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Human Mirror Neuron System Based Alarms in the Cockpit: A Neuroergonomic Evaluation

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Abstract

Controlled Flight Into Terrain (CFIT) events still remain among the deadliest accidents in aviation. When facing the possible occurrence of such an event, pilots have to immediately react to the ground proximity alarm ("Pull Up" alarm) in order to avoid the impending collision. However, the pilots' reaction to this alarm is not always optimal. This may be at least partly due to the low visual saliency of the current alarm and the deleterious effects of stress that alleviate the pilot's reactions. In the present study, two experiments (in a laboratory and in a flight simulator) were conducted to (1) investigate whether hand gesture videos (a hand pulling back the sidestick) can trigger brainwave frequencies related to the mirror neuron system; (2) determine whether enhancing the visual characteristics of the "Pull Up" alarm could improve pilots' response times. Electrophysiological results suggest that hand gesture videos attracted more participants' attention (greater alpha desynchronization in the parieto-occipital area) and possibly triggered greater activity of the mirror neuron system (greater mu and beta desynchronizations at central electrodes). Results obtained in the flight simulator revealed that enhancing the visual characteristics of the original "Pull Up" alarm improved the pilots' reaction times. However, no significant difference in reaction times between an enlarged "Pull Up" inscription and the hand gesture video was found. Further work is needed to determine whether mirror neuron system based alarms could bring benefits for flight safety, in particular, these alarms should be assessed during a high stress context.

Keywords Flight safety · Cockpit warnings · Mirror alarms · Human mirror neuron system · Neuroergonomics · EEG

Introduction

Controlled Flight into Terrain Accidents

Since the beginnings of commercial aviation, Controlled Flight Into Terrain (CFIT) represents one of the deadliest categories of accidents (International Air Transport Association 2016, 2018). In these events, an airworthy aircraft under the complete control of the crew is inadvertently flown into terrain, water, or an obstacle (Moroze and Snow 1999). Pilots are generally unaware of the potential danger of the situation until the last moment before the impact. In the early 1970s and after an important number of CFIT accidents (Cooper 1995), aviation authorities required both aircraft manufacturers and airline companies to equip aircraft with the "Ground Proximity Warning Systems" (GPWS), and later with the Enhanced-GPWS (European Aviation Safety Agency 2007). This alarm system alerts the pilots that the aircraft is in immediate danger of hitting the ground and prompts them to perform an immediate recovery maneuver. In Airbus aircraft, the latter consists of pulling back the sidestick and pushing forward the power levers on the Take-off/Go Around (TO/GA) position to respectively regain altitude and thrust. Ideally, the reaction from the crew should be fast and instinctive (Moroze and Snow 1999). In most of the modern aircraft, the GPWS alarm is multimodal and combines two channels of sensory information with a spoken "Pull Up" pronounced by a synthetic voice and a red-colored "Pull Up" inscription flashing in the Primary Flight Display (PFD; i.e., display presenting the primary flight parameters, located just in front of the pilots). The "Pull Up" alarm is

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played repeatedly until the pilots correct the flight path of the aircraft (Breen, 1999). While GPWS technology has led to a reduction in the number of CFIT accidents, they still remain the second cause of fatalities in commercial aviation (International Air Transport Association, 2016, 2018), with three-quarters of CFIT accidents resulting in the death of all passengers and crew members (Moroze and Snow 1999; Scoot 1996).

The Effects of Mental Workload and Stress on Pilots' Reactions to "Pull Up" Alarms

Flying an aircraft requires to handle many tasks (e.g. prioritizing the tasks, switching from a task to another), which is likely to generate a high mental workload in the pilots (Chou et al. 1996; Funk 1991; Iani and Wickens 2007; Woods 1995). Various accident investigations concluded that high mental workload can obliterate the pilots' capacity to react properly to warning events (e.g. Korean Air flight 801 in 1997; National Transportation Safety Board 2000). These conclusions are supported by various experimental studies showing that high mental workload can disrupt both the detection and the reaction to the alarms (Bliss and Dunn 2000; Causse et al. 2016; Dehais et al. 2014; Giraudet et al. 2015). Not surprisingly, an important proportion of CFIT accidents occurs during the approach and landing phases (Corwin 1995), where the altitude is low and the pilots' mental workload is high (Causse et al. 2012a; Lee and Liu 2003; Wilson 2002). Generally, when the GPWS alarm sounds in the cockpit, the crew is unaware of the actual position of the aircraft. Pilots' poor reactions to the GPWS alarm were found to contribute to 38% of the CFIT accidents while the GPWS system was functional (International Air Transport Association, 2018). In these cases, the GPWS alarm left enough time to react, but the crews delayed their response or made an inadequate maneuver (Kuchar 2001).

