Bruno Berberian,
Patrick Le Blaye,
Nicolas Maille,
Jean-Christophe Sarrazin
(Onera)

E-mail: bruno.berberian@onera.fr

Sense of Control in Supervision Tasks of Automated Systems

We live in an increasingly technological world. Automated systems certainly can make life easier, but they can also create complexity and uncertainty. Moreover, it is clear that automation does not merely supplant human activity, but also transforms the nature of human work. This review examines an original account of this transformation – a link between automation technology and the sense that our actions cause effects on the outside world (so-called 'agency'). Accordingly, we first discuss the human factor issues related to automation technology. Particularly, we introduce the out-of-the-loop performance problem. Then, we introduce recent findings about agency. We propose that several recently developed psychological approaches to the self-promise to enhance our comprehension of the transformation induced by increased automation. Next, we address the controversial issue of agency measuring, particularly the necessary dissociation between explicit and implicit agency measurement. In particular, we introduce the intentional binding effect as an implicit agency measurement, and we discuss the problems and issues related to the generalization of this effect to more complex situations. Finally, we suggest that the investigation of this authorship processing in the field of human-machine interaction may be fruitful, both to elaborate concrete design recommendations and to evaluate the potentiality for an HMI to satisfy the agency mechanism.

Automation and human control in complex systems

"The burning question of the near future will not be how much work a man can do safely, but how little." [85]

There is perhaps no facet of modern society in which the influence of automation technology has not been felt. Whether at work or at home, while travelling or while engaged in leisurely pursuits, human beings are becoming increasingly accustomed to using and interacting with sophisticated computer systems designed to assist them in their activities. Even more radical changes are anticipated in the future, as computers increase in power, speed and "intelligence".

We have usually focused on the perceived benefits of new automated or computerized devices. This is perhaps not surprising, given the sophistication and ingenuity of design of many such systems (e.g., the automatic landing of a jumbo jet, or the docking of two spacecraft). The economic benefits that automation can provide, or is perceived to offer, also tend to focus public attention on the technical capabilities of automation. However, our fascination with the possibilities afforded by technology often obscures the fact that new computerized and automated devices also create new burdens and complexities for the individuals and teams of practitioners responsible for operating, troubleshooting and managing high-consequence systems. Whatever the merits of any particular automation technology, it is clear that automation does not merely supplant human activity but also transforms the nature of human work. As a matter of fact, the role of the human actors may possibly evolve from direct control to supervision. Understanding the characteristics of this transformation is vital for successful design of new automated systems.

Automation and OOL performance problem

When new automation is introduced into a system, or when there is an increase in the autonomy of automated systems, developers often assume that adding "automation" is a simple substitution of a machine activity for human activity (substitution myth, see [92]). Empirical data on the relationship of people and technology suggest that this is not the case and that traditional automation has many negative performance and safety consequences associated with it stemming from the human out-of-the-loop (OOL) performance problem (see [22], [50]).

Classically, the out-of-the-loop performance problem leaves operators of automated systems handicapped in their ability to take over manual operations in the event of automation failure [22]. The OOL performance problem has been attributed to a number of underlying factors, including human vigilance decrements (see [7], [86]),

complacency (see [63], [68], [86]) and loss of operator situation awareness (SA) (see [15], [21], [22]). Cognitive engineering literature has discussed at length the origins of vigilance decrements (e.g., low signal rates, lack of operator sensitivity to signals), complacency (e.g., over trust in highly reliable computer control) and the decrease in SA (use of more passive rather than active processing and the differences in the type of feedback provided) in automated system supervision and has established associations between these human information processing shortcomings and performance problems. However, though all of these undoubtedly play an important role in the out-of-the-loop performance problem, we consider that these different factors have masked a preliminary question: what is the difference between action resulting from my intention, beliefs or desires and others' action or involuntary action? What is the difference between being an agent or not? What is the difference between supervisors in control and complacent supervisors? Our belief is that the investigation of the agency mechanism may be fruitful in the comprehension of the OOL performance problem.

An aeronautical problem: feeling of control in automated systems

A possible interpretative framework on the nature of the transformation induced by the automation can be tracked back to the agency mechanism, that is, the feeling of being causally involved in an action (the sense of agency, [30]). This hypothesis is echoed by the claim of Baron when he states:

"***Perhaps the major human factor concern of pilots in regard to the introduction of automation is that, under some circumstances, operations with such aids may raise the critical question, who is in control now, the human or the machine?***" [4]

