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# Cognitive conflict in human–automation interactions: A psychophysiological study

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## ABSTRACT

The review of literature in sociology and distributed artificial intelligence reveals that the occurrence of conflict is a remarkable precursor to the disruption of multi-agent systems. The study of this concept could be applied to human factors concerns, as man–system conflict appears to provoke perseveration behavior and to degrade attentional abilities with a trend to excessive focus. Once entangled in such conflicts, the human operator will do anything to succeed in his current goal even if it jeopardizes the mission. In order to confirm these findings, an experimental setup, composed of a real unmanned ground vehicle, a ground station is developed. A scenario involving an authority conflict between the participants and the robot is proposed. Analysis of the effects of the conflict on the participants' cognition and arousal is assessed through heart-rate measurement (reflecting stress level) and eye-tracking techniques (index of attentional focus). Our results clearly show that the occurrence of the conflict leads to perseveration behavior and can induce higher heart rate as well as excessive attentional focus. These results are discussed in terms of task commitment issues and increased arousal. Moreover, our results suggest that individual differences may predict susceptibility to perseveration behavior.

## 1. Introduction

### 1.1. Conflict in human–system interactions: a complementary metric to human error

Traditionally, human error – defined as a deviation between the human operator's real activity and the expected task – is a measure used to predict the online degradation of human–system interactions (Callantine, 2002; Lesire and Tessier, 2005; Steinfeld et al., 2006). Nevertheless, this method shows its limits as it faces two epistemological problems regarding the existence and of the status of human error. Indeed, the identification of a so-called human error is risky as long as the concepts of norms and the procedures to which it relates are not always defined or formalized. Moreover, it is recognized that operators change and adapt procedures for new ones that are sometimes safer and more effective (Dekker, 2003). The occurrence of an error does not necessarily lead to the degradation of human–system interactions. For example, expert operators inevitably make errors but fix most of them (Rizzo et al., 1987), and such a production–detection–fixation cycle of errors is a characteristic of

expertise (Allwood, 1984). Eventually the occurrence of errors plays a positive role in the self-assessment of the human operator's performance (e.g., fatigue). An alternative approach is to consider the concept of *conflict* as a means to assess human–system performance. First, from a formal point of view, this concept of conflict is more interesting than the concept of human error in the way that it does not systematically relate to a procedure. The conflict between agents exists without any norm or truth and may be formalized as follows (Dehais et al., 2010a; Rushby, 2002): its essence is contradiction, the difference between two points of view (Castelfranchi, 2000). According to this perspective, the conflict is considered as the impossibility for an agent or a group of agents to reach a goal that matters (Castelfranchi, 2000; Dehais et al., 2003; Easterbrook, 1991). The impossibility to reach a goal may stem from inconsistent cues in the user interface (Orasanu and Fischer, 1997), insufficient mental models (Woods and Sarter, 2000), limited physical or cognitive resources (Mozer and Sitton, 1998), an action of another agent (Castelfranchi, 2000), or an environmental constraint (e.g., weather). The fact that a goal matters may stem from safety reasons (e.g., succeeding in an anti-collision maneuver) or from time or economical pressure (e.g., achieving the landing in order to avoid a go-around).

Secondly, the concept of conflict is not limited to its structural aspect, as it merges both psychological and affective attributes. Indeed, sociology shows that the presence of conflict is an indicator

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of a dynamic of tension and opposition between individuals (Lewin et al., 2004; Sherif and Sherif, 1953; Simmel, 1955). In aviation psychology, the analysis of air safety reports (Holbrook et al., 2003) have shown that the occurrence of a cognitive conflict is a remarkable precursor to the degradation of human operators' performance, provoking plan continuation error (Orasanu et al., 2001). Experimentations conducted in flight simulators revealed that, such conflict could lead to patterns of behaviors that indicate perseveration (Dehais et al., 2003; Dehais et al., 2010b). This particular behavior is defined – within the psychology literature – as the tendency to continue or repeat an activity after the cessation of the original stimulation, and to an extent that the activity is often no longer relevant to the task at hand. More precisely, Sandson and Albert (1984) identified three distinct categories of perseveration, among which the stuck-in-set perseveration, “the inappropriate maintenance of a current category or framework”. Once caught up in perseveration behavior, it is assumed that most of the human operators' resources are summoned up toward conflict solving. As a consequence, the cognitive abilities of the operators are impaired with a strong tendency for attentional shrinking that can lead to excessive focusing on one display, to the neglect of other information (e.g., alarms) that could question their reasoning. Conflict not only occurs between humans, but may also be induced while interacting with artificial systems. Indeed, similar attentional issues have been widely described within crew-automation conflicts known as ‘automation surprises’ (Sarter and Woods, 1995; Sarter et al., 1997) whereby the autopilot does not behave as expected by the crew. This cooperation breakdown can lead to accidents with an airworthy airplane where the crew persists in solving a minor conflict (Billings, 1996) “instead of switching to another means or a more direct means to accomplish their flight path management goals” (Woods and Sarter, 2000, p. 347), and this can occur despite the onset of auditory alarms (Beringer and Harris, 1999). Such hazardous situations are not only relevant in aviation but also in the context of human supervisory control of unmanned vehicles (UVs) where careless design of authority sharing (Inagaki, 2003) degrades the human operator's performance leading to inadequate behaviors (Parasuraman and Wickens, 2008; Van Ginkel et al., 2006). Moreover, some authors (Meyer, 2001; Parasuraman and Wickens, 2008; Rice, 2009) revealed that unreliable diagnostic automation (i.e. miss-prone vs. false alarm-prone automation) and automation complacency might lead to conflictual situations that also negatively impact attentional resources (Metzger and Parasuraman, 2005; Wickens et al., 2005) and deteriorate the human operator's global performance (Dixon et al., 2007; Wickens and Dixon, 2007).

