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Mitigation of Conflicts with Automation: Use of Cognitive Countermeasures

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Objective: The aim of this study was to empirically assess the efficacy of cognitive countermeasures based on the technique of information removal to enhance human operator attentional disengagement abilities when facing attentional tunneling.

Background: Lessons learned from human factors studies suggest that conflict with automation leads to the degradation of operators' performance by promoting excessive focusing on a single task to the detriment of the supervision of other critical parameters.

Method: An experimental setup composed of a real unmanned ground vehicle and a ground station was developed to test the efficiency of the cognitive countermeasures. The scenario (with and without countermeasure) involved an authority conflict between the participants and the robot induced by a battery failure. The effects of the conflict and, in particular, the impact of cognitive countermeasures on the participants' cognition and arousal were assessed through heart rate measurement and eye tracking techniques.

Results: In the control group (i.e., no countermeasure), 8 out of 12 participants experienced attentional tunneling when facing the conflict, leading them to neglect the visual alarms displayed that would have helped them to understand the evolution of the tactical situation. Participants in the countermeasure group showed lower heart rates and enhanced attentional abilities, and 10 out of 11 participants made appropriate decisions.

Conclusions: The use of cognitive countermeasures appeared to be an efficient means to mitigate excessive focus issues in the unmanned ground vehicle environment.

Applications: The principle of cognitive countermeasures can be applied to a large domain of applications involving human operators interacting with critical systems.

Keywords: assistant system, attentional tunneling, alarm misperception, conflict, automation, eye tracking, psychophysiological measurement, unmanned vehicle

INTRODUCTION

There is a growing interest in unmanned vehicles (UVs) for civilian or military applications, as they prevent the exposure of human operators to hazardous situations. In these domains, automation is crucial because the human operator is not embedded within the system (Tvaryanas, 2004), and hazardous events may interfere with human-robot interactions (e.g., communication breakdown and latencies). The design of authority sharing is therefore critical (Inagaki, 2003) because conflict between the robot and human operator could seriously compromise mission success (Parasuraman & Wickens, 2008; Van Ginkel, de Vries, Koeners, & Theunissen, 2006). Such problems have motivated researchers (Meyer, 2001; Parasuraman & Wickens, 2008; Rice, 2009) to study imperfect diagnostic automation (i.e., miss-prone vs. false alarm–prone automation). Unreliable diagnostic automation has been shown to negatively affect attentional resources (Wickens, Dixon, Goh, & Hammer, 2005) and to degrade global human operator performance (Dixon, Wickens, & McCarley, 2007; Wickens & Dixon, 2007).

Interestingly, these findings are consistent with research in aviation psychology whereby crew-automation conflicts known as *automation surprises* (Sarter & Woods, 1995; Sarter, Woods, & Billings, 1997) occur when the autopilot does not behave as expected. These situations can lead to accidents with an airworthy airplane if, despite the presence of auditory warnings (Beringer & Harris, 1999), the crew persists with 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 & Sarter, 2000, p. 347). Flight simulator experiments demonstrate that in cases of cognitive conflict with mission management systems, human operators' attentional resources are almost exclusively engaged in solving the conflict (Dehais, Tessier, & Chaudron,

2003) to the extent that critical information, such as visual or auditory alarms, are neglected (Dehais, Tessier, Christophe, & Reuzeau, 2010), a phenomenon known as *attentional tunneling* (Wickens & Alexander, 2009).

Attentional impairment thus presents interface designers with a paradox: How can one expect to "cure" human operators from attentional tunneling if the alarms or systems designed to warn them are neglected? One solution is to consider Posner and Dehaene's (1994) theory of attention by which *cognitive countermeasures* can be designed as a means to mitigate such cognitive bias. Posner and Dehaene postulate that selective attentional processes are carried out by three distinct attentional networks: alerting, executive control, and orienting. The *alerting* network relates to sustained attention in response to a stimulus, the *executive control* network is engaged in activities that involve planning and decision making (Posner & Fan, 2007; see also Packwood, Hodgetts, & Tremblay, 2011), and the *orienting* network has been associated with disengaging, shifting, and reengaging attention.

There is evidence that impairment of the orienting network, induced by stressors (Pecher, Quaireau, Lemercier, & Cellier, 2010), may cause attentional neglect. Moreover, orienting visual attention (Posner & Dehaene, 1994) has been defined as disengaging, shifting, and reengaging attention. Experimentation conducted in a flight simulator showed that the absence of response to either auditory or visual alarms may be explained by an inability to disengage attention: The warning systems are based on providing the operator with additional information, but this information is of little use if the warning system is not also efficient at disengaging attention from the current task (Dehais et al., 2003). In contrast, the principle of cognitive countermeasures relies on the temporary removal of information on which the human operator is focusing for it to be replaced by an explicit visual stimulus to change the attentional focus. The user interface acts as a cognitive prosthesis as it performs the attentional disengagement and attentional shifting.

Present Study

The main objective of this study was to assess the efficiency of a cognitive countermeasure to assist the human operator when facing conflicts with highly automated systems. The domain of UV–human operator interactions was chosen to test this principle, as it offers a generic framework to study conflict with automation. Moreover, compared with aviation or nuclear power plants, this domain is relatively recent and research is sparse.

The experimental setup involved an unmanned ground vehicle (UGV), a ground station, and a computer interface dedicated to triggering special hazards within the scenario. It was necessary for the experimenter to initiate the major failures at the appropriate time from "behind the scenes," as the robot could be driven at different speeds, meaning that scenarios for each participant would unfold at a different rate. A scenario was designed so that an authority conflict was induced by a low-battery event at a point when participants were deeply involved in a target identification task. This hazard led to a safety procedure that allowed the robot to return to base autonomously. Three visual alerts were displayed on the user interface to warn the participants of the development of the situation. The visual modality was chosen because we aimed to understand the effects of conflicts and cognitive countermeasures on visual attention and on disengagement abilities in particular.