This is not a simple question and it is certainly not merely a matter of the pilots' self-esteem being threatened by the advance of the machine age. "The question goes to the very heart of the nature of piloting, the seemingly divided authority between human and machine and, mainly, what is the role of the pilot as minder of equipment that is not only increasingly sophisticated, but also increasingly autonomous" ([86], p.452). The concern is legitimate. The interposition of more and more automation between the pilot and the vehicle tends to distance pilots from many details of the operation. They are isolated from most of the physical structures of the aircraft. At the same time, the automation tends to isolate the crew from the operation of the aircraft, because the automatic equipment monitors and controls it, providing little or no trace of its operations to the crew, isolating them from the moment-to-moment activities of the aircraft and of the controls [62]. This combination of relative physical and mental isolation from the basics of flying helps to contribute to a decreased feeling of control by the pilots. At the extreme, some pilots argue that automation reduces the status of the human to a "button pusher" [87] describes those who build automated systems as "trying to take humans out of the loop". How to design systems to allow the crew to remain an intentional agent (i.e., "in the loop") is a crucial question, but is also an extremely difficult problem.

To solve this question, it is necessary to understand how automation influences the humans who work with it and how humans feel about action control. However, few studies in the aviation domain have investigated this question. In contrast, the mechanism of self-attribution has enjoyed particular interest in the fields of social psychology, movement science and neuroscience. This area of research is well-known as the science of agency (see [31]).

Agency: state of the art

When we act, we usually feel ourselves controlling our own action and causing the accompanying action–effect. This experience of oneself as the agent of one's own actions has been described as "the sense of agency" [30].

One way to get at the concept of the sense of agency is to distinguish it from the sense of ownership for movement [30]:

- Sense of ownership: the pre-reflective experience or sense that I am the subject of the movement (e.g. a kinesthetic experience of movement).
- Sense of agency: the pre-reflective experience or sense that I am the cause or author of the movement (e.g. an experience that I am in control of my action).

Though agency refers to the sense of intending and executing actions, body ownership only refers to the sense that one's own body is the source of sensations. Although in the normal experience of willed action the self-agency and the sense of self-ownership coincide and appear indistinguishable, both may be partly independent and have different processes by which each of them is constructed. It is possible to say that I am moving and therefore that it is my movement, and thus have a sense of ownership for it, in cases where there is no sense of agency for the movement, for example in reflex or involuntary movements.

Interesting example of such dissociation is proposed by Penfield's classic finding on movements induced through electrical stimulation of the motor cortex [64]. Conscious patients were prompted by stimulation of the exposed brain to produce movements that were not simple reflexes and instead appeared to be complex, multi-staged and voluntary. Yet, their common report of the experience was that they did not "do" the action and instead felt that Penfield had "pulled it out" of them. This observation only makes sense if we consider that sense of ownership for an action ("my arm is moving") does not suffice for recognizing oneself as agent of this action ("I voluntary move my arm"). This asymmetry suggests that agency and ownership may have different processes by which each of them is constructed and should have different effects on awareness of the body. Therefore, we can raise the following question: what must be added to be able to self-ascribe a movement ("I am moving")?

Sense of agency: different approaches

Most people can readily sort many events in the world into those that they have authored and those that they have not. This observation suggests that each person has a system for authorship processing [80], a set of mental processes that monitors indications of authorship to judge whether an event, action, or thought should be ascribed to self as a causal agent (see [35], [48], [81]). However, these mental processes are not clear at the moment.

In recent years, laboratory studies have attempted to shed more light on this mechanism. Empirical data in recent psychology (e.g., [1], [20], [23], [45], [60], [67]), in psychopathology (e.g., [27], [28],

[71]) and in neuroscience (e.g., [9], [18], [26], [74], [75]) have been accumulated and two different approaches have emerged.

The ***"bottom-up" approach*** considers that the higher-order attributions of agency may depend on the first-order experience of agency [31]. In this case, authorship is a given, a kind of knowledge that arises in the very process whereby actions are produced. Authorship processing seems inherent in the way the action is produced (for an original illustration, see box 1). However, several works suggest that action and agency do not always properly coincide. Clinical evidence, such as the "***Alien hand syndrome***" [36] or schizophrenic syndromes (see [9], [11], [29], [69]), neuropsychological evidence (see [34], [42], [43], [53]) and works on automatism (see [2], [3], [70], [77]) show that the sense of agency is fallible. For example, the priming studies imply that the sense of agency may even occur in situations in which the participant plays no objective role in bringing about the outcome. In a "shelping hands" pantomime task (see figure 1), subjects experienced high degrees of agency for movements that were in fact performed by another agent, when only the other agent's hands appeared in the place where subjects' hands would normally appear and when subjects could hear instructions previewing each movement [81] (see also the rubber hand illusion, [12]). If so, we must accept that authorship identification needs processing which is separate from the mechanistic process of real mental causation.