## 1.2. Present study

The main objective of this study was to show that the occurrence of a conflict with automation is a precursor to the degradation of the human operator's performance and the shrinking of their attention (Dehais et al., 2003; Dixon et al., 2007; Sarter et al., 1997). To test this hypothesis, the human-UV operator interactions domain was chosen as it offered a generic framework to study conflict with automation. Moreover, this domain of application is relatively recent and only a few studies have been conducted compared to aviation or nuclear power plants. A scenario was designed whereby an authority conflict was initiated by a low-battery event while participants were deeply involved in a target identification task. This hazard triggered a safety procedure that allowed the UV to return to base autonomously. It was hypothesized that the occurrence of this typical ‘automation surprise’ scenario would induce psychological stress and lead participants to excessively focus on the identification task without understanding the automation logic.

Three types of measurements were proposed to assess the effects of the conflict. Firstly, decision making at the time of the failure was examined, as it was necessary to ensure that participants did not detect the failure and did not understand the robot behavior by letting it go back to base. Secondly, participants' ocular activity was recorded to detect the occurrence of an excessive attentional focus revealed by decreased saccadic activity, long concentrated eye fixations (Cowen et al., 2002; Tsai et al., 2007), and fewer scanned areas of interest on the user interface. Finally, heart rate was also collected to confirm that catabolic activity was increased, as this would suggest psychological stress (Dehais et al., 2011b) and mobilization of mental energy (Causse et al., 2010) to deal with the conflict. Indeed, conflict is likely to produce stress and emotional reaction (Mann, 1992), introducing barriers to “rational” decision making.

## 2. Method

### 2.1. Participants

Thirteen healthy adults (mean age = 27.84, SD = 6.53; mean level of education = 17.15, SD = 1.86), all French defense staff from Institut Supérieur de l'Aéronautique et de l'Espace (ISAE) who had experience of operating robots, were recruited by local advertisement. All participants gave their informed consent after having received complete information about the nature of the experiment.

### 2.2. Material

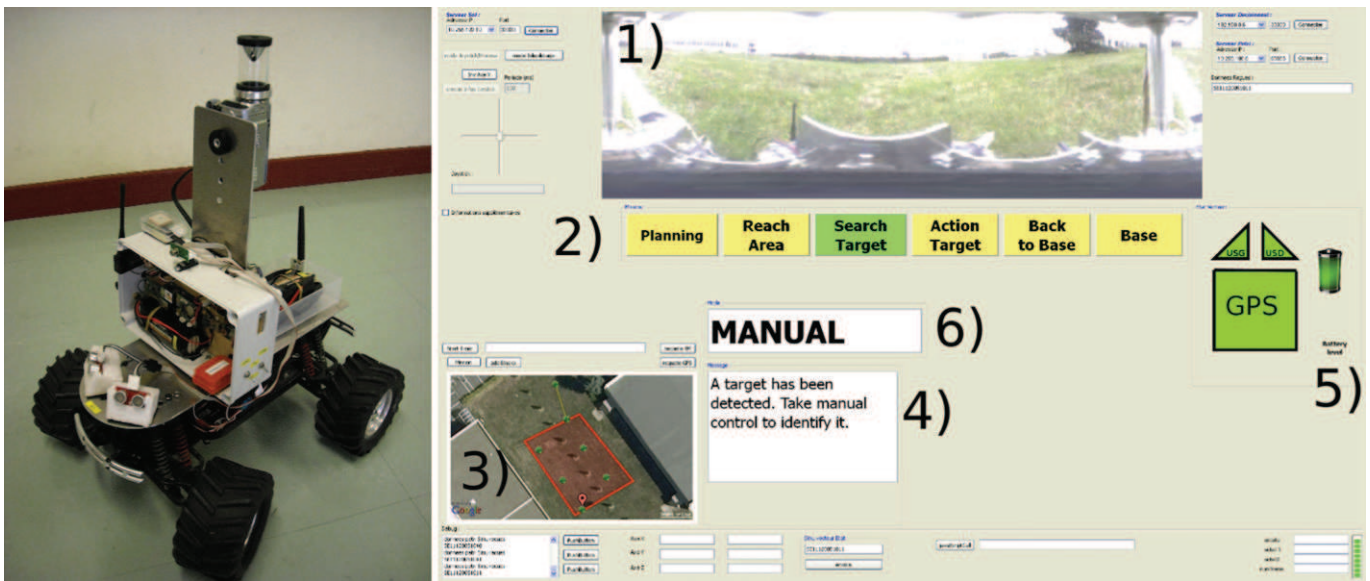
The experimental setup, developed at ISAE, was composed of an unmanned ground vehicle (UGV), a ground station to interact with the robot, and a computer interface dedicated to triggering special hazards within the scenario (e.g., failure). The UGV (see Fig. 1) was equipped with two microprocessors, an embedded real-time Linux, a Wi-Fi module, a high-frequency emitter, and a set of sensors (a GPS module, an inertial central, ultrasound sensors, a panoramic camera, and an odometer). The UGV could be operated in “manual mode” or in “supervised mode”. In manual mode, the UGV was controlled by the human operator with a joystick. In supervised mode, the UGV performed waypoint navigation, but any actions of the human operator with the joystick let her/him take over until the joystick was released.