One prediction is that the occurrence of this typical automation-surprise scenario would induce stress and lead the participants to attentional tunneling on the identification task without understanding the automation logic. According to the literature, such an excessive focus is associated with decreased saccadic activity, long concentrated eye fixations (Cowen, Ball, & Delin, 2002; Tsai,Viirre, Strychacz, Chase, & Jung, 2007), and fewer scanned areas of interest on the user interface (Thomas & Wickens, 2004).

Three types of measurements served to assess the efficiency of the cognitive countermeasure. First, decision making at the time of the failure was examined, as it was necessary to ensure that participants had detected the failure and understood the robot behavior by letting it go back to base. Second, participants' ocular activity was recorded to ensure that attentional shrinking was mitigated, as indicated by increased saccadic activity and a greater number of scanned areas of interest. Finally, heart rate (HR) was also measured to establish whether sympathetic activity is reduced because of the countermeasure, thus suggesting less psychological stress and less mobilization of mental resources to deal with the situation (Causse, Sénard, Démonet, & Pastor, 2010).

METHOD

Participants

For this study, 23 healthy participants (mean age = 29.52 years, *SD* = 9.14), all French defense staff from Institut Supérieur de l'Aéronautique et de l'Espace (ISAE) and from Office Nationale d'Etude et de Recherche Aérospatiale, were recruited by local advertisement (mean level of education = 17.43 years, *SD* = 2.23). Participants gave their informed consent after receiving complete information about the nature of the experiment. Participants were randomly assigned into two independent groups: control and countermeasure.

The control group consisted of 12 participants (mean age = 28.25, *SD* = 6.64; mean level of education = 17.41, *SD* = 2.27) for whom no countermeasure was used to solve the conflict when the battery failure occurred.

The countermeasure group acted as the experimental group and consisted of 11 participants (mean age = 30.90, *SD* = 11.45; mean level of education = 17.45, *SD* = 2.30) for whom the countermeasure was administered to help solving the conflict at the time of the battery failure.[1]

Experimental Design

The experimental setup, developed at ISAE, was composed of a UGV and a ground station to interact with the robot. The UGV (see Figure 1) was equipped with two microprocessors, an embedded real-time Linux, a wireless Internet 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 manually controlled by the human operator with a joystick. In supervised mode, the UGV performed waypoint navigation, but any actions made with the joystick allowed the human operator to take over until the stick was released.

The ground station (see Figure 1) was displayed on a 24-inch screen and offered different information to control and to supervise the UGV: (a) a panoramic video scene screen placed in the upper part of the graphic user interface (GUI); (b) a panel that states the current segment of the mission in green (e.g., "search target") below the panoramic video; (c) a Google map, in the lower left corner, displaying the tactical map and the position of the robot; (d) an interactive panel sending messages and requests; (e) a "health" panel indicating the status of the robot (GPS status, ultrasound status, and battery level); and (f) a mode annunciator (supervised vs. manual).

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 approximately 4 min and was segregated into four main segments: S1, "Reach the area"; S2, "Scan for target"; S3, "Identify target"; and S4, "Battery failure." At the beginning of the mission, the UGV navigated in supervised mode to reach the search area (S1). After arrival, it then started scanning to detect 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 the UGV in manual mode so as to identify possible similarities in the two messages ("OK" and "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 the 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 in the mission, when 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

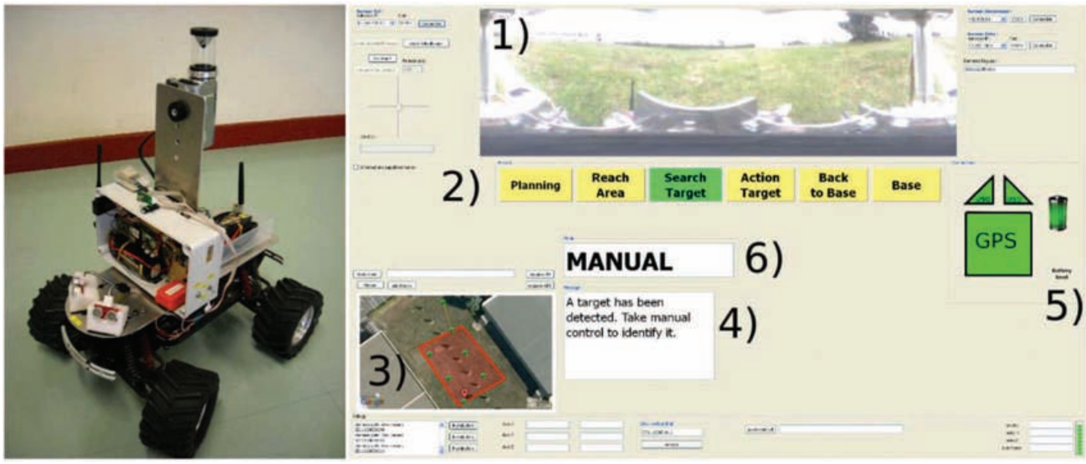

Figure 1. The left panel shows the unmanned ground vehicle developed at Institut Supérieur de l'Aéronautique et de l'Espace, and the right panel displays the user interface dedicated to control and to supervise the robot. The critical parts of the graphic user interface are labeled: (1) panoramic video scene screen, (2) synoptic, (3) tactical map, (4) interactive panel, (5) "health" panel, and (6) mode annunciator.