In order to transcend these limits, the ***"top-down" approach*** considers that our conscious awareness of action is subserved by an inferential process (e.g. [19], [39], [71], [78], [79], and [82]). As pointed out by Wegner ([77] p. 218), ''we are not intrinsically informed of our own authorship" and instead, we use sensory evidence to "make sense" of our actions and their antecedent/subsequent events. In other words, the inferential process would generate the experience of action by accumulating sensory evidence about actions in the same way that other perceptual/inferential processes rely on sensory evidence about external events. An interesting illustration of the top-down approach has been proposed by Wegner ([77], [82]).

The early insight of Hume in A Treatise on Human Nature [44] was that the "constant union" and "inference of the mind" that underlies the perception of causality between physical events must also give rise to perceived causality in "actions of the mind".

Drawing on this idea, the theory of apparent mental causation ([77], [82]) suggests that the experience we have of causing our own actions arises whenever we draw a causal inference linking our thought to our action. This inference occurs in accordance with principles that follow from research on cause perception and attribution (see [24], [38], [55], [56]) – principles of priority, consistency, and exclusivity. [82] argues that, when a thought occurs prior to an action, is consistent with the action and the action has no plausible alternative cause, then we experience the feeling of consciously willing the action. In contrast, when thoughts do not arise with such priority, consistency and exclusivity, we experience the ensuing actions as less willed or voluntary.

Box 1 - Why can't you tickle yourself? Sense of agency illustrated

Researchers have increasingly studied how we can distinguish between sensations that are produced by our own movements and sensations that are caused by a change in the environment ([14]; [47]; [88]; [89]). These studies have repeatedly demonstrated that the sensory consequences of self-generated movements are perceived differently than identical sensory inputs that generated externally. In particular, there is now substantial evidence that the sensory effects of self-produced movement are attenuated (see for example [11]).

A recent study by Blakemore and collaborators [10] is relevant in this context. Using a robotic interface, delays of 100, 200 and 300 ms and trajectory rotations of 30", 60" and 90" were introduced between the movement of the left hand and the resultant tactile stimulation on the right palm. Increase in temporal and spatial discrepancies between the subject's movement and the resultant tactile stimulation make it possible to differentiate between the perception of self-produced sensation (no delays and no trajectory rotations) and the perception of externally produced sensation. Participants were asked to rate the tactile stimulus in terms of several sensations, including tickliness (painful, intense, pleasant, irritating, and tickly). Interestingly, the authors observed a systematic increase in the sensation experienced as the discrepancy between the applied movement and the felt movement increased in time or space. In other words, conscious experience of being tickled is highly dependent on the source of the action.

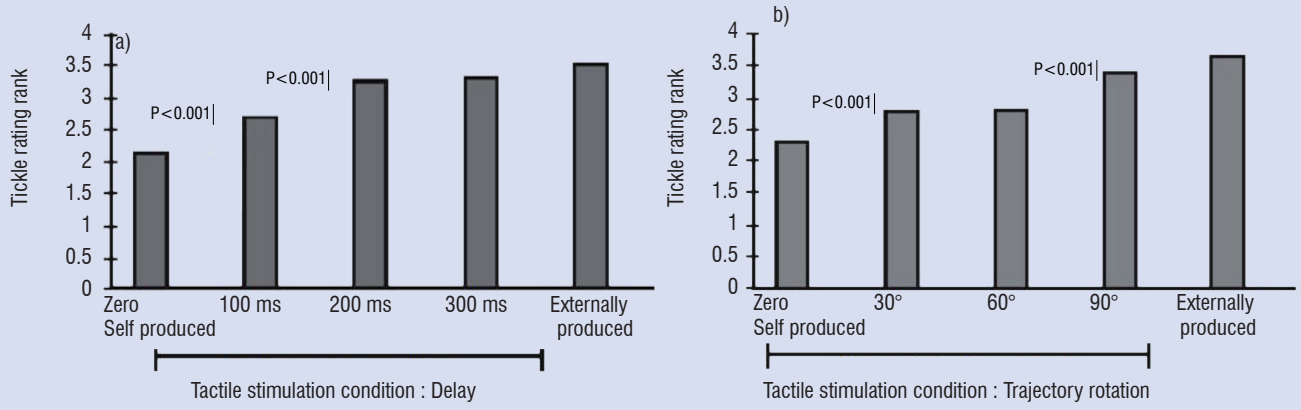

Figure B1-01- Graph to show that the tickliness of a tactile stimulus increases with increasing delay (a) and trajectory rotation (b) between the movement of the left hand and the tactile stimulus on the right palm. Reproduced from [10].

Figure 1 - Experimental paradigm used by [81]: a participant viewed from the front, as she would see herself in the mirror (on left), and participant with hand helper as viewed from the side (on right). Participants watch themselves in a mirror while another person behind them, hidden from view, extended hands forward on each side where participants' hands would normally appear and performed a series of movements. When participants could hear instructions previewing the movements, their sense of agency for these movements was enhanced, but such vicarious agency was not felt when the instructions followed the movements. Reproduced from [81].