The ground station (see Fig. 1) was displayed on a 24-inch screen and offered different information to control and to supervise the UGV: 1) a panoramic video scene screen placed in the upper part of the graphic user interface (GUI); 2) a mission synoptic stating the current segment of the mission (e.g., “search target”) below the panoramic video; 3) a Google map, in the lower left corner, displaying the tactical map and the position of the robot; 4) an interactive panel sending the messages and the requests; 5) a “health” panel indicating the status of the robot (GPS status, ultrasound status, and battery level); and 6) a mode annunciator (“supervised” vs. “manual”).

### 2.3. Experimental scenario

The scenario consisted of a target localization and identification task. The target was made of black metal with red stripes (length: 1 m; height: 80 cm) and two short messages written in white on each side (front side “OK”; back side “KO”). The camera scene of the robot needed to be placed at 1.5 m maximum from the target to read the message.

The mission lasted around 4 min and was segregated in four main segments: S1 – “Reach the area”, S2 – “Scan for target”, S3 – “Identify target”, and S4 – “Battery failure” segment. At the



**Fig. 1.** The left panel shows the unmanned ground vehicle developed at ISAE while the right panel displays the graphic user interface (GUI) dedicated to controlling and supervising the robot. The critical parts of the GUI are labeled: (1) panoramic video scene screen; (2) synoptic; (3) tactical map; (4) interactive panel; (5) “health” panel; (6) mode annunciator.

beginning of the mission, the UGV navigated in supervised mode to reach the search area (S1). Upon arrival, it then started scanning for detecting the target (S2). When the robot was in the vicinity of the target, a message was sent to the human operator to take over and to control in manual mode the UGV for identifying possible similarities of the two messages (OK/KO) written on each side of the target (S3). While the human operator was involved in the identification task, a ‘low-battery’ event was then sent out by experimenter (S4). In turn, this event led to a safety procedure that allowed the robot to return to base in supervised mode.

As this failure happened at a crucial moment of the mission where the human operator was handling the robot near the target, we expected that this event would create an authority conflict between the human’s goal—to identify the target—and the robot’s goal—to return to base. Moreover, we hypothesized that the human operator would not notice the alerts on the interface dedicated to warn him/her of the low-battery event.

#### 2.4. Failure

As mentioned in Section 2.3, the low-battery event triggered an automatic procedure that let the UGV take over and go back to base by the shortest route. The human operator was informed of the occurrence of this event by three main changes in the GUI (see Fig. 2): 1) the battery icon was turned to orange and a “Low battery” message was displayed below it; 2) the new guidance mode “Supervised” flashed two times, and 3) the segment displayed on the synoptic was evolving from “Search Target” to “Back to Base”.

#### 2.5. Psychophysiological measurement and oculometry

Cardiac and ocular activities were recorded during the four segments of the mission. An electrocardiogram (ECG) was used to collect the participants’ cardiac activity at a sampling rate of 2048 Hz with the ProComp Infinity system (Thought Technology). Three electrodes connected to an extender cable were applied to the participant’s chest using Uni-Gel to enhance the quality of the signal. The BioGraph Infiti© software was used to export and filter the heart rate (HR) derived from the inter-beat interval. Due to a commonly observed difference in HR baseline values among

participants, HR values were then standardized to allow a between-participants comparison: they were recorded at rest for 3 min before working while participants sat in a comfortable chair without any stimulation. The mean HR of the resting period was subtracted from the mean HR calculated for each of the four segments of the mission. This data reduction provided the mean HR change for each segment.