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 warning of the low-battery event.

Failure and Cognitive Countermeasure

As mentioned in the previous section, 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 user interface (see Figure 2): (a) The battery icon was turned to orange and a *Low battery* message was displayed below it; (b) the new guidance mode, *Supervised*, was flashed twice; and (c) the segment status evolved from "Search target" to "Back to base."

A cognitive countermeasure (see Figure 3) was designed to help the human operators in the countermeasure group to deal with the conflict. As it was hypothesized that operators would be excessively focused on the part of the panoramic video screen for target identification, we removed this part for 1 s, sending thereafter the explanation of the robot behavior for another 3 s. After, the panoramic video screen was displayed again with the conflict explanation information superimposed for 3 s before it disappeared. The robot was stopped while the cognitive countermeasure was sent.

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 2,048 Hz with the ProComp Infinity system (Thought Technology).
We applied three electrodes connected to an extender cable to the participant's chest using Uni-Gel to enhance the quality of the signal. The BioGraph Infiniti software was used to export and filter the HR derived from the interbeat interval. Because of a commonly observed difference in HR baseline values among participants, HR values were then standardized to provide interparticipant comparison. We recorded HR values at rest for 3 min while participants were sitting 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.

Figure 2. The upper panel shows the graphical user interface (GUI) before the failure, and the bottom panel displays the GUI with the low-battery event: The mission segment changes from "Search target" to "Back to base," the battery icon turns from green to orange with an associated message, and the message on the interactive panel disappears.

Figure 3. These four panels respectively represent the four steps of the cognitive countermeasure dedicated to disengage the human operator's attention focus from the panoramic video and to enhance his or her situation awareness. Top left panel, Step 1: The panoramic video was removed for 1 s. Top right panel, Step 2: The relevant information to understand the behavior of the robot was placed in the human operator visual field for 3 s. Bottom left panel, Step 3: The video panoramic screen reappeared with the relevant information superimposed on it for 3 more seconds. Bottom right panel, Step 4: End of the cognitive countermeasure. Note that the robot was stopped while the cognitive countermeasure was triggered.

In parallel, a Pertech head-mounted eye tracker was used to analyze the participants' ocular behavior. This device has 0.25° of accuracy and a 25-Hz sampling rate. Dedicated software (EyeTechLab) provides data, such as time stamps and the *x*- and *y*-coordinates of the participants' eye gaze on the visual scene. Eight areas of interest (AOIs) on the user interface were defined as follows: (a) tactical map, (b) interactive panel, (c) mode annunciator, (d) mission segment panel, (e) back to base, (f) GPS and ultrasound status, (g) battery status, and (h) panoramic video. We considered a ninth AOI to collect the ocular fixations out of the previous eight. We considered different oculometric variables (Duchowski, 2007) to assess the effect of the conflict and the cognitive countermeasure 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. The number of scanned AOIs was also measured for each of the four segments. Similar to the principle of the HR measurement, we examined the gaze switching rate, which corresponded to the number of gaze transitions from AOI to AOI per minute for each of the four segments. As the cognitive countermeasure consisted of removing the panoramic video screen for 1 s, the very first saccade was analyzed after the triggering of the countermeasure.

Procedure

Participants sat in a comfortable chair placed 1 m from the user interface in a closed room with no visual contact to the outdoor playground where the robot evolved. The ECG electrodes were arranged on the participant's chest, and the eye tracker was placed on his or her head. Next, participants completed a 13-point eye tracker calibration and then had to rest for 3 min to determine their physiological baseline. The mission was explained and the user interface was detailed. The two guidance modes were presented with particular care given 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.

Participants were told that four main hazards might occur during the mission. The associated procedure and the expected robot behavior were explained as following for each of these hazards: For low-battery event, "let the robot go back to base in supervised mode immediately"; for communication breakdown or GPS loss, "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 for ultrasound sensor failure, "manually assist the robot to avoid obstacles." The means to diagnose these four issues on the user interface were also explained: For low-battery event, "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*"; for communication breakdown, "the user interface is frozen"; for GPS loss, "the GPS icon turns to red and the guidance mode changes to manual control"; and for ultrasound sensor failure, "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. The timing was identical for the two groups, except that the cognitive countermeasure was sent simultaneously to the failure in the countermeasure group. After the experimentation, participants were asked whether they perceived the low-battery event and understood the robot's behavior. Participants in the countermeasure group were also asked whether the cognitive countermeasure helped them to deal with the situation.

Statistical Analysis

All behavioral data were analyzed with Statistica 7.1 (StatSoft, Tulsa, OK, USA). The Kolmogorov-Smirnov goodness-of-fit test showed that data distribution was normal; therefore, parametric repeated-measures ANOVA and Fisher's LSD (least significant difference) were used to examine the effects of the mission segment type on HR and the various oculometric measurements. We introduced a categorical explanatory variable in the analysis to check for differences between the two groups during S4 and to uncover the countermeasure effect. The relationship between HR and visual ocular activity was analyzed with Bravais-Pearson correlation.

