Data Transmission Latency and Sense of Control

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Abstract. Latency has been identified as a major bottleneck for usability of human-system interaction devices. However, the theoretical basis of the effect of latency on action control mechanisms remains weak. In this study, we aimed to investigate the cognitive implications of latency for Human-Computer Interaction. We proposed models of agency (i.e., mechanism underlying the feeling of control) as a possible interpretative framework on the nature of the transformation induced by latency. In a series of 3 experiments, we propose to tackle this problem by (1) characterizing the effects (performance and agency) of transmission delays on UAS camera control, and (2) designing and evaluating HMI solutions to mitigate these effects with regard to the agency principle. Our results showed that (1) latency decreases sense of agency and human performance, (2) models of agency could provide HMI solution for latency compensation. Interests of agentive experience accounts for better system design are discussed.

Keywords: Latency, Agency, Action Control, UAS, Cognition.

1 Introduction

Latency, or lag, is the time delay in device position updates [4]. Latency has been shown to dramatically degrade human performance in motor-sensory tasks with interactive systems as well as planning and performance in teleoperation scenarios [2; 8; 14; 15]). In general, the effect involves a reduction in control accuracy which ultimately drives the operator to adopt a “move and wait” strategy when latency exceeds about 300 ms (see [3; 11; 12; 13]). This problem of latency is particularly true when you consider Unmanned Aircraft System (UAS) operation, latency generally exceeding 300 ms in such system. Clearly, data transmission latencies between Unmanned Aerial Vehicles (UAVs) and control stations affect the effective operator control of these UAVs.

However, if lag is currently considered by User Interface Designers as a major bottleneck for usability of human-system interaction devices [8], the theoretical basis of the effect of latency on action control mechanisms remains weak. We assume that characterizing how latency impacts the cognitive processing involved in action

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control should provide guidelines to User Interface Designers for latency compensation. A possible interpretative framework on the nature of the transformation induced by latency can be tracked back to the mechanism of agency. When we act, we usually have a clear feeling that we control our own action and can thus produce effects in the external environment. This experience of oneself as the agent of one's own actions has been described as "the sense of agency" (for reviews, see [5]). Models of agency suggest that the experience we have of causing our own actions arises whenever we draw a causal inference linking our thought (or intention) to our action. This inference occurs in accordance with principles that follow from research on cause perception and attribution (see [5; 6; 9; 10]). Interestingly, temporal contiguity is central for sense of agency: immediate cause–effect pairings are generally privileged [18; 17; 19] and task-meaningful temporal windows introduced between a cause and its effect is necessary [1]. So that, to perceive a sense of control, the effect cannot start too soon or start too late; it has to be on time just after the action.

In this context, we hypothesized that (1) the data transmission latency directly impacts the sense of agency, (2) designing HMI solutions offering the maximal agency could compensate the negative effect of latency on a teleoperation control task. In a series of 3 experiments, we propose to tackle this problem by (1) characterizing the effects (performance and agency) of transmission delays on UAS camera control, and (2) designing and evaluating HMI solutions to mitigate these effects with regard to the agency principle.

2 Experiment 1: Latency and Agency in Simple Paradigm

The first experiment was designed to characterize the link between agency and latency. To address this issue, we used the classical Fitts' task in a discrete version. In this paradigm, participant had to move a cursor as quick and as accurate as possible, toward a target from a home position (one-dimensional movement). Latency was introduced between the initiation of the physical movement of the device (stylus) and the time the corresponding update appears on the screen (movement of the visible cursor). Effect of input device latency on human performance and sense of agency were computed. As showed by), we hypothesized that the latency directly impacts (1) human performance in such pointing task (see [8]) and (2) the sense of agency (see [19]).

2.1 Method

Participants. Nine right-handed from the French Aerospace lab volunteered to participate in this experiment. All had normal vision and were naïve as to the hypothesis under investigation. Their mean age was 24 (range = 21–32 years).