Evidence from several experiments has accumulated in relation to this theory. For example, Gibson and collaborators [37] asked participants to type letters randomly at a computer keyboard without seeing the screen. They were told that the experiment examined "automated typing" and that their random responses would be analyzed. Just before this, participants were exposed to the word deer in an ostensibly unrelated task. Then "the automatic typing" began and participants typed for 5 minutes. The experimenter ostensibly ran a program on the typed text to extract the words that had been typed, and then asked participants to rate words to indicate the degree to which they felt they had authored that word. None of the words rated were actually produced, yet participants reported higher authorship ratings for the word they had seen in the prior computer task (deer) relative to other words. This finding suggests that people can experience will for an action that was never performed, merely when they have prior thoughts consistent with the action (see also [1]).

Because human agents have access to a variety of sources of information about authorship (e.g., one's own thoughts, interoceptive sensations, external feedback, etc.), the identification of authorship indicators involved in the authorship processing becomes a first concern. Several indicators have been already proposed, including body

Box 2 - Wegner principle in an aeronautical context: a first attempt

Recently, we have proposed a preliminary experiment, addressing the effect of automation over the feeling of agency in a simulated control task involving authority sharing with a robot [6]. The experiment consisted in controlling a robot moving on a plane in a 2D video game. The task of the participants was to bring the robot to the target, while avoiding various obstacles. The robot was semi-automated and designed to avoid the obstacles by itself and go to the target. If the participant considered that its behaviour was not optimal, he could operate on two parameters: robot velocity, and robot direction. Latency (the time before considering operator command, 400 ms or 1000 ms), Level of Authority (the level of authority assigned to the operator, 30 %, 50 % or 70 %) and Feedback (presence of feedback about the command sent by the automatism with direction, velocity and detection signal) were manipulated and the role of these different factors on performance and feeling of control was measured. The main results showed that (1) the feeling of control depends both on the level of operator authority and on the performance obtained in the task, (2) the latency had no effect on the feeling of control and (3) the presence of feedback about an automatism's intention does not influence the feeling of control.

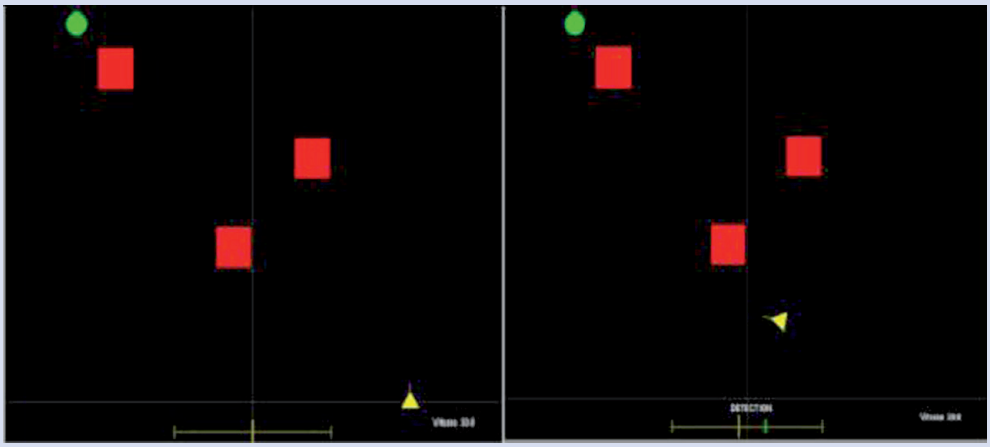

Figure B2-01 - Experimental paradigm used by [6]. The experiment consists in controlling a robot moving on a plane in a 2D video game. The visual scene (see figure 1) was composed of: one semi-automated robot represented by a yellow triangle with an arrow marking the displacement direction, one target represented by a green circle and three obstacles represented by red squares. The task of the participants was to bring the robot to the target, while avoiding the obstacles. Reproduced from [6].

These results were discussed in regard to the three principles enounced by Wegner –principles of priority, consistency and exclusivity. Even though further studies are clearly needed to make progress on this issue, this first experiment shows the importance of the concept of agency in the question of human-automation coupling, its ability to be assessed by a participant's judgment and its usefulness to understand the factors enabling a feeling of control even in a supervisory task.

and environment orientation cues (e.g., [76]), direct bodily feedback (e.g., [32]; [35]), direct bodily feedforward (e.g., [8]; [9]), visual and other indirect sensory feedback (e.g., [17]; [61]), social cues (e.g., [51]; [57]), agent goal information (e.g., [52]) and own behavior-relevant thought (e.g., [77]; [78]; [82]). In our mind, the investigation of such indicators in supervisory tasks could improve our comprehension of the OOL performance problem significantly (for a first attempt, see box 2).