RESULTS

Behavioral Results

Results of the control group revealed that 8 participants out of 12 (67.67%) persisted in detecting the target instead of letting the robot go back to base. Although they felt surprised by the behavior of the robot, these participants all declared that they noticed neither the low-battery event nor the other changes on the user interface. The other 4 participants reported to

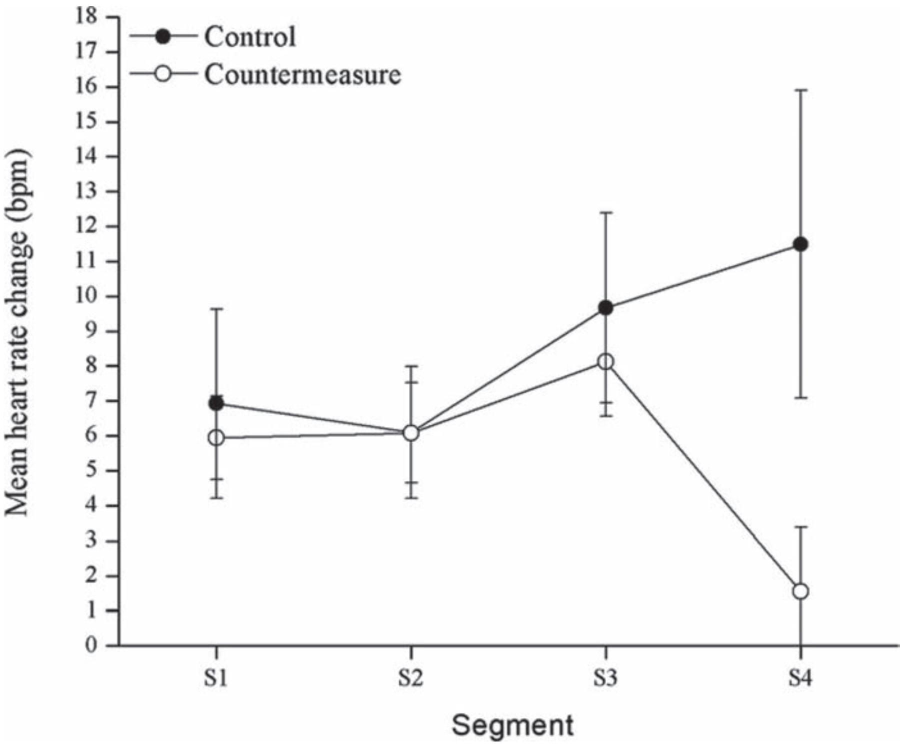

Figure 4. Mean heart rate change across the four mission segments for each group. Error bars represent the standard error of the mean.

have rapidly noticed the failure and decided to let the robot go back to base.

In contrast, all of the 11 participants from the countermeasure group noticed the battery failure and understood the behavior of the robot. They reported that the cognitive countermeasure helped them deal with the problematic situation. In this group, 10 out of 11 participants made the decision to stop the mission and let the robot go back to base in supervised mode. Only one consciously persisted to identify the target for 50 s until the end of the experiment. That participant believed there remained enough power despite the occurrence of the battery failure.

Psychophysiological Results

Heart rate. Mean HR response is plotted in Figure 4 as a function of group and segment type. The two-way repeated-measures ANOVA showed a significant interaction between group and segment type, $F(3, 63) = 6.19$, $p < .001$, $\eta_p^2 = .22$. Whereas no group difference appeared during the three first segments, paired comparisons showed that mean HR change differed between the control group and the countermeasure group during S4 ($p = .008$), the segment containing the battery failure. In the control group, the battery failure generated an increased HR, whereas HR came back close to the baseline in the countermeasure group (+11.48 beats per minute vs. +1.55 beats per minute, respectively).

Percentage of fixation duration on the panoramic video. Figure 5 shows mean percentage of time spent on the panoramic video as a function of group and segment type. There was a significant interaction between group and segment type, $F(3, 63) = 14.45$, $p < .001$, $\eta_p^2 = .40$. Paired comparisons showed that the mean percentage of time spent on the panoramic video increased progressively during the three first segments within the two groups with no group difference (S1 < S2, $p < .001$; S1 < S3, $p < .001$;

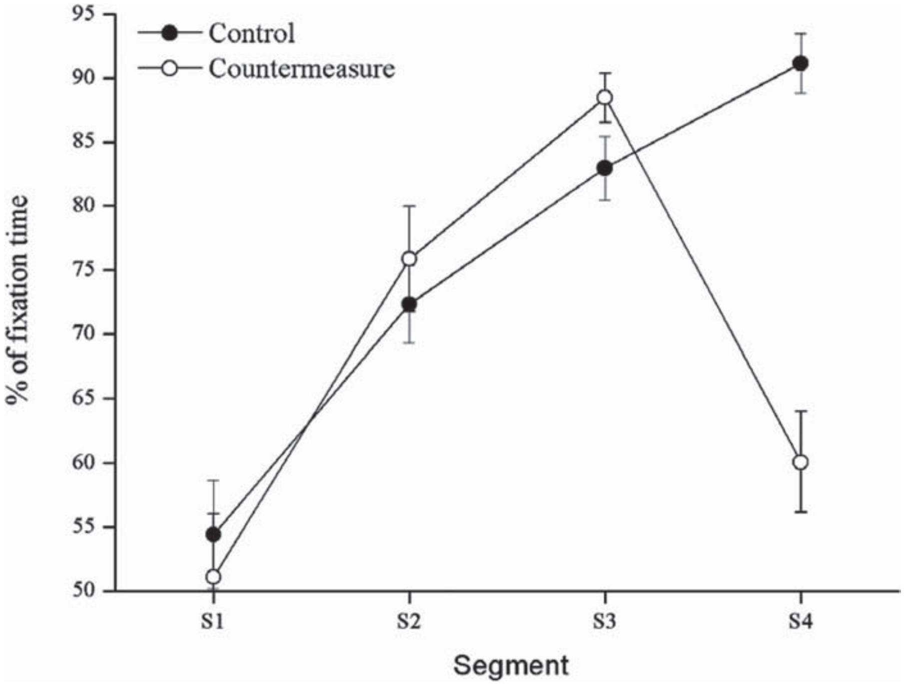

Figure 5. Mean percentage of time spent on the panoramic video according to the four segments for both groups. Error bars represent the standard error of the mean.