In parallel, a Pertech head-mounted eye-tracker was used to analyze the participants’ ocular behavior. This 80-g non-intrusive device has .25 degree of accuracy and a 25-Hz sampling rate. A dedicated software (EyeTechLab©) provides data such as time-stamps and the x,y coordinates of the participants’ eye gaze on the visual scene. Eight areas of interest (AOI) were defined on the GUI as follows: 1) “tactical map”, 2) “interactive panel”, 3) “mode annunciator”, 4) “synoptic”, 5) “back to base”, 6) “GPS and ultrasound status”, 7) “battery status”, and 8) “panoramic video”. A ninth AOI was considered in order to collect the ocular fixations out of the other eight previous ones. We first examined the fixations on the battery status AOI during the management of the failure (S4). Other oculometric variables (Duchowski, 2007) were also considered to assess the effect of the conflict on the distribution of visual fixations. The mean percentage fixation time on the panoramic video was mainly considered during each segment as it was hypothesized that the authority conflict would induce an excessive focus on this particular AOI. We also measured for each of the four segments the number of scanned AOIs and the gaze switching rate, which corresponded to the number of gaze transitions from AOI to AOI per minute, in order to examine whether the conflict would be associated with reduced saccadic activity ensuing from attentional shrinking (Cowen et al., 2002; Tsai et al., 2007).

#### 2.6. Procedure

Participants sat in a comfortable chair placed 1 m from the GUI in a closed room that had no visual contact with the outdoor playground where the robot evolved. The ECG electrodes were arranged on the participants’ chest and the eye tracker was placed on their head. Next, participants completed a 13-point eye-tracker calibration and then had to rest for 3 min to determine their cardiovascular baseline. The mission was explained and the GUI

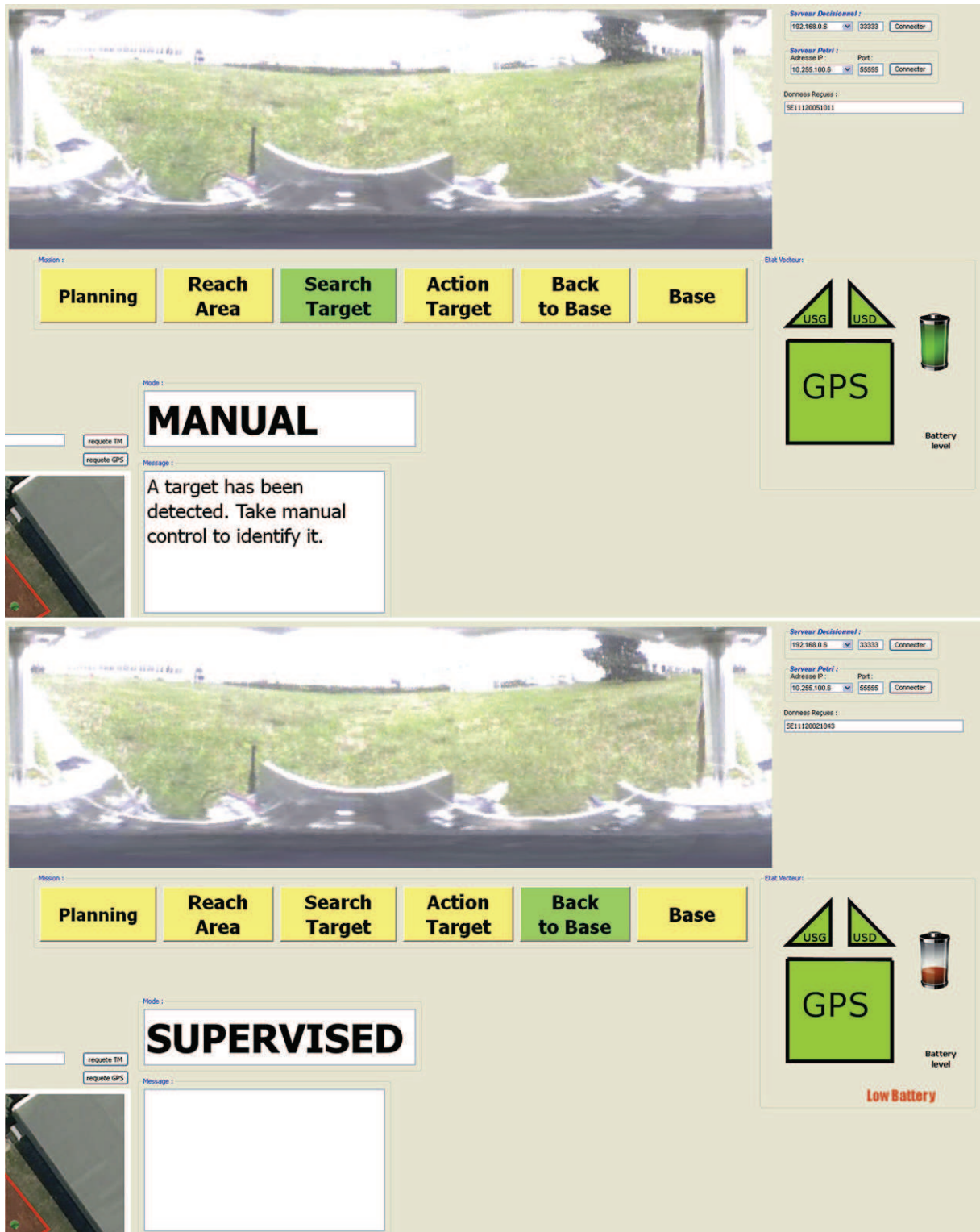


Fig. 2. The left panel shows the graphic user interface (GUI) before the failure while the right panel displays the GUI with the low-battery event.