Another explanation for the pilots' poor reaction may be the aggressive and disturbing nature of the GPWS auditory modality, which tends to make the situation more stressful (Bliss 2003; Doll et al. 1984; Edworthy et al. 1991; Peryer et al. 2005). A large body of literature has demonstrated that a high level of stress is likely to disrupt flight performance (Rigby and Edelman 1968), as it temporarily impairs important cognitive abilities such as reasoning, decision-making, and/or executive functioning (Arthur et al. 2004; Casner and Schooler 2015; Porcelli et al. 2008; Scholz et al. 2009; Staal 2004). A sudden rise in the stress level can also slower reactions (Farber and Spence 1956), trigger freezing states (Schmidt et al. 2008) and dangerous reactions such as the startle effect for instance (Martin et al. 2012, 2015, 2016). Consequently, "Pull Up" events are likely to impact the crew capacity to evaluate the situation and to react appropriately.

Improving the GPWS Alarm?

Multimodal alarms, like the GPWS, are considered to be more easily detected and consequently more efficient than unimodal alarms (Alirezaee et al. 2017; Child and Wendt 1938; Hughes et al. 1994; Liu 2001). However, the high visual and auditory perceptual load in the cockpit (e.g. numerous displays and communications) is likely to affect the pilots' ability to detect and process the alarms (Salzer and Oron-Gilad 2014; Van Veen and Van Erp 2000). In this context, the small font size of the "Pull Up" inscription currently used in airline aircraft can make it difficult to detect (Corwin 1995). This can be problematic as human beings tend to rely more on visual information than on other forms of sensory information (Colavita 1974); and also because visual alarms are overall processed faster than auditory alarms (Donohue et al. 2013; Mrugalska et al. 2016; Posner et al. 1976). Finally, the inattentional deafness phenomenon can alter the ability to perceive the auditory modality of an alarm in the cockpit (Dehais et al. 2014; Giraudet et al. 2015). It is thus desirable to use more visually salient and intuitive alarms.

A first step to enhance the efficiency of the GPWS alarm would be to increase its visual saliency by enlarging the "Pull Up" text font size. However, enlarging the inscription may not be sufficient to cope with the loss of cognitive performance due to the stress generated by the "Pull Up" event. An alternate solution would be to display a video showing the actions to perform in response to the "Pull Up" alarm. This solution could have significant advantages. First, gesture videos were shown to strongly attract attention (Abrams and Christ 2003). This recruitment of attentional resources has been associated with a decrease in electroencephalographic (EEG) alpha-band power (8–12 Hz) at parieto-occipital sites (Fink et al. 2005; Keil et al. 2006; Klimesch 2012; Klimesch et al. 1998; Ray and Cole 1985). Second, a gesture video is also likely to activate the mirror neuron system, which might facilitate the initiation of the motor response to the "Pull Up" alarm (Rizzolatti et al. 1996). Mirror neurons have the distinguishing properties of firing both when one makes and/or observes another individual making an action (Buccino et al. 2004; Rizzolatti and Craighero 2004). They were found to play a key role in the understanding and the imitation of actions (Iacoboni et al. 1999; Jeannerod 1994; Meltzoff and Prinz 2002). EEG studies investigating the neural signature of the mirror neuron system have shown modulations in the power of the mu (i.e. 8–12 Hz) and the beta rhythms (i.e. 13–25 Hz) in response to both the performance and the observation of actions (Debnath et al. 2019; Hobson and Bishop 2016; Järveläinen et al. 2001; Muthukumaraswamy et al. 2004;

Pfurtscheller et al. 1997). A desynchronization of the mu and beta rhythms was found at the central electrodes (i.e. C3 and C4; Stancák and Pfurtscheller 1996) when subjects performed and/or observed movements (Babiloni et al. 1999, 2002; Gastaut and Bert 1954; Iacoboni et al. 1999; Muthukumaraswamy et al. 2004; Nam et al. 2011; Pfurtscheller et al. 1996; Rizzolatti and Craighero 2004). In this sense, mu and beta rhythms are interpreted as being an index of the human mirror neuron system activity. A large body of literature has shown that the mirror neuron system responds to videos of gestures performed by humans, robots, and avatars (e.g. Gangitano et al. 2004; Gazzola et al. 2007; Kilner et al. 2009; Molnar-Szakacs et al. 2006; Oberman et al. 2007; Press et al. 2005; Tai et al. 2004), even though stronger responses are found for real-life actions (Järveläinen et al. 2001). Some studies suggest that the observation of hand movement associated with transcranial magnetic stimulation of the motor cortex increased motor evoked potentials in hand muscles (Fadiga et al. 1995). In addition, the simple observation of static snapshots of hands suggesting a pincer grip action was found to induce an increase in corticospinal excitability (Urgesi et al. 2006). Taken together, these studies suggest that displaying a video of the gesture to be performed in case of an imminent collision with the ground may activate the mirror neuron system and then facilitate the initiation of the motor response to the “Pull Up” alarm.