S2 < S3, $p < .001$). On the contrary, during S4, the control and countermeasure groups differed ($p < .001$): Whereas the control group spent 91.13% of time on the video during this segment, the countermeasure group spent only 60.05% of time on the video. This latter result shows that the cognitive countermeasure was successful in reducing participants' excessive focusing on the panoramic video.

Number of scanned AOIs. There was a significant interaction between group and segment type, $F(3, 63) = 12.11$, $p < .001$, $\eta_p^2 = .36$. Paired comparisons showed that the number of scanned AOIs increased strongly from S3 to S4 in the countermeasure group ($p < .001$), whereas this number remained stable in the control group. Coherently, the number of scanned AOIs was significantly higher within the countermeasure group (7.81) than in the control group (4.66) during S4 ($p < .001$). As for fixation duration, this latter result confirms that the cognitive countermeasure helped the participants to redistribute their ocular activity toward other AOIs. See Figure 6.

Switching rate. The same analysis performed on the gaze switching rate (gaze transitions from AOI to AOI per min) also revealed a Group × Segment type interaction, $F(3, 63) = 18.30$, $p < .001$, $\eta_p^2 = .51$). Whereas the transition rate fell progressively during the first three segments in both groups (S1 > S2, $p < .001$; S1 > S3, $p < .001$; S2 > S3, $p = .005$), during S4, the transition rate differed between the control group and the countermeasure group ($p < .001$). In this latter segment, the mean transition rate continued to diminish in the control group (–31.59%; S4 < S3, $p = .033$), whereas it increased drastically in the countermeasure group (+328.33%; S4 > S3, $p < .001$). This latter result confirms again that the countermeasure was efficient in stimulating the participant's ocular shifting abilities. See Figure 7.

First saccade analysis following the cognitive countermeasure. Finally, we examined the very first gazed AOI when the panoramic video screen was removed during the 1-s period of the cognitive countermeasure. Although all the participants were focused on the panoramic video

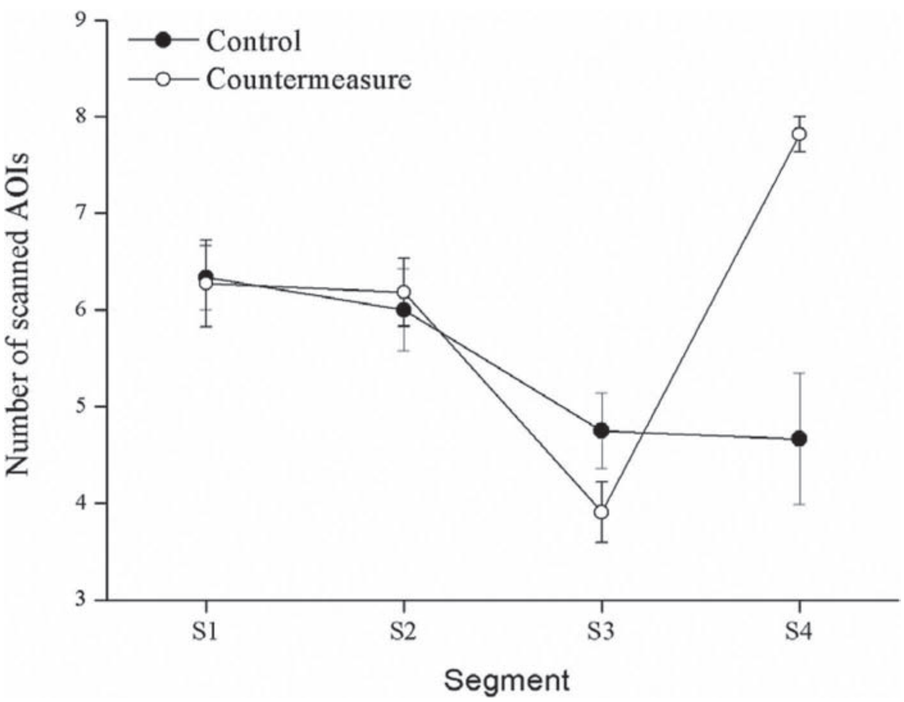

Figure 6. Mean number of scanned areas of interest according to the four segments for both groups. Error bars represent the standard error of the mean.