was detailed. The two guidance modes were presented with particular attention to the supervised mode. Participants were trained for 20 min to handle the robot through the panoramic video screen in the two guidance mode conditions. They were told that four main hazards may occur during the mission such as (1) a low-battery event, (2) a communication breakdown, (3) a GPS loss, or (4) an ultrasound sensor failure. For each of these hazards, the

associated procedure and the expected robot behavior were explained: (1) "Let the robot go back to base in supervised mode immediately", (2) "Wait for the communication or the GPS signal to come back and check the battery level to decide whether or not to abort the mission", and (3–4) "Manually assist the robot to avoid obstacles". The means to diagnose these four issues on the GUI were also explained: (1) "The battery icon turns to orange with an

associated orange message; the mode changes to *Supervised* and is flashed twice; the segment of the mission becomes *Back to base*"; (2) "The user interface is frozen"; (3) "The GPS icon turns to red and the guidance mode changes to manual control", and (4) "The ultrasound icons turn to red". Participants were trained to detect and manage each situation once. After the briefing, we double-checked the participants' understanding of the instructions and procedures. After the experimentation, participants were asked whether they perceived the low-battery event and understood the robot's behavior.

### 2.7. Statistical analysis

All behavioral data were analyzed with Statistica 7.1 (© StatSoft). The Kolmogorov–Smirnov goodness-of-fit test has been used for testing normality of our variable distributions. As these latter were not normal, we used non-parametric Friedman's ANOVA and Wilcoxon Signed-rank tests (as post hoc comparison tests) to examine the effects of the mission segment type on HR and the various oculometric measurements. Table 1 shows the main effects and the pairwise comparisons for each of the four psychophysiological measures.

## 3. Results

### 3.1. Behavioral results

Results revealed that 9 participants out of 13 (69.2%) persisted on detecting the target instead of letting the robot go back to base as they should have done. Although they felt surprised by the behavior of the robot, these participants all declared that they neither noticed the low-battery event nor the other changes on the GUI. The other four participants reported to have rapidly noticed the failure and decided to let the robot go back to base. In order to assess the impact of the conflict on performance, statistical analyses carried out on the psychophysiological measures were restricted to the nine perseverative participants. Due to the small number of participants who did not persevere, no inferential statistical analyses were performed on their psychophysiological data. However, we nevertheless plotted these data against those of the perseverative participants to highlight the descriptive difference in the pattern of results between the two groups.

### 3.2. Psychophysiological and oculometric results

#### 3.2.1. HR change

Mean HR change for both perseverative and non-perseverative groups, in beats per minute (bpm), is plotted in Fig. 3 as a function of Segment type. The ANOVA performed on the perseverative group showed that mean HR change increased progressively after

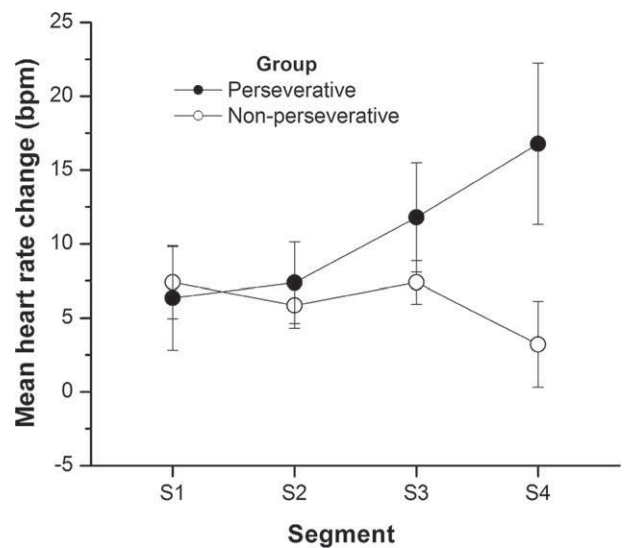


Fig. 3. Mean HR change (bpm), across the four mission segments for perseverative and non-perseverative participants. Error bars represent the standard error of the mean.

the second segment,  $\chi^2(3) = 18.33, p < .001$ . Interestingly, while mean HR change during S4 continued to increase (16.77 bpm) for the perseverative participants, it nearly came back to baseline in the non-perseverative group (3.21 bpm). Such a result suggests that participants who perseverated in controlling the robot encountered more psychological stress and deployed more mental energy when dealing with the conflict than those who let the robot go back to base.