Agency measurement

A second important question relates to the measurement of this sense of agency. The sense of agency has proved difficult to quantify. Historically, philosophical and psychological approaches to the agency have focused on the mechanism of self-attribution or, in other words, one's ability to refer to oneself as the author of one's own actions (for reviews, see [19]; [30]). These involve participants introspecting upon his or her sense of agency by answering questions such as ''Did you do that?" In particular, previous studies of priming (e.g. [1]; [82]) used explicit judgments to measure the sense of agency. A significant number of theorists have argued that the introspective report is the only legitimate marker of agency in any context. Where a creature is unable to produce introspective reports of any kind, then we have no reason to think that there is a sense of agency. However, [72] recently highlighted the distinction between the feeling of agency, as captured by implicit measures, and explicit judgments of agency. In particular, we can distinguish two different aspects of the self the 'narrative' self and the 'minimal' self [30]. The narrative self corresponds to "a more or less coherent self (or self-image) that is constituted by a past and a future in the various stories that we and others tell about ourselves" ([30], p. 15). Clearly, introspective reports deal with this first aspect of the self. The minimal self, on the other hand, corresponds to a more primitive and embodied sense of self.

It is the pre-reflective feeling that a given movement is performed by me, or that a given experience is had by me. This reference to self is distinguished from the autobiographical sense of having a narrative self that persists across experiences. The minimal self is more like an instantaneous feeling of "mineness", with which experiences are labeled. As suggested by Gallagher [30], this aspect of the self depends on an ecologically embedded body, but one does not have to know or be aware of this to have an experience that still counts as a self-experience. In other words, the minimal self cannot be reduced to self-attribution reports. In this context, we have to make a distinction between the fact that I own a certain mental or bodily state and the fact that I recognize this state as mine (see also, [14]).

From a conceptual, a phenomenological and an empirical point of view, the relations between a minimal or core self and an extended, narrative, or autobiographical self remain controversial (for a general discussion about the relationship between implicit measure and verbal report, see [40]. They may be seen to be complementary notions. But is the core self a (logical and temporal) precondition for the extended (narrative or autobiographical) self? Or is the core self, on the contrary, a subsequent abstraction; is it simply a stripped-down version of what must count as the genuine and original self [94]? To resolve this question, the study of the self needs to go further than the simple use of attribution judgments and to explore the possible dissociations between the minimal and the narrative self in change detection. In particular, if the minimal self is a precondition for the narrative self and could exist in absence of self-attribution reports, explicit judgment tasks are no longer sufficient and it becomes a key concern to find an implicit measure of agency, — one that is sensitive to the minimal self. In our mind, the identification of accurate agency markers is essential if the science of agency is to have any chance of success. Intentional binding appears as a good candidate for such implicit measurement.

Intentional binding as an implicit measurement of agency

Time appears as a first concern regarding the sense of agency. Two key findings have placed linkage across time at the heart of this approach. First, the mental representation of the action predicts the later effect ([25]; [46]). Second, the strength of association, and thus the feeling of agency, operates over a limited time window. As the interval between an action and its sensory effect increases, subjects become less likely to agree that they caused the sensory effect [82].

If the temporal contiguity between one's action and the resultant effects is central to the sense of agency ([77], [79], [93]), the reverse seems also true: being an agent of an event may affect the perceived time of such an event. Particularly, 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 shorter than the interval between a physically similar involuntary movement and an outcome.

In an experiment based on Libet's time judgment paradigm [54], Haggard and collaborators [43] asked participants to press a key, which produced an auditory stimulus a short interval afterwards. Participants were supposed to estimate, in separate blocks, the time of either when they made the action or when they heard the tone, by referring to a rotating clock hand. The main results showed a temporal attraction between action and effect (actions are perceived as shifted forward in time towards the effects that they produce, while the effects of intentional actions are perceived as shifted backwards in time towards the actions that produced them) in case of intentional action (see figure 2). In contrast, involuntary movements (movement resulting from transcranial magnetic stimulation) show a perceptual repulsion. This ''intentional binding" effect [43] is taken to be a measure of the sense of agency, because the binding between voluntary actions and effects reliably occurs in situations in which the participant is an agent relative to non-agency situations such as passive movement.