Objectives and Hypotheses

The present study was conducted following a Neuroergonomic approach, whose goal is to better understand the human brain functioning in realistic settings to improve technology and safety (Parasuraman 2003). As long as the operator is a key agent in charge of complex systems, the definition of metrics able to understand and anticipate his/her performance is a great challenge (Causse et al. 2010). Two separate experiments were conducted aiming at: (1) investigating whether hand gesture videos (i.e. a hand pulling back the sidestick) can increase brainwave frequencies associated with the activity of mirror neuron system; (2) determining whether enhancing the visual characteristics of the “Pull Up” alarm could improve pilots’ response times. The first experiment was performed in laboratory conditions to examine the brain signatures to three different alarms: the current “Pull Up” alarm (i.e. currently used in large aircraft); an enlarged “Pull Up” alarm (i.e., current “Pull Up” alarm with an increased font size but displayed at the bottom of the PFD); and the “Pull Up” gesture video also displayed at the bottom of the PFD, presenting the gesture to perform in response to the “Pull Up” alarm (i.e. otherwise called “mirror alarm”). No motor response from the participants was asked during this experiment. The second experiment was performed in a flight simulator and aimed at measuring participants’ reaction times to the three different alarms.

Regarding the first experiment with EEG measures, we predicted that (1) the hand gesture videos should attract more attention. This should be indexed in particular by a greatest desynchronization of the alpha rhythm at parieto-occipital sites. We also predicted that (2) the hand gesture videos should trigger a greater activation of the mirror neuron system, facilitating the motor preparation of the appropriate actions. This increase in mirror neuron system activity should be indexed by greater mu and beta desynchronizations at central sites. Regarding the second experiment, we predicted to observe (3) faster reactions to the two enhanced “Pull Up” alarms compared to the current “Pull Up” alarm, with even faster reactions to the “Pull Up” video. Finally, we also expected (4) a greater detection rate of the two visually enhanced alarms compared to the current alarm.

Experiment 1—EEG Study

Material and Methods

Participants

Twenty-five private pilots ($M_{age}=25.5$, $SD \pm 4.14$, age range 21–35 years old; 1 female) participated in this study. Twenty were right-handed, four were left-handed, and one was ambidextrous, as assessed by the Edinburgh handedness inventory (Oldfield 1971). All had a normal or corrected-to-normal vision. None of the participants reported a history of prior neurological disorder. Only participants who held a Private Pilot License (PPL) were recruited with an average flight experience of 177.5 h ($SD \pm 120.9$ h) and an average time since licensing of 4.6 years ($SD \pm 4.5$ years). These pilots operated light aircraft where there is generally no GPWS. They had not received any specific training related to GPWS nor had experience with these alarms in real flight conditions. All participants were informed of their rights and gave written informed consent for participation in the study.

Ethics Statement

The present study was carried out in accordance with the recommendations of CERNI no. 2018–107, the Research Ethics Committee of the University of Toulouse (France). All subjects gave written informed consent in accordance with the Declaration of Helsinki.

Material

Stimuli. Three different “Pull Up” alarms (alarms of interest) were presented to the participants. The first alarm was