#### 3.2.2. Fixation on the battery status AOI during S4

Consistently with the behavioral results, we find that the 9 perseverative volunteers did not glance at the battery status AOI whereas the 4 non-perseverative volunteers glanced at least one time on this particular AOI.

#### 3.2.3. Percentage of fixation duration on the panoramic video

Fig. 4 shows the mean percentage of time spent fixating the panoramic video as a function of Segment type for both groups. There was a significant Segment type effect in the perseverative group,  $\chi^2(3) = 23.53, p < .001$ . Paired comparisons showed that the time spent on the video increased progressively during the four segments. Again, we compared the perseverative group to the non-perseverative group. Whereas the perseverative group spent 95.43% of fixation time on the video during S4, the non-perseverative group spent only 82.10% of fixation time on it. This latter result showed that the miscomprehension of the situation led participants to focus on the panoramic video in an excessive manner.

#### 3.2.4. Number of scanned AOIs

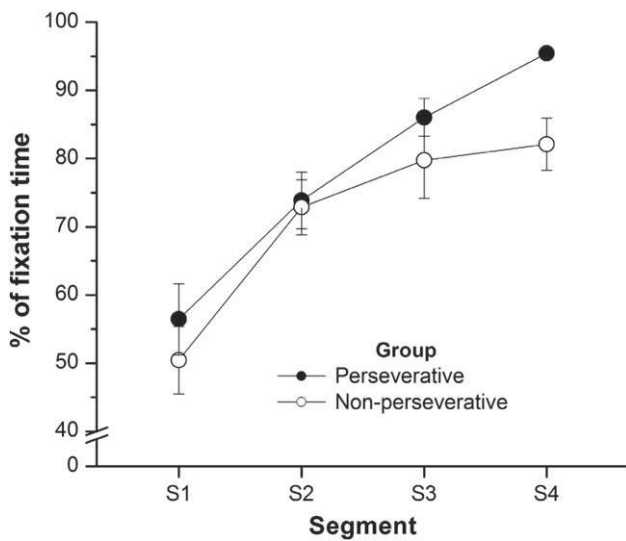
The mean number of AOIs that were scanned by the two groups during each of the four segments is plotted in Fig. 5. The effect of Segment type was significant for the perseverative group,  $\chi^2(3) = 19.13, p < .001$ . Paired comparisons showed that the number of scanned AOIs started decreasing after S2. Again, the examination of the perseverative and non-perseverative groups revealed a different pattern of results with regards to the passage from S3 to S4. The number of scanned AOIs continued to decrease from S3 to S4 in the perseverative group whereas it increased dramatically within the non-perseverative participants (3.11 vs. 7.75, respectively). As for fixation duration, this latter result

Table 1

ANOVA summary table for segment type effects on HR and the various oculometric measurements for the perseverative participants ( $N = 9$ ).

Predictors (Segment type effect)	$p$	Post hoc comparisons <sup>a</sup>
Mean HR (bpm)	<.001	S4 > S1 & S3; S3 > S1 & S2
% of fixation duration on the video	<.001	All comparisons are significant
Number of scanned AOIs	<.001	S1 > S3 & S4; S2 > S3 & S4; S3 > S4
Gaze switching rate (transitions/min)	<.001	S1 > S2 & S4; S2 > S4; S3 > S4

<sup>a</sup> Wilcoxon signed-rank tests significant at  $p < .05$ .

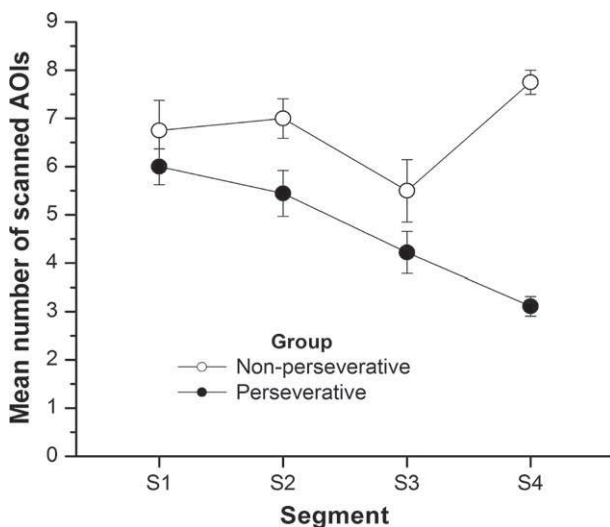


**Fig. 4.** Mean percentage of time spent fixating the panoramic video across the four segments for perseverative and non-perseverative participants. Error bars represent the standard error of the mean.