Based on this preliminary work (see also [41]), several studies have explored the necessary and sufficient conditions of temporal binding. [43] again highlighted the centrality of intentions for temporal binding and showed that temporal binding depends on the predictability and temporal proximity of the effect. They found larger perceptual shifts for fixed than for randomized movement–effect intervals. Additionally, short intervals yielded larger perceptual shifts than long intervals. More recently, several studies have confirmed the effect of the statistical relation between events on the binding effect ([58]; [59]), which is generally thought relevant to the perception of causation [49]. Temporal binding also depends on the physical characteristics of the effect: The more salient an auditory effect, the stronger the temporal binding of the movement to the effect [90]. Furthermore, temporal binding is not limited to the perception of self-generated movements, but is also found in the observation of other human agents, as opposed to non-biological agents [91]. Similarly, passive movements of the participant's body are less bound to their effects than actively initiated

ones ([73], [90]). Thus, temporal binding has been described as an associative mechanism that is specific to intentional action. However, recent research has shown that intentional action is not sufficient to produce temporal binding and has confirmed that causality is the critical trigger [13]. At the same time, several studies have shown that intentional binding also depends on external sensory evidence regarding the source of the action. For example, using prime in order to modify the content of conscious thought prior to moving, Moore and collaborators [60] show that general inferences about external events could modulate the perceived interval between action and effect for involuntary movements.

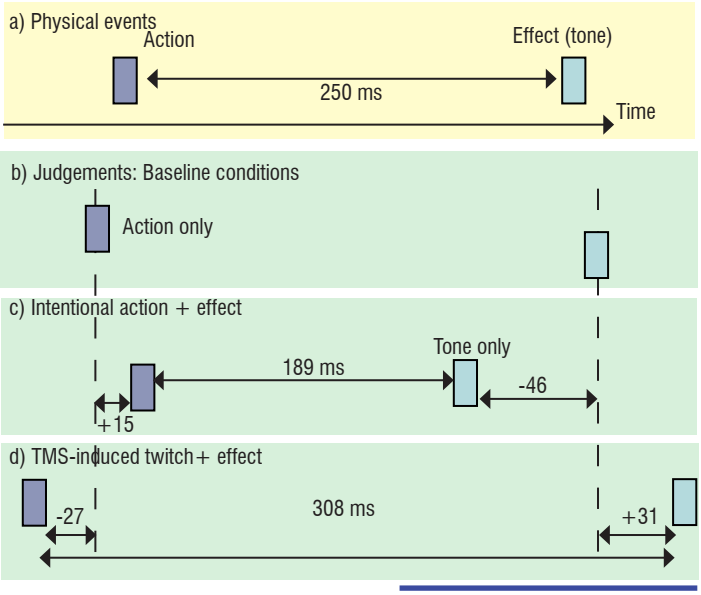

Figure 2 - Intentional binding between voluntary actions and their effects.
(a) Subjects make voluntary action to evoke a tone 250 ms later.
(b) The perceived time of action and tone are first estimated in baseline conditions in which only the action or the tone occurs.
(c) When action and tone occur together, the perceived time of the action shifts forwards in time from the baseline value, towards the tone. The perceived time of the tone shifts earlier in time, towards the action. Action and tone are bound together across time, implying a reduction in the perceived interval between them.
(d) Replacing the intentional action with a physically similar involuntary movement evoked by TMS abolishes and reverses the binding effect.
Data from [43].

Though several questions remain concerning the necessary and sufficient conditions of temporal binding, we could assume that this phenomenon offers a robust measurement of the sense of agency. This has been shown with a variety of methods over a considerable interval range, ([16]; [20]; [23]; [45]; [60]; [83]; [84]). Our concern in the following part of this article is the possibility of using this implicit agency measurement in the comprehension of the OOL performance problem.

Intentional binding: a window on to OOL performance problem?

In the first part of this review, we have proposed that the mechanism of agency be considered as a potential origin for the OOL performance problem. Interactions with complex machinery are clearly one area where sense of agency is important, but may be difficult to achieve. In regard to the large body of research concerning the intentional binding effect, this phenomenon appears as a good candidate to tackle such a relation. However, some issues and problems must be addressed, in order to generalize intentional binding for a more complex situation, like the situations encountered in an aeronautical context.

First, how robust is the binding effect? Specifically, the problem is to determine whether an intentional binding effect could be extended to more complex situations. Indeed, nearly all previous investigations have based their methods on a very simple paradigm, typically asking participants to press a key and judge either the time of their key-pressing or a subsequent tone. Few or none (excepted [20]) have studied how binding occurs for the kinds of actions performed and events encountered in everyday life, such as kicking a ball and watching it fly away, in such a way that the external validity of this effect remains unclear. Particularly, interactions with machines regularly involve sending a command to a system and monitoring the system response, and we regularly feel a sense of controlling how the machine behaves in such situations. Under such a condition, we can require the robustness of the binding effect for this more demanding task and with a more complicated device that most experimenters use to find such nuanced psycho physical effects.