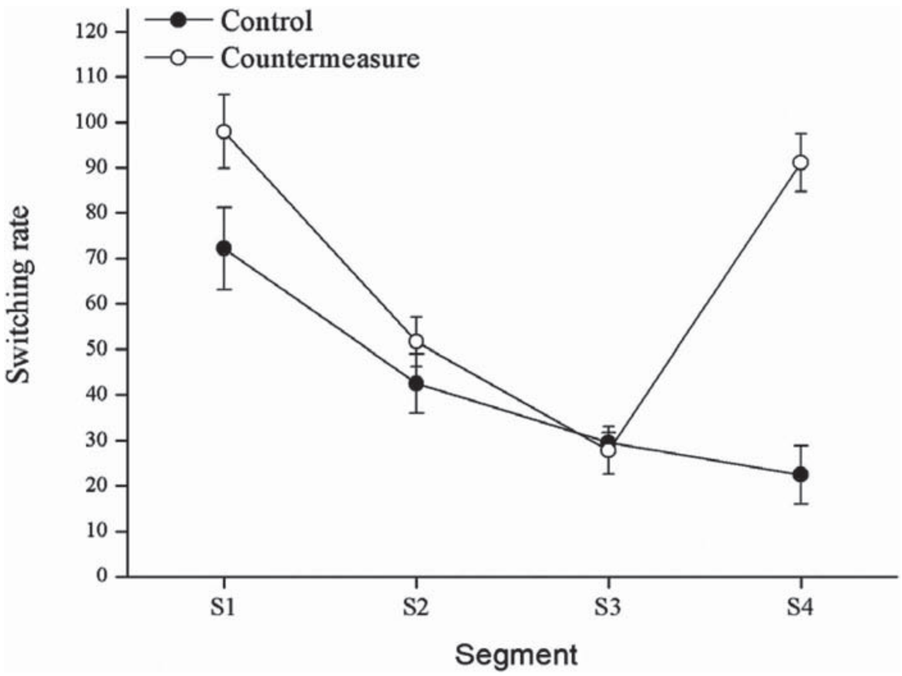

Figure 7. Gaze switching rate according to the four segments for both groups. Error bars represent the standard error of the mean.

screen, this information removal led 81.82% of the participants to have saccadic activity from this AOI to another one within 1 s. Among these latter participants, 45.45% of them gazed at the battery gauge, 27.27% at the mission segment panel, and 9.09% at the tactical map—all key instruments to understand the automation behavior.

DISCUSSION

The main objective of this study was to determine the efficiency of a cognitive countermeasure to enhance participants' attentional abilities when facing an authority conflict. A scenario was designed in the context of UGV operations whereby an authority conflict was induced by a low-battery event. The results of the control group revealed that such conflict provoked typical *automation surprise* behavior (Sarter et al., 1997) that is associated with an attentional shrinking. In a similar way to Sarter et al.'s (2007) study, participants neglected relevant information necessary for understanding the automation behavior. In contrast, the results of the countermeasure group revealed the beneficial effects of information removal and its temporary replacement with an explicit visual stimulus to change attentional focus during the automation conflict. Participants in this group exhibited reduced HR compared with those who did not receive the countermeasure, which may suggest a decreased level of stress (Simpson, Snyder, Gusnard, & Raichle, 2001) during the conflict.

Moreover, all participants who received the countermeasure perceived the failure, and all but one decided immediately to let the robot go back to base. The behavior of this latter participant, who decided deliberately to persist in identifying the target, may show some limits of the cognitive countermeasure procedure. This finding is consistent with a previous experiment conducted on a flight simulator in which 2 out of 13 pilots from a countermeasure group consciously continued to land even though they were aware of the danger of such an action (Dehais et al., 2003).

The design of the cognitive countermeasure was grounded in Posner and Dehaene's (1994) theory of attention. This innovative solution was in contrast to the classical trend of adding warning systems or increasing the saliency of alarms (Beringer & Harris, 1999). Although this traditional approach is effective in engaging and capturing attention (Bustamante, 2008), it may be counterproductive (Edworthy, 1993) by failing to disengage attention from the ongoing task. The present results suggest that for most participants of the countermeasure group, the principle of information removal was efficient enough to cause a saccade from the video panoramic to another AOI. Given that saccades reflect visual attentional processing (McCarley & Kramer, 2006), it may be argued that this rapid change of focus revealed an attentional disengagement induced by the countermeasure.

Engaging and maintaining attention on particular information, such as the video panoramic, relies on a tonic inhibition process (especially implemented in the pulvinar nucleus) to filter out distracting visual items (LaBerge, Carter, & Brown, 1992), especially during increased arousal (Tracy et al., 2000). By suppressing the panoramic video screen on which attention was locked, one could argue that the cognitive countermeasures contribute to releasing the inhibition process and to allowing a saccade toward another area.

In future experiments, we intend to demonstrate that cognitive countermeasures can be efficient in helping human operators in cases when audio alerts have been neglected, as suggested by preliminary results in the aeronautical domain (Dehais et al., 2010). These cognitive countermeasures could rely on classical visual information removal, but also "aural" cognitive countermeasures could also be considered. A study conducted by Meredith et al. (1995) suggests that simultaneous aural alerts can confuse human operators; as such, information removal could consist of inhibiting low-priority alerts until the high-priority goals have been achieved.

The present research was applied to the context of human-UV interactions; however, the issues of attentional shrinking and the use of cognitive countermeasures go beyond the domain of UV operations. Indeed, these issues also apply to other critical systems, such as aviation, driving, and medicine, in which attentional tunneling is likely to appear (Cook & McDonald, 1988; Crundall, Underwood, & Chapman, 1999; Thomas & Wickens, 2004). The principle of cognitive countermeasures could be particularly suited to head-up displays (HUD) that are vulnerable to attentional tunneling (Thomas & Wickens, 2004; Wickens & Alexander, 2009); moreover, the principle of information removal would not be critical in this case, as the displayed information on the HUD is redundant.

Whatever the domain, the use of the cognitive countermeasures has to be considered as a last option when the other traditional alerts have proven to be inefficient. The use of the cognitive countermeasure has to be strictly limited to highly hazardous situations in which safety could be at risk, such as the threat of collision, erroneous fuel management, loss of control, or inappropriate vehicle configuration (e.g., landing gear). Removing information, even for a short period, could be critical for safety, and the decision to trigger a cognitive countermeasure has to be based on a reliable analysis of the context by formal methods (Dehais, Mercier, & Tessier, 2009).

Research on adaptive systems (Wilson & Russell, 2007) could also provide interesting insights as they aim to infer the human operator's cognitive state from different measurement techniques and then adapt the nature of the interaction to overcome cognitive bottlenecks (St. John, Kobus, Morrison, & Schmorrow, 2004). Regarding the measurements used in this study, the HR response appeared to be a relevant a posteriori indicator of participants' sympathetic activity induced by the task. Nevertheless, this metric faces limitations for predicting human operator behavior in a real-time perspective because it can be confounded by emotion (Causse, Sénard, Démonet, Pastor, 2010).