Materials and Apparatus. We used an interactive graphics system using targets displayed on a LCD (Dell P2210, 22") and a cursor manipulated by an input device (graphic tablet WACOM Intuos 4 XL + stylus). Stylus movements over a graphics tablet motion of a vertical green line cursor. A vertically elongated white bar on the screen represented the target against a grey background. The stylus' position was sampled at a frequency of 150 Hz. An adjacent monitor (17'' touch screen) showed two horizontal lines used for agency measures recording (see later).

Procedure. The participants' task was to move a cursor as quick and as accurate as possible, toward a target from a home position (one-dimensional movement). The sequence of events on each trial is described in Figure 1. (1) Participants' cursor is situated at the central position. (2) After a short interval, a sound got the signal for the beginning of the movement. (3) The participant moved the cursor as quick as possible towards the target. (4) The cursor reached the target. (5) After a controlled temporal delay, an acoustic feedback concerning the success of the target was given. (6) After each trial, measures of agency were computed (details in *Measure of agency* section). In order to test the effect of latency on agency, a temporal gap was introduced between the initiation of the physical movement of the device (stylus) and the time the corresponding update appears on the screen (movement of the visible cursor). Four different levels of latency were tested (0, 250, 750 or 1500ms). In a last condition, called control condition, the movement of the cursor was externally produced (i.e., participant only observed). Task difficulty was also manipulated by using two different target sizes (30 mm for *ID2* versus 10 mm for *ID3*).

Measure of Agency. If the sense of agency has been proved to be difficult to quantify, it is now accepted that different aspects has to be considered, conscious and unconscious aspects. Conscious aspect refers to the explicit judgement of causal control. In contrast, unconscious aspect refers to change involved in voluntary action (i.e., agentive situation), particularly perceptual change. An interesting one relates to the perceived duration of intervals between actions and effects. Recent research has shown that human intentional action is associated with systematic changes in time perception: the interval between a voluntary action and an outcome is perceived as short as the interval between a physically similar involuntary movement and an outcome. This phenomenon called intentional binding [7] offers an implicit measure of the sense of agency. Relative to these two aspects of agency, two measures were collected for each trial. Unconscious aspect of agency was evaluated by the temporal delay perceived between action and effect. Participant had to estimate on a scale from 0s to 1s the temporal delay perceived between the entrance in the target and the appearance of the success feedback. If they were told that the possible range of delays was between 1 ms and 1000 ms, only three Action/Effect delays (250 ms, 500 ms, and 750 ms) were presented, in a random order. Conscious aspect of agency was evaluated by judgement of agency. Participants has to report how strongly they felt that they controlled the pointing movement, using a scale from 0 (no causal involvement) to 1 (strong causal involvement).

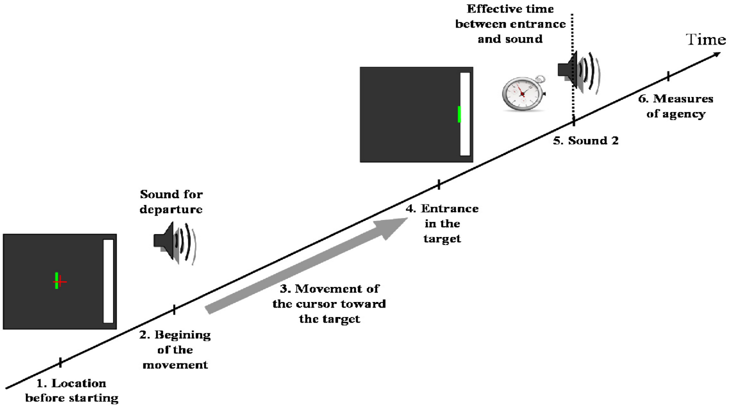


Fig. 1. Typical sequence of events for one trial

To summarize, we have (1) five conditions of *latency*, (2) two index of *difficulty* (ID2 versus ID3) and (3) three effective *Action/Effect delays*. Each participant made two trials for each combination of *Latency*, *Difficulty* and *Action/Effect Delay*, being in total sixty trials per participants. The trials were tested in random order.