Secondly, how gradual is the binding effect? The gradual nature of the binding effect, particularly the role of action selection in binding, has been poorly explored at the moment. Indeed, previous tasks relied either on explicit binary judgments of agency vs. non-agency in self-other discrimination paradigms [17], or on contrasting binding between entirely voluntary and entirely involuntary situations [43]. In such a case, the intentional binding is viewed as an all-or-none phenomenon. Such a view of the binding effect is not suited to the real nature of agency in a multi-agent environment. For example, agency comes by degrees: one can feel more or less in control. This variation is particularly clear when using machines. The feeling of control varies quite subtly as the relation between operator inputs and machine response. Whether or not the binding effect is sensitive to this gradual component of agency is an important issue in regard to the use of this phenomenon in more complex situations.

Thirdly, the temporal range in which binding operates remains ambiguous. Early studies on binding showed that longer action–outcome intervals were associated with reduced binding ([41]; [43]; [20]). Authors concluded that the strength of association operates over a limited time window and intentional binding is limited to sensorimotor timescales. Clearly, such a timescale does not match with the complex nature of the actions and their effects in an aeronautical context. The possibility to find intentional binding for larger intervals becomes a first concern. Recent works have already discussed the presence of binding for large intervals, as well as the increase of binding with time (for a discussion see [45]; [84]). Using a magnitude estimation procedure, more recent work by Buehner and Humphreys [13] has shown that temporal binding occurs over intervals far greater than those previously explored (up to 4s). Interestingly, they showed that this temporal binding effect increased with interval size and that initial binding limitation in time only depends on the artificial constraints of the Libet Clock method. How can we reconcile these inconsistent results? What we propose, is to go further than the classical acceptance that temporal contiguity is an important factor for the sense of agency (see [43]; [79]). Temporal contiguity is certainly a key factor

for the sense of control, but this contiguity must be considered in regard to the temporality of the task carried out. As explained by Wegner [77], causal events precede their effects, usually in a timely manner. To be perceived as a truly worthy cause, the event can't start too soon or start too late - it must be on time just before the effect. In other words, we propose that temporal contiguity is task-dependent and that intentional binding occurs in a specific "window of opportunity", which may vary across tasks and may also depend on the range of action-effect delays experienced in a given setting. For example, operant learning is similarly sensitive to the natural time delays of the system linking actions to effects, even for systems as familiar as one's own body. Particularly, when rats learn to avoid eating food associated with illness, the optimal delay between eating and illness is not the shortest possible delay, but rather a delay consistent with their normal digestive operation [33].

Accordingly, in a recent and original experiment [5], we investigated intentional binding in a complex naturalistic situation (see box 3). It is noteworthy that the temporal judgment effects were found despite the demanding nature of the task and despite the fact that the complicated simulator is not the kind of device that most experimenters use to find such nuanced psychophysical effects. That the temporal judgments were observed is a testament to the robustness of the phenomenon of intentional binding. This initial study provides interesting perspectives as it asks many questions.

A fertile way of investigation

In the current context of a continued increase in automation, the OOL performance problem becomes a major human factor question. In this review, I have tried to show that psychological ideas about the self, and particularly the concept of agency, can help to understand the performance problem. Our first studies about the agency mechanism in supervision tasks involving highly automated systems clearly show the relationship between automation and a feeling of control. However, more research is needed to fully understand the role of the sense of agency in the OOL performance problem.

Relation between sense of control and operator performance

The next step would be to test whether systems that produce a stronger subjective sense of agency also produce better performance. When we get on an airplane, we believe (and hope!) that the pilot feels in control of the aircraft. Interestingly, in the case of a high

Box 3 - Intentional binding in aeronautical context: a first trial

In a recent study [5], we have decided to explore intentional binding in a complex naturalistic situation involving flying an aircraft with various degrees of autopilot assistance. Particularly, we assessed the influence of the level of automation on participants' jugement of agency, as well as on intentional binding.

Important results were obtained:

- **replication** of the basic binding effect **in a more complex situation** (with high face-validity);
- quantitative changes in **binding** are **strongly associated** with quantitative changes in **explicit reports** of agency;
- **a Gradual** increase in the interval estimates with the in creasing level of automation;
- Iintentional binding occurs in a specific **"window of opportunity"**, which depends on the range of action-effect delays experienced in a given setting.

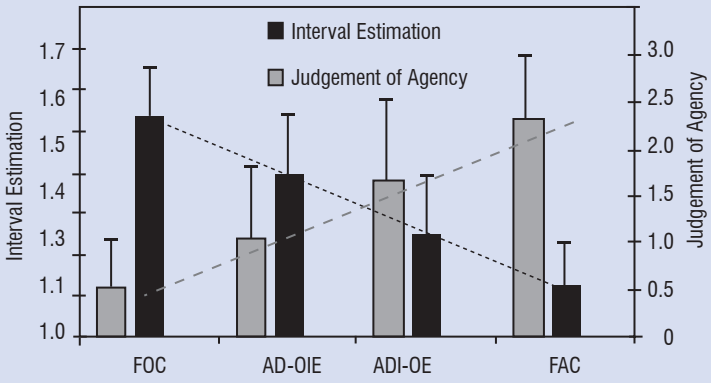

Figure B3-01 - Modulation of interval estimates (in gray) and explicit judgment of agency (in black) by automation level. The gradual increase in automation (from left to right) comes with a gradual increase in interval estimation (decrease in the binding effect) and a gradual decrease in the feeling of agency. Reproduced from [5].