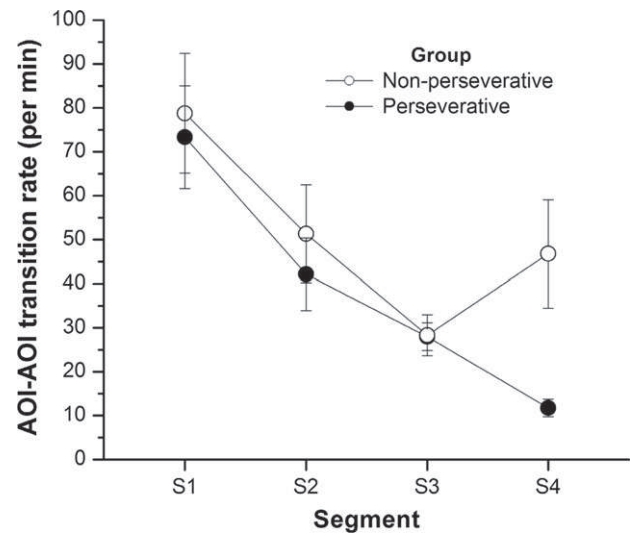
suggests that perseverative participants were excessively focusing on the panoramic video during the conflict.

### 3.2.5. Switching rate

Fig. 6 shows the gaze switching rate (gaze transitions from AOI to AOI per min) across the four mission segments for both perseverative and non-perseverative participants. We found a significant Segment type effect,  $\chi^2(3) = 21.13, p < .001$ . Paired comparisons showed that the transition rate fell progressively during the course of the scenario (except between S2 and S3). Interestingly, the transition rate differed between perseverative and non-perseverative participants during S4. While analysis performed on the perseverative group showed a significant decrease in the shifting rate between S3 and S4, the transition rate increased drastically in the non-perseverative group. The latter result suggests, once again, that participants unaware of the failure failed to redistribute their ocular activity and then produced excessive focusing on the panoramic video.



**Fig. 5.** Mean number of scanned AOIs in each of the four segments for perseverative and non-perseverative participants. Error bars represent the standard error of the mean.



**Fig. 6.** Gaze switching rate across the four segments for perseverative and non-perseverative participants. Error bars represent the standard error of the mean.

## 4. Discussion

The objective of this study was to show that the occurrence of a conflict during mission management is a precursor to the degradation of human operator–automation interactions. The behavioral results showed that a majority of operators (9 out of 13) persevered to achieve the no-longer-relevant identification task, despite the three different items of information displayed on the GUI dedicated to alerting them. The particular behavior of the robot, that started to roll away on its own as soon as the joystick was released, provoked typical ‘automation surprise’ situations (Sarter et al., 1997) and led most participants to continuously take over in order to drive the robot close to the target. Only four participants (i.e., 30.8%) perceived and understood the origin of the conflict and then decided rapidly to let the robot go back to base. This is testimony to the robustness of perseveration behavior, and stresses the importance of understanding the reasons that conflicts lead the human operator to persevere, and the factors that contribute to the adoption of the appropriate behavior when dealing with a conflict. As proposed in Section 1.1, one point of view is to consider the conflict (Dehais et al., 2003) as the impossibility for an agent or a group of agents to reach a goal that matters. Therefore, conflict solving requires the involved agent(s) to either revise partially (i.e. the so-called ‘compromise’) or to eventually drop their initial goal (Castelfranchi, 2000). Classical psychosociological theories (Beauvois et al., 1995; Festinger, 1957; Milgram, 1974) state that the higher and the longer the commitment to achieve a goal, the harder it is to drop this goal even if it is no longer relevant. Indeed in our experiment, as the target identification task was particularly crucial for the mission, it may have led participants to be particularly strongly committed to its success whatever the state of the robot. Another possible explanation to understand the absence of reaction to the visual alerts may rely on the theory of the ‘first failure’ effects (Parasuraman and Manzey, 2010) where first automation failure remains often unnoticed when operators have competing or conflicting goals. Though in our experiment, the automation behavior did not fail but reacted consistently to the battery failure, this theory contains some possible explanations as this latter behavior may have appeared erratic from the participants’ point of view.

The authority conflict also impacted the participants’ autonomic nervous system and especially their attentional abilities with a trend for excessive focus. Of course the switch from an automated

guidance mode to a manual mode would be expected to increase stress and workload (Roscoe, 1993). However, participants who persevered in maneuvering the robot showed higher levels of energy mobilization during conflict management, and such excessive focus on the panoramic video that they neglected alerts on the GUI. This latter result is akin to an eye-tracking study where automation-surprise scenarios led pilots to neglect the relevant information needed to understand the automation behavior (Sarter et al., 2007). Taken together, these results may indicate that conflict induces attentional shrinking as participants tend to focus on information from a particular display to the exclusion of information presented outside this highly attended area (Thomas and Wickens, 2001). Different authors postulate that such narrowing of the visual scene may be explained by an increase in foveal load (Williams, 1985, 1995) or by stressors (Bahrick et al., 1952; Easterbrook, 1959; Easterbrook, 1991; Weltman and Egstrom, 1966). This latter explanation seems to be more consistent with our results. It is more likely that in our study the occurrence of the conflict acted as a stressor, as demonstrated by the cardiovascular response during S4, given that there was no increase in the foveal load between S3 and S4.