2.2 Results and Discussion

In this study, our primary concern is the relationship between latency and sense of agency, at both unconscious and conscious levels. The impact of latency on performance is also computed.

Unconscious Aspect of Agency: Temporal Judgement. The first measure of agency collected concerns the perceived duration of intervals between actions and effects. As previously introduced (see Intentional binding effect), if latency reduces the sense of agency, action/effect interval estimation should increase with the level of latency. To test this hypothesis, we performed a 5*2*3 ANOVA with *Latency* (0, 250, 750, 1500ms, control condition), *Difficulty* (ID2, ID3) and *Action/Effect delay* (250, 500, 750 ms) as within subject factors. Our results (see Figure 2A) show a significant effect of *Latency* on interval estimation ($F(4,68)= 11.91$, $p<.01$). Post-hoc analysis revealed that interval estimates increased monotonically with the level of latency: the more the cursor movement was delayed, or the less it relied on participant's actual movement, the longer the action-effect interval was perceived, and this even if the actual action/effect delays are completely independent of the latency introduced in the system. Interestingly, no significant difference ($p>.01$) was observed between the conditions with large latency (750 and 1500 ms) and the control condition (movement externally produced). These results indicate that the unconscious aspect of agency is sensitive to the latency, with increasing latency leading to a higher interval estimate, which we interpret as a gradual decrease in sense of agency.

Conscious Aspect of Agency: Explicit Judgement of Agency. The second measure of agency collected concerns the judgement of agency: How much do you feel in control? As for the unconscious aspect of agency, this feeling of control should decrease with latency. Our results (see Figure 2B) confirm such hypothesis, since a significant effect of *Latency* on verbal reports was observed ($F(3, 51) = 60.76$, $p<.01$). Post hoc analysis shows that judgement of causality decreased monotonically with the level of latency (all ps,.01). These results indicate that the conscious aspect of agency is sensitive to the latency, with increasing latency leading to a gradual decrease in judgement of agency. A significant effect of *Difficulty* is also observed ($F(1,17) = 25.96$, $p<.01$). Post-hoc analysis for *Difficulty* reveals that subject have larger sense of control for easier task (ID2), results not observed for time estimation ($F(1,17)= 1.32$, n.s.). More particularly, conscious aspect of agency seems more sensitive to performance than unconscious aspect. A possible explanation could be found regarding the relation between performance and judgement of agency.

Performance: Movement Time. Finally, we computed the effect of the latency on movement time. As previously observed by MacKenzie and Ware [8], we observe a significant effect of *Latency* on movement time ($F(3,51) = 51.37$, $p<.01$) (see Figure 2C). Post-hoc analysis reveals a progressive decrease in movement time in regard to the latency. These results indicate that the performance is sensitive to the latency, with increasing latency leading to a poorer performance (i.e., a larger movement time).

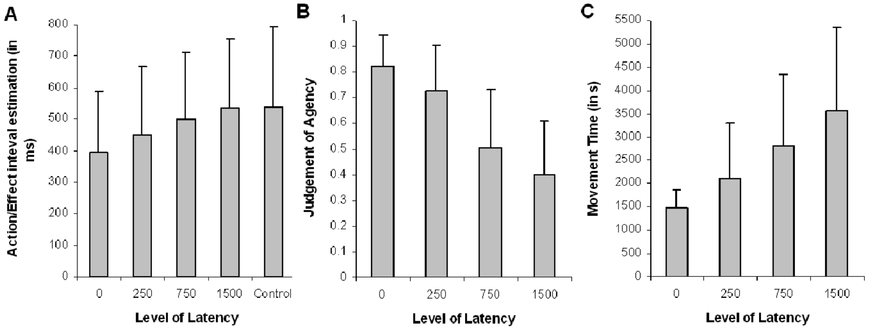


Fig. 2. Modulation of (A) Interval Estimates, (B) Judgement of Agency, and (C) Movement Time by actual level of *Latency*