This research presents additional compelling evidence for the existence of the binding effect in a new paradigm that is substantially more ecologically-valid than the traditional laboratory paradigms that have been used to asses intentional binding. It is noteworthy that this binding effect was found despite the demanding nature of the task and despite the fact that the complicated simulator is not the kind of device that most experimenters use to find such nuanced psychophysical effects. Such a result bears witness to the robustness of the intentional binding phenomenon.

Our findings are important, not just for theories regarding the special nature of voluntary action in the mind/brain but for the improvement of the interactions between humans and machines. Human welfare depends increasingly more on the successful interaction between humans and machines, as is obvious in the cockpit of any commercial airplane. Intentional binding may be a useful measure in the understanding and optimization of this interaction.

level of automation, pilots have reported increased problems in understanding and anticipating aircraft behavior, and in tasks such as programming the FMS [65]. For instance, automation surprises [66] arise when the technology autonomously performs tasks that cause the aircraft to behave in a manner that the pilots had not anticipated. We assume that such a decrease in situation awareness arises from a non-satisfaction of the agency mechanism. How does agency influence the operator performance? How does agency modulate the consciousness threshold? Many questions remain unclear concerning the relationship between agency and performance, and further studies are needed.

How can the operators' sense of control be modulated in a highly automated system?

Another important issue concerns the psychological factors underlying the feeling of control. Indeed, the research of factors affecting the feeling of control of the operator could lead to interesting design principles offering the maximal agency. According to [78], the feeling of control seems to occur in accordance with various principles– priority, consistency and exclusivity. Indeed, Wegner argues that when a thought occurs prior to an action, is consistent with the action and the action has no plausible alternative cause, then we experience the feeling of consciously willing the action. In contrast, when thoughts do not arise with such priority, consistency and exclusivity, we experience the ensuing actions as less willed or voluntary. We believe that these principles could be an interesting way to artificially modulate the feeling of control of an operator in interaction with highly automated systems. The investigation of this authorship processing in the field of human-machine interaction may be fruitful. Indeed, different solutions may be envisaged when designing a human-machine interface (HMI). In our opinion, such design decisions should be based on a precise understanding of the effects of key design variables (e.g. level of automation, command & control devices, modalities of the feedback) and of the mechanisms involved in authority sharing.

Binding effect: a new tool for HMI evaluation

To conclude, we assume that this topic of research will lead to the creation of technologies that inspire new ways of working. The ability to measure the sense of agency quantitatively is important, since it allows the sense of agency to be used as a measure in evaluating human-automation performance. We think that such works will lead to the introduction of a new methodology for the specification and evaluation of the potentiality for an HMI to satisfy the agency mechanism, and by extension, to keep the operator in the loop. New progress in HMI optimization should follow. We also believe that this new methodology could be used in the evaluation of the immersive quality of a virtual environment. In a simulated environment, the operator needs to feel in control of the simulated action. We assume that the intentional binding effect could quantify this immersive quality of the simulator ■

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Acronyms

SA (Situation Awareness)
OOL (Out-Of-the-Loop)
HMI (Human Machine Interface)
FMS (Flight Management System)

AUTHORS

Bruno Berberian received his Ph.D. in Human Movement Science, from the University of Mediterranee in 2007. After a post-doctoral position in the Consciousness, Cognition and Computation group (Belgium), he joined Onera in 2009. His primary research interests concern human factor issues related to an aeronautical context, specifically in the areas of feeling of control and consciousness.

Patrick Le Blaye has been a research engineer at Onera since 1992. His research interest includes flight safety and human automation interaction.

Nicolas Maille graduated from a French engineering school (Supaero) in 1993 and received a PhD in 1999. Since 2000, he has conducted research at Onera in the field of artificial intelligence and human factors. His activity includes the development of experience feedback methodologies and tools for aircraft operators.

Jean-Christophe Sarrazin, PhD in Life Science and Health (Aix-Marseille 2), joined Onera in 2007 after two postdocs (Inria and UE). He is currently a research engineer in the Systems Control and Flight Dynamics department and a member of the scientific committee of the Systems and Information Processing branch. He is also an expert for the ANR. His main research topic concerns human modeling for human factor engineering in aeronautics.