[35] Shengmei Liu, Mark Claypool, Atsuo Kuwahara, James Scovell, and Jamie Sherman. 2021. The Effects of Network Latency on Competitive First-Person Shooter Game Players. In *2021 13th International Conference on Quality of Multimedia Experience (QoMEX)*. IEEE, Montreal, QC, Canada, 151–156. doi:10.1109/QoMEX51781.2021.9465419

[36] Shengmei Liu, Mark Claypool, Atsuo Kuwahara, Jamie Sherman, and James J Scovell. 2021. Lower Is Better? The Effects of Local Latencies on Competitive First-Person Shooter Game Players. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, Yokohama Japan, 1–12. doi:10.1145/3411764.3445245

[37] Shengmei Liu, Eren Eroglu, Miles Gregg, Federico Galbiati, Atsuo Kuwahara, James Scovell, and Mark Claypool. 2024. Waiting to Play - Measuring Game Load Times and Their Effects on Player Quality of Experience. In *Proceedings of the 19th International Conference on the Foundations of Digital Games*. Association for Computing Machinery, Worcester MA USA, 1–11. doi:10.1145/3649921.3649937

[38] Shengmei Liu, Xiaokun Xu, and Mark Claypool. 2022. A Survey and Taxonomy of Latency Compensation Techniques for Network Computer Games. *Comput. Surveys* 54, 11s (Sept. 2022), 1–34. doi:10.1145/3519023

[39] Michael Long and Carl Gutwin. 2018. Characterizing and Modeling the Effects of Local Latency on Game Performance and Experience. In *Proceedings of the 2018 Annual Symposium on Computer-Human Interaction in Play*. Association for Computing Machinery, Melbourne VIC Australia, 285–297. doi:10.1145/3242671.3242678

[40] Thomas Lumley, Paula Diehr, Scott Emerson, and Lu Chen. 2002. The Importance of the Normality Assumption in Large Public Health Data Sets. *Annual Review of Public Health* 23, 1 (May 2002), 151–169. doi:10.1146/annurev.publhealth.23.100901.140546

[41] I. Scott MacKenzie. 1992. Fitts' Law as a Research and Design Tool in Human-Computer Interaction. *Human–Computer Interaction* 7, 1 (March 1992), 91–139. doi:10.1207/s15327051hci0701_3

[42] I. Scott MacKenzie and Poika Isokoski. 2008. Fitts' Throughput and the Speed-Accuracy Tradeoff. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Florence, Italy) *(CHI '08)*. Association for Computing Machinery, New York, NY, USA, 1633–1636. doi:10.1145/1357054.1357308

[43] M. Meehan, S. Razzaque, M.C. Whitton, and F.P. Brooks. 2003. Effect of Latency on Presence in Stressful Virtual Environments. In *Proceedings of the IEEE Virtual Reality 2003*. IEEE Computer Society, Los Angeles, CA, USA, 141–148. doi:10.1109/VR.2003.1191132

[44] Rolf Molich and Jakob Nielsen. 1990. Improving a human-computer dialogue. *Commun. ACM* 33, 3 (1990), 338–348. doi:10.1145/77481.77486

[45] Manuel Olguin Munoz, Roberta Klatzky, Junjue Wang, Padmanabhan Pillai, Mahadev Satyanarayanan, and James Gross. 2021. Impact of Delayed Response on Wearable Cognitive Assistance. *PLoS ONE* 16, 3 (2021), e0248690. doi:10.1371/journal.pone.0248690

[46] Yik Hang Pang, Errol R Hoffmann, and Ravindra S Goonetilleke. 2019. Effects of gain and index of difficulty on mouse movement time and fitts' law. *IEEE Transactions on Human-Machine Systems* 49, 6 (2019), 684–691. doi:10.1109/THMS.2019.2931743

[47] Andriy Pavlovych and Carl Gutwin. 2012. Assessing Target Acquisition and Tracking Performance for Complex Moving Targets in the Presence of Latency and Jitter. In *Proceedings of Graphics Interface 2012 (GI '12)*. Canadian Information Processing Society, CAN, 109–116.

[48] Andriy Pavlovych and Wolfgang Stuerzlinger. 2011. Target Following Performance in the Presence of Latency, Jitter, and Signal Dropouts. In *Proceedings of Graphics Interface 2011* (St. John's, Newfoundland, Canada) *(GI '11)*. Canadian Human-Computer Communications Society, Waterloo, CAN, 33–40.