3 Experiment 2 and 3: Wegner Principle for Latency Compensation

Our first experiment indicates that latency (1) decreases conscious and unconscious aspects of agency, (2) impacts human performance. It clearly demonstrates that increase in latency is correlated to a decrease in sense of agency. Such decrease is congruent with models of agency (see [18; 17]). Indeed, as claimed by priority principle, to perceive a sense of control, the effect cannot start too soon or start too late; it has to be on time just after the action. In this context, we hypothesized that designing HMI solutions that enhance agency (particularly in regard to priority principle) could compensate the negative effect of latency. To tackle this question, we focused on teleoperation control task. The aim was to propose human-machine interface (HMI) solutions that reduce the effects (oscillatory behaviour) of latency on an operator's performance.

The HMI solution developed was a predictive cue called the "Payload Director". The goal of this help is to provide immediate feedback to the operator about the predicted position of the payload due to the user input. The aim of the design is to satisfy the condition of temporal contiguity for sense of agency. Indeed, by presenting an anticipated effect of the action, we decrease the gap between the command sent by the operator and the perceived effect of this action, even if action is really effective only several seconds after. Figure 3 is the screen shot of the payload director. The circle indicates the position which the crosshair will centre on as a result of the user input. The position of the circle is calculated using the known control function of the payload controller. Figure 4 illustrates the function of the Payload Director.

Fig. 3. Payload Director (PD)

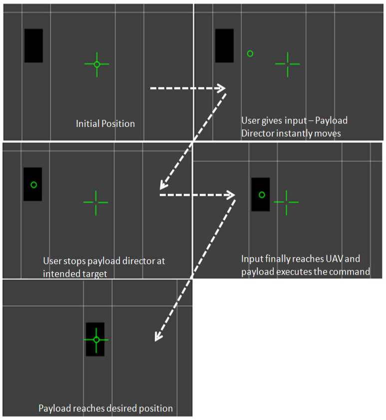


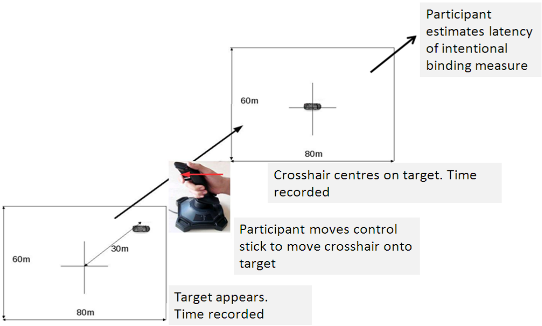
Fig. 4. Illustration of PD's function

Two experiments were designed to evaluate this HMI solution in a complex setting involving controlling a UAS camera for target acquisition. Particularly, two groups of participants performed respectively a pointing task (acquire a fixed target as quick as possible) and a tracking task (track a moving target). These two experiments were conducted using ONERA's remote piloted system simulator. This simulator comprises a UAS pilot station which includes payload control sticks (for camera command) and video screen (for camera control, i.e. visualization of the camera's image). Delays were introduced between the stick command input and the movement of the camera and their effects on agency and performance were observed with or without the Payload Director.

3.1 Method

Participants. Eight and ten right-handed from the French Aerospace lab participated respectively in the pointing and the tracking tasks. All had normal vision and were naïve as to the hypothesis under investigation. Their mean age was 26 (range = 22–31 years) for the pointing task, 27 (range = 23–34 years) for the tracking task.