There is also considerable variability across individuals (Vila et al., 2007), and changes in the operator's state can be difficult to detect within small time periods (Berntson, Quigley, & Lozano, 2007), which is necessary for adaptive systems (Scerbo, 2007).

In contrast, the ocular activity analysis appeared to be a reliable indicator of attentional impairment. Indeed, the proposed oculometric variables were efficient in identifying attentional shrinking and assessing the effects of the cognitive countermeasure. Moreover, the eye tracking technique provides clues about not only the timing of attentional tunneling but also the location on the user interface on which it takes place. These indications could be used in an adaptive system perspective to decide when and where to remove information.

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NOTE

1. The cognitive group originally consisted of 12 participants, but technical issues regarding the eye tracking measurement on 1 participant led us to remove him from the analysis.

KEY POINTS

- Conflict with automation might induce attentional tunneling.
- Cognitive countermeasures were designed to counter attentional tunneling.
- The principle of cognitive countermeasures relied on the temporary removal of information and its replacement by an explicit stimulus in the visual field.
- Behavioral and physiological measurements revealed the efficiency of cognitive countermeasures to mitigate attentional tunneling and to assist human operators.

REFERENCES

Bahrick, H. P., Fitts, P. M., & Rankin, R. E. (1952). Effect of incentives upon reactions to peripheral stimuli. *Journal of Experimental Psychology*, *44*, 400–406.

Beringer, D. B., & Harris, H. C., Jr. (1999). Automation in general aviation: Two studies of pilot responses to autopilot malfunctions. *International Journal of Aviation Psychology*, *9*, 155–174.

Berntson, G. G., Quigley, K. S., & Lozano, D. (2007). Cardiovascular psychophysiology. *Handbook of psychophysiology* (pp. 182–210). Cambridge, UK: Cambridge University Press.

Billings, E. E. (1996). *Aviation automation: The search for a human-centered approach*. Hillsdale, NJ: Lawrence Erlbaum.

Bustamante, E. A. (2008). Implementing likelihood alarm technology in integrated aviation displays for enhancing decision making: A two-stage signal detection modeling approach. *International Journal of Applied Aviation Studies*, *8*, 241–262.

Causse, M., Sénard, J. M., Démonet, J. F., & Pastor, J. (2010). Monitoring cognitive and emotional processes through pupil and cardiac response during dynamic versus logical task. *Applied Psychophysiology and Biofeedback*, *35*, 115–123.

Cook, R., & McDonald, J. (1988). Cognitive tunnel vision in the operating room: Analysis of cases using a frame model. *Anesthesiology*, *69*(3A), A497.

Crundall, D., Underwood, G., & Chapman, P. (1999). Driving experience and the functional field of view. *Perception-London*, *28*, 1075–1088.

Cowen, L., Ball, L., & Delin, J. (2002). An eye-movement analysis of web-page usability. In *People and computers XVI: Memorable yet invisible. Proceedings of HCI* (pp. 317–335). **CITY: PUBLISHER.**

Dehais, F., Mercier, S., & Tessier, C. (2009). Conflicts in human operator and unmanned vehicles interactions *Engineering psychology and cognitive ergonomics* (Vol. 5639, pp. 498–507). **CITY**: Springer LNCS.

Dehais, F., Tessier, C., & Chaudron, L. (2003). Ghost: Experimenting conflicts countermeasures in the pilot's activity. *International Joint Conference on Artificial Intelligence (IJCAI)*, *18*, 163–168.

Dehais, F., Tessier, C., Christophe, L., & Reuzeau, F. (2010). The perseveration syndrome in the pilot's activity: Guidelines and cognitive countermeasures. *Human Error, Safety and Systems Development*, 68-80.

Dirkin, G. R., & Hancock, P. A. (1984). Attentional narrowing to the visual periphery under temporal and acoustic stress. *Aviation, Space and Environmental Medicine*, *55*, 457.

Dixon, S. R., Wickens, C. D., & McCarley, J. S. (2007). On the independence of compliance and reliance: Are automation false alarms worse than misses? *Human Factors*, *49*, 564–572.

Duchowski, A. T. (2007). *Eye tracking methodology: Theory and practice*. New York, NY: Springer-Verlag.

Edworthy, J., & Meredith, C. S. (1993). Cognitive psychology and the design of alarm sounds. *Medical Engineering and Physics*, *16*, 445–449.

Inagaki, T. (2003). Automation and the cost of authority. *International Journal of Industrial Ergonomics*, *31*, 169–174.

LaBerge, D., Carter, M., & Brown, V. (1992). A network simulation of thalamic circuit operations in selective attention. *Neural Computation*, *4*, 318–331.

McCarley, J. S., & Kramer, A. F. (2006). Eye movements as a window on perception and cognition. In R. Parasuraman & M. Rizzo (Eds.), *Neuroergonomics: The brain at work* (pp. 95–112). New York, NY: Oxford University Press.

Meredith, C., & Edworthy, J. (1995). Are there too many alarms in the intensive care unit? An overview of the problems. *Journal of Advanced Nursing*, *21*, 15–20.

Meyer, J. (2001). Effects of warning validity and proximity on responses to warnings. *Human Factors*, *43*, 563–572.

Parasuraman, R., & Rizzo, M. (2007). *Neuroergonomics: The brain at work*. New York, NY: Oxford University Press.

Parasuraman, R., & Wickens, C. D. (2008). Humans: Still vital after all these years of automation. *Human Factors*, *50*, 511–520.