It is also worth noticing that the four participants who did not persevere exhibited lower HR during the conflict management. Moreover, these participants demonstrated better attentional abilities as they spent less time on the panoramic video and scanned more AOs throughout the scenario. These descriptive results are consistent with the findings of a study conducted in aviation (Thomas and Wickens, 2004) where eye-tracking data revealed that the participants who scanned more displays and more frequently had better abilities to detect off-normal events. Interestingly enough in our study, it appeared that the better performance of the four participants during S4 could be predicted regarding their oculometric and physiological patterns since the beginning of the mission. Indeed, these four participants had lower HR during S2 and S3, they spent less time on the video and scanned more AOs during S1, S2 and S3, and eventually they had a better switching rate during S1 and S2 than the nine perseverative participants. These results are consistent with the conclusion of Thomas and Wickens (2004) that individual differences could predict resistance to excessive focus on a single display. Such precursors pave the way for an online diagnosis of attentional shrinking based on a formal approach, such as that proposed by Mandryk and Atkins (2007).

One potential issue of this study is the relatively small sample size that limits the robustness of our conclusion concerning the perseveration behavior. Although our results converge towards the presence of perseveration, one cannot exclude that this behavior may have partly occurred by chance because the false positive rate is likely to be high with 13 participants. However, the use of a real "outdoor" robot is constraining (availability, important number of technicians and engineers required to prepare the robot...) and requires the recruitment of specialized participants that have limited time to devote to experimental work. Nevertheless, taken together the important differences between the perseverative and non-perseverative groups at both the behavioral and psychophysiological levels pointed towards other factors than mere chance to explain the creation of these groups. The 9 perseverative participants declared during the debriefing that they never noticed the failure and did not understand the behavior of the robot despite the 50 s allowed to detect the failure. This was obviously not the case for the non-perseverative participants. The failure to notice and understand the behavior of the robot seemed to be confirmed by the eye-tracking results: none of the 9 perseverative participants glanced at the battery status icon during the conflict management whereas the 4 non-perseverative participants did. During S4, the physiological and

eye-tracking measurements of the perseverative group were statistically different from the previous segments (i.e., S1–S3). Moreover, while the two groups showed a similar pattern of results across the first three segments, they differed substantially on every metric during the last segment (i.e., during the conflict). Another limitation of our study to confirm our assertions is related to the use of a single event, the three other possible failures embedded in our scenario (e.g., GPS failure) could not provoke authority conflict. These three other failures were introduced in order to increase the complexity of the scenario and avoid participant to expect the occurrence of a specific event (i.e. the battery failure) during the experiment. Hence, we intend to replicate the present experiment, using a new "indoor" setup composed of smaller robots, with more participants and a wider range of conflicting situations.

Eventually, the present study raises the question of how to solve conflictual human–automation situations. On the one hand, automation provides benefits (Billings, 1996) and ideally it has to override human operators' actions when this latter may jeopardize safety (e.g., automated flight protection systems are designed to avoid manual stall in Airbus aircrafts). On the other hand, our results suggest that, as with other findings (Sarter and Woods, 1995; Woods and Sarter, 2000), such an approach is meaningless while the human operator is out of the loop and does not understand the automation behavior. Moreover, the design of automation is pre-determined and its rigidity fails to adapt in the case of conflicts that may provoke "oscillating" behaviors, whereby both the human and the system aim to override each other as seen in the present experiment. One solution could consist of proposing a dynamic adaptive automation system (Parasuraman and Wickens, 2008) or a dynamic authority sharing system in which conflict detection is used to modify the level of automation and authority (Dehais et al., 2009). Nevertheless, this approach would not be sufficient as one must consider also that such a conflicting situation leads the user interface designers to face a paradox: how can one "cure" persevering human operators when they face a conflict, if the alarms/systems designed to warn them are neglected? Therefore, rather than adding new alarms, an optimal solution would be to use *cognitive countermeasures* to explain the conflict to the operator, as has shown to be effective with persevering light aircraft pilots and commercial pilots (Dehais et al., 2010b). Derived from a neuroergonomics approach to cognitive biases (Parasuraman and Rizzo, 2007), cognitive countermeasures (Dehais et al., 2003) are based on the temporary removal of information upon which the human operator is focusing, to be replaced by an explicit visual stimulus designed to change the attentional focus. Such an approach could help, for example, reducing excessive focus on the panoramic video for perseverative operators. This promising avenue in resolving human-automation authority conflict using cognitive countermeasures is currently under investigation in our laboratory (Dehais et al., 2011a).

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