Procedure for the Pointing Task. The participants' task was to move a cursor as quick and as accurate as possible, toward a target from a home position (two-dimensional movement). The sequence of events on each trial was as follows (see Figure 5). At the beginning of each trial, participants' cursor is situated at the central position (home position). (2) After a short interval, a target appeared. There were 6 different target positions at equi-distance from the crosshair of the payload (see Figure 6). (3) The participant moved the camera as quick as possible towards the target. (4) The cursor reached the target (visual feedback for target acquisition). (5) After each trial, measures of agency were computed. Relative to the two aspects of agency (conscious and unconscious), two different measures were collected. Unconscious aspect of agency was evaluated by the temporal delay perceived between action and effect. Particularly, participant had to estimate on a scale from 0s to 2s the latency perceived between their action on the stick and the movement of the camera. Conscious aspect of agency was evaluated by verbal reports. Participants made an explicit judgement of agency, by reporting how strongly they felt that they controlled the pointing movement, using a scale from 0 (no causal involvement) to 1 (strong causal involvement). In order to test the effect of latency on agency, four different levels of *Latency* were tested (0, 250, 750 or 1500ms). Finally, each level of latency was performed with or without help. Altogether, each participant performed 32 trials (4 repetitions for each combination *Latency/Help*). The trials were tested in random order.



Participant estimates latency of intentional binding measure

Crosshair centres on target. Time recorded

Participant moves control stick to move crosshair onto target

Target appears. Time recorded

Fig. 5. Typical sequence of events for one trial

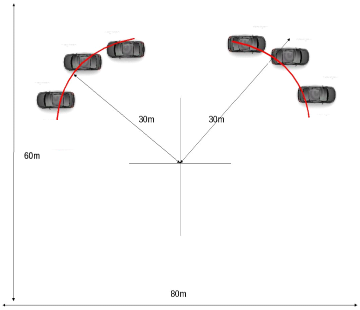


Fig. 6. Equi-distant targets

Procedure for the Tracking Task. The participants' task was to keep the payload cursor on a moving target from a moving UAV (two-dimensional movement). The sequence of events on each trial was as follows (see Figure 5). At the beginning of each trial, participants' cursor is situated at the central position (home position). (2) After a short interval, a moving target appeared. There were 24 different paths made up of repeatable components in different order for similar difficulty. Frequency and sharpness of turns are controlled. Path time was of 50 seconds. (3) The participant moved the camera to keep crosshair in the moving target. (4) After each trial, measures of agency were computed in the same way than in the pointing task. Three different levels of *Latency* were tested (0, 500, or 1000ms). Finally, runs were performed for each level of latency with or without help. Altogether, each participant performed 24 runs (4 repetitions for each combination *Latency/Help*). The trials were tested in random order. The measure of agency was computed at both unconscious (temporal estimation of latency) and conscious (explicit judgement of control) levels.

3.2 Results and Discussion

As observed in our first experiment, latency reduces the sense of agency at both unconscious and conscious levels, but also human performance. In this study, we aimed to propose an HMI solution to compensate these negative effects. If efficient, our help should increase sense of agency and performance in presence of latency. In other words, for a same level of *Latency*, we anticipated better performance and sense of control in presence of the help proposed (the Payload Director) than without.

Unconscious Aspect of Agency: Temporal Judgement. At the unconscious level, a decrease in agency leads to a larger estimation of the temporal delay between my action and its effect (Action/Effect interval). We hypothesized that the Payload Director could partially mitigate this effect. To test this hypothesis, we compared the effect of Latency on Action/Effect delay estimation with and without the Payload Director in the two tasks. Whatever the target, fixed or moving, we observed a significant difference in Action/Effect delays estimation with or without the Payload Director (with $F(1,7) = 52.15$, $p<.01$ for fixed target and $F(1,19) = 45.62$, $p<.01$ for moving target) (see Figure 7A). Post-hoc analysis reveals that the Action/Effect delays are estimated shorter with the Payload Director for the two experiments. These results indicate that the HMI solution proposed partially mitigates the effect of Latency in regard to the unconscious aspect of agency.