[49] Hannah Pelikan and Emily Hofstetter. 2023. Managing Delays in Human-Robot Interaction. *ACM Transactions on Computer-Human Interaction* 30, 4 (Sept. 2023), 1–42. doi:10.1145/3569890

[50] Roland Pfister and Markus Janczyk. 2012. Harleß' Apparatus of Will: 150 Years Later. *Psychological Research* 76, 5 (Sept. 2012), 561–565. doi:10.1007/s00426-011-0362-3

[51] Wolfgang Prinz. 1990. A Common Coding Approach to Perception and Action. In *Relationships Between Perception and Action: Current Approaches*, Odmar Neumann and Wolfgang Prinz (Eds.). Springer Berlin Heidelberg, Berlin, Heidelberg, 167–201. doi:10.1007/978-3-642-75348-0_7

[52] R Core Team. 2024. *R: A Language and Environment for Statistical Computing (version 4.4.0)*. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

[53] Martina Rieger. 2007. Letters as Visual Action-Effects in Skilled Typing. *Acta Psychologica* 126, 2 (Oct. 2007), 138–153. doi:10.1016/j.actpsy.2006.11.006

[54] Andreas Schmid, David Halbhuber, Thomas Fischer, Raphael Wimmer, and Niels Henze. 2023. Small Latency Variations Do Not Affect Player Performance in First-Person Shooters. *Proceedings of the ACM Human-Computer Interaction* 7, CHI PLAY, Article 381 (oct 2023), 20 pages. doi:10.1145/3611027

[55] Valentin Schwind, David Halbhuber, Jakob Fehle, Jonathan Sasse, Andreas Pfaffelhuber, Christoph Tögel, Julian Dietz, and Niels Henze. 2020. The Effects of Full-Body Avatar Movement Predictions in Virtual Reality Using Neural Networks. In *26th ACM Symposium on Virtual Reality Software and Technology*. Association for Computing Machinery, Virtual Event Canada, 1–11. doi:10.1145/3385956.3418941

[56] Yun Kyoung Shin, Robert W. Proctor, and E. J. Capaldi. 2010. A Review of Contemporary Ideomotor Theory. *Psychological Bulletin* 136, 6 (2010), 943–974. doi:10.1037/a0020541

[57] Ben Shneiderman. 1984. Response Time and Display Rate in Human Performance with Computers. *Comput. Surveys* 16, 3 (Sept. 1984), 265–285. doi:10.1145/2514.2517

[58] Robert J. Teather, Andriy Pavlovych, Wolfgang Stuerzlinger, and I. Scott MacKenzie. 2009. Effects of Tracking Technology, Latency, and Spatial Jitter on Object Movement. In *2009 IEEE Symposium on 3D User Interfaces*. IEEE, Lafayette, LA, USA, 43–50. doi:10.1109/3DUI.2009.4811204

[59] Roland Thomaschke, Johanna Bogon, and Gesine Dreisbach. 2018. Timing Affect: Dimension-specific Time-Based Expectancy for Affect. *Emotion* 18 (2018), 646–669. doi:10.1037/emo0000380

[60] Roland Thomaschke and Carola Haering. 2014. Predictivity of System Delays Shortens Human Response Time. *International Journal of Human-Computer Studies* 72, 3 (2014), 358–365. doi:10.1016/j.ijhcs.2013.12.004

[61] Hadley Wickham, Mara Averick, Jennifer Bryan, Winston Chang, Lucy D'Agostino McGowan, Romain François, Garrett Grolemund, Alex Hayes, Lionel Henry, Jim Hester, Max Kuhn, Thomas Lin Pedersen, Evan Miller, Stephan Milton Bache, Kirill Müller, Jeroen Ooms, David Robinson, Dana Paige Seidel, Vitalie Spinu, Kohske Takahashi, Davis Vaughan, Claus Wilke, Kara Woo, and Hiroaki Yutani. 2019. Welcome to the tidyverse. *Journal of Open Source Software* 4, 43 (2019), 1686. doi:10.21105/joss.01686

[62] Shota Yamanaka. 2020. Evaluating temporal delays and spatial gaps in overshoot-avoiding mouse-pointing operations. In *Proceedings of Graphics Interface 2020* (University of Toronto) *(GI 2020)*. Canadian Human-Computer Communications Society, 440 – 451. doi:10.20380/GI2020.44

[63] Shota Yamanaka and Wolfgang Stuerzlinger. 2024. The Effect of Latency on Movement Time in Path-steering. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, Honolulu HI USA, 1–19. doi:10.1145/3613904.3642316

[64] Euijung Yang and Michael Dorneich. 2015. The Effect of Time Delay on Emotion, Arousal, and Satisfaction in Human-Robot Interaction. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 59 (Sept. 2015), 443–447. doi:10.1177/1541931215591094