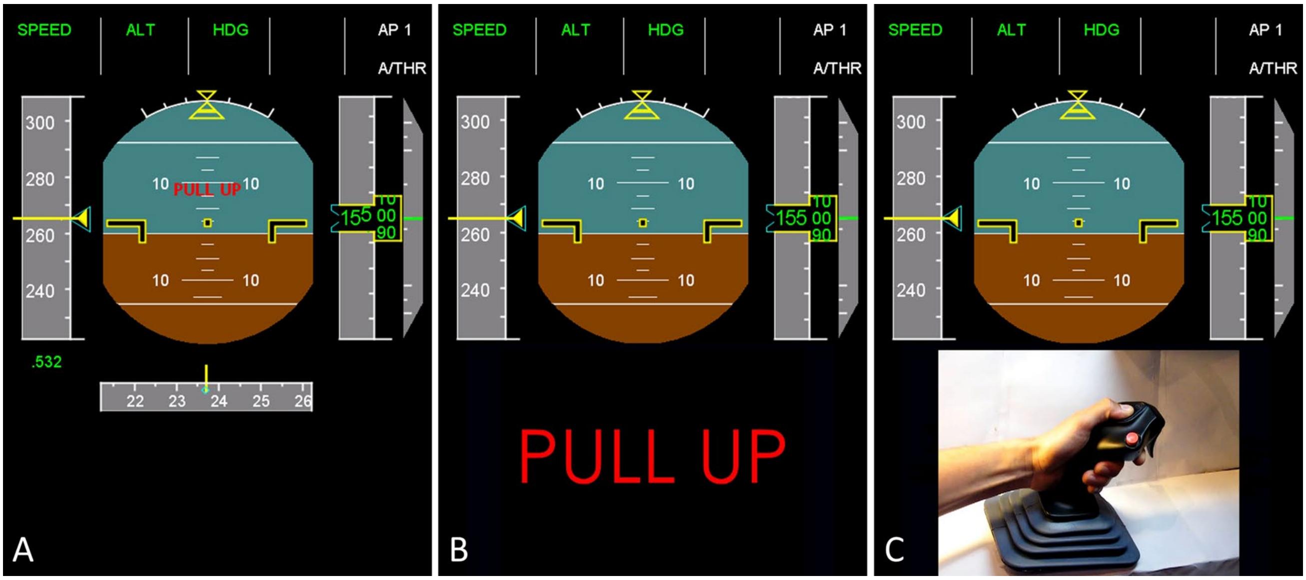

Fig. 1 Illustration of the three types of alarms. **a** the Current "Pull Up" alarm; **b** the Enlarged "Pull Up" alarm; **c** the "Pull Up" video

identical to the "Pull Up" alarm currently used in airline aircraft (i.e. current "Pull Up", see Fig. 1a). It consisted of a red 1 Hz-blinking "Pull Up" inscription (Arial font size 18). The second alarm was a "Pull Up" alarm with an enlarged inscription (i.e. enlarged "Pull Up", see Fig. 1b), consisting of a large 1 Hz-blinking red "Pull Up" inscription (Arial font size 85 corresponding to an 18-fold increase in size). The third alarm was a 1024 × 768 video of the gesture that the pilots have to perform in response to the GPWS alarm, namely a pilot's hand pulling the stick back ("Pull Up" video, see Fig. 1c). The alarms were displayed for 2.8 s. The two "Pull Up" inscriptions (current and enlarged) blinked two times and the "Pull Up" video was played two times. In this way, an alarm of interest was composed of one video (1.15 s), one blank (0.5 s), and another video (respectively 1.15 s + 0.5 s + 1.15 s = 2.8 s; see Fig. 2). The auditory component of the GPWS alarm was turned off to prevent potential interaction effects between the auditory modality and the visual modality of the alarm.

Experimental apparatus. The experimental paradigm was presented with a personal computer using E-Prime 2 (Psychology Software Tools, Inc., Pittsburgh, PA). Participants were seated in a chair and placed in front of a 19″ monitor.

Electroencephalographic (EEG) recordings. The EEG signals were recorded and amplified with the Biosemi system using 64 Ag–AgCl active scalp electrodes (Fp1, AF7, AF3, F1, F3, F5, F7, FT7, FC5, FC3, FC1, C2, C3, C5, T7, TP7, CP5, CP3, CP1, P1, P3, P5, P7, P9, PO7, PO3, O1, Iz, Oz, POz, Pz, CPz, Fpz, Fp2, AF8, AF4, AFz, Fz, F2, F4, F6, F8, FT8, FC6, FC4, FC2, FCz, Cz, C2, C4, C6, T8, TP8, CP6, CP4, CP2, P2, P4, P6, P8, P10, PO8, PO4, O2) arranged according to the international 10–20 system. Two electrodes were placed on the mastoids, which served as reference electrodes. Four electrodes (2 vertical electrodes, 2

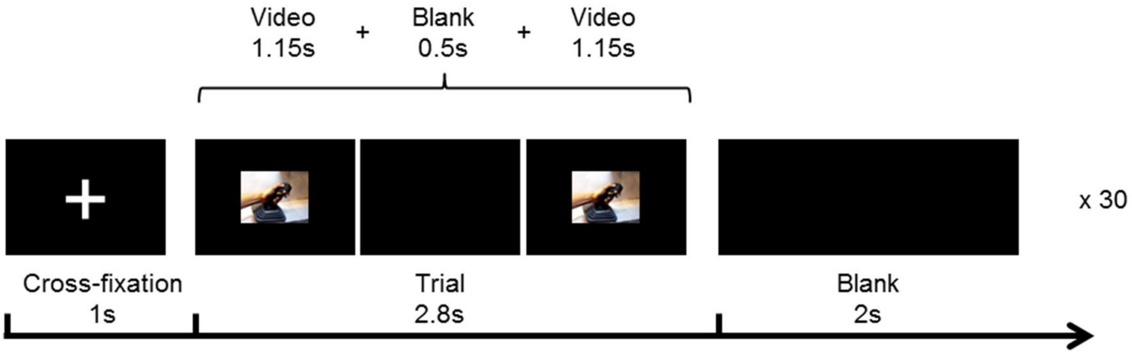

Fig. 2 