Conscious Aspect of Agency: Explicit Judgement of Agency. At the conscious level, a decrease in agency leads to a decrease in the judgement of control. As hypothesized for unconscious aspect of agency, we anticipated that the Payload Director could partially mitigate this effect. To test this hypothesis, we compared the effect of Latency on judgement of agency with and without the Payload Director in the two tasks. Our results (see Figure 7B) showed a significant difference in judgement of agency with or without the Payload Director (with $F(1,7) = 29.33$, $p<.01$ for fixed target and $F(1,19) = 25.16$ $p<.01$ for moving target). Post-hoc analysis reveals that subjects have larger sense of control with the Payload Director than without for the two tasks. These results indicate that the HMI solution proposed partially mitigates the effect of Latency in regard to the conscious aspect of agency.

Performance. Concerning the performance measure, we used the time for acquisition in the pointing task, and the percentage of time the payload cursor is on the moving target (Ratio of time Crosshair-Over-Target or COT Ratio) for the tracking task. In the two tasks, we observed an increase in performance with the Payload Director. In the pointing task, our results showed a significant difference between time for acquisition with and without the Payload Director (F(1,7) = 55.92, p<.01). Post-hoc analysis reveals shorter time for acquisition with the Payload Director (see Figure 7C). The same effect was observed in the tracking task. Wilcoxon Signed Rank Test shows that the overall difference in performance between Payload Director and No Help condition were statistically significant (*p*<.01). Particularly, the time over the target is larger with the Payload Director than without. These results indicate that the HMI solution proposed partially mitigates the effect of Latency in regard to the operator performance.

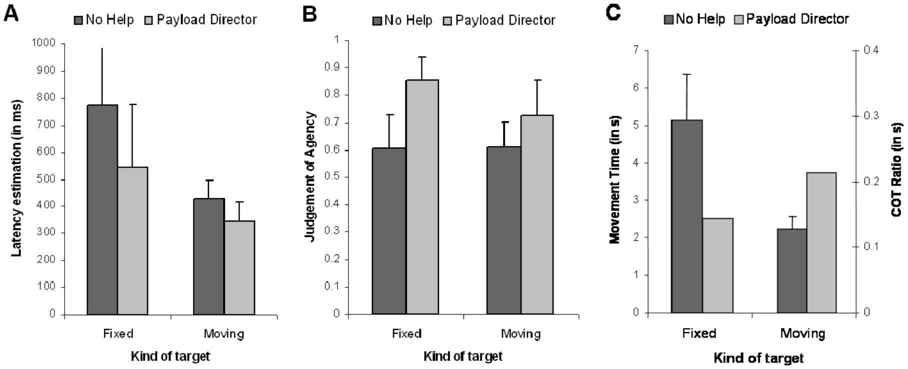


Fig. 7. Modulation of (A) Latency Estimates, (B) Judgement of Agency, and (C) Performance (Movement Time or COT ratio) by the HMI solution proposed (i.e., the Payload Director)

4 Conclusion

In the current context of continue increase in complexity, latency problem becomes a major human factors question. This is particularly true considering the use of UAS. In this context, we aimed to investigate the cognitive implications of latency for Human-Computer Interaction. Our study yielded two important results. First, we showed that the sense of agency evolves as a function of latency. Particularly, increase in latency leads to a decrease in sense of agency. Second, we showed that the Wegner formal framework of agency (for a review, see [16]) provides principles to design Human-Machine Interfaces capable of compensate the negative effects of latency on action control. By this way, we show that psychological ideas about the self, and particularly the concept of agency, can help to (1) understand the theoretical basis of the effect of latency on action control mechanisms, (2) propose HMI solutions to mitigate latency effect on action control. More generally, we consider that accounts of agentive experience could provide guidelines for better system design.

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