Pecher, C., Quaireau, C., Lemercier, C., & Cellier, J. M. (2010). The effects of inattention on selective attention: How sadness and ruminations alter attention functions evaluated with the Attention Network Test. *European Review of Applied Psychology*.

Posner, M. I., & Dehaene, S. (1994). Attentional networks. *Trends in Neurosciences*, *17*, 75–79.

Posner, M. I., & Fan, J. (2007). Attention as an organ system. In J. Pomerantz (Ed.), *Neurobiology of perception and communication*: From synapse to society. *De Lange Conference IV* (pp XX–XX). London, UK: Cambridge University Press.

Posner, M. I., Inhoff, A. W., Friedrich, F. J., & Cohen, A. (1987). Isolating attentional systems: A cognitive-anatomical analysis. *Psychobiology*, *15*, 107–121.

Posner, M. I., Walker, J. A., Friedrich, F. J., & Rafal, R. D. (1984). Effects of parietal injury on covert orienting of attention. *Journal of Neuroscience*, *4*, 1863.

Rice, S. (2009). Examining single-and multiple-process theories of trust in automation. *Journal of General Psychology*, *136*, 303–322.

Sarter, N. B., & Sarter, M. (2003). Neuroergonomics: Opportunities and challenges of merging cognitive neuroscience with cognitive ergonomics. *Theoretical Issues in Ergonomics Science*, *4*, 142–150.

Sarter, N. B., & Woods, D. D. (1995). How in the world did we ever get into that mode? Mode error and awareness in supervisory control. *Human Factors*, *37*, 5–19.

Sarter, N. B., Woods, D. D., & Billings, C. E. (1997). Automation surprises. In G. Salvendy (Ed.), *Handbook of human factors and ergonomics* (pp. 1926–1943). New York, NY: Wiley.

Scerbo, M. (2007). Adaptive automation. In R. Parasuraman & M. Rizzo (Eds.), *Neuroergonomics: The brain at work* (pp. 239–252). New York, NY: Oxford University Press.

Simpson, J. R., Snyder, A. Z., Gusnard, D. A., & Raichle, M. E. (2001). Emotion-induced changes in human medial prefrontal cortex: I. During cognitive task performance. *Proceedings of the National Academy of Sciences of the United States of America*, *98*, 683.

St. John, M., Kobus, D. A., Morrison, J. G., & Schmorrow, D. (2004). Overview of the darpa augmented cognition technical integration experiment. *International Journal of Human-Computer Interaction*, *17*, 131–149.

Thomas, L., & Wickens, C. D. (2001). Visual displays and cognitive tunneling: Frames of reference effects on spatial judgments and change detection. In *Proceedings of the 45th Annual Meeting of the Human Factors and Ergonomics Society* (pp. 336–340). Santa Monica, CA: Human Factors and Ergonomics Society.

Thomas, L., & Wickens, C. D. (2004). Eye-tracking and individual differences in off-normal event detection when flying with a synthetic vision system display. In Proceedings of the 48th Annual Meeting of the Human Factors and Ergonomics Society (pp. 223–227). Santa Monica, CA: Human Factors and Ergonomics Society.

Tracy, J. I., Mohamed, F., Faro, S., Tiver, R., Pinus, A., & Bloomer, C., et al. (2000). The effect of autonomic arousal on attentional focus. *Neuroreport*, *11*(18), 4037.

Tsai, Y., Viirre, E., Strychacz, C., Chase, B., & Jung, T. (2007). Task performance and eye activity: predicting behavior

relating to cognitive workload. *Aviation, Space, and Environmental Medicine*, *78*, 176–185.
Tvaryanas, A. P. (2004). Visual scan patterns during simulated control of an uninhabited aerial vehicle (UAV). *Aviation, Space, and Environmental Medicine*, *75*, 531–538.
Van Ginkel, H. T. A., de Vries, M. F. L., Koeners, J. J. M., & Theunissen, E. (2006). *Flexible authority allocation in unmanned aerial vehicles*. In Proceedings of the 50th Annual Meeting of the Human Factors and Ergonomics Society (pp. 530–534). Santa Monica, CA: Human Factors and Ergonomics Society.
Vila, J., Guerra, P., Muñoz, M. Á., Vico, C., Viedma-del Jesús, M. I., Delgado, L. C., & Rodríguez, S. (2007). Cardiac defense: From attention to action. *International Journal of Psychophysiology*, *66*, 169–182.
Wickens, C. D., & Alexander, A. L. (2009). Attentional tunneling and task management in synthetic vision displays. *International Journal of Aviation Psychology*, *19*, 182–199.
Wickens, C. D., & Dixon, S. R. (2007). The benefits of imperfect diagnostic automation: A synthesis of the literature. *Theoretical Issues in Ergonomics Science*, *8*, 201–212.
Wickens, C. D., Dixon, S., Goh, J., & Hammer, B. (2005, **MONTH**). *Pilot dependence on imperfect diagnostic automation in simulated uav flights: An attentional visual scanning analysis*. Paper presented at the 13th Annual International Symposium of Aviation Psychology, Oklahoma City.
Wilson, G. F., & Russell, C. A. (2007). Performance enhancement in an uninhabited air vehicle task using psychophysiologically determined adaptive aiding. *Human Factors*, *49*, 1005–1018.
Woods, D. D., & Sarter, N. B. (2000). Learning from automation surprises and going sour accidents. In M. Sarter & R. Amalberti (Eds.), *Cognitive engineering in the aviation domain* (pp. 327–354). Hillsdale, NJ: Lawrence Erlbaum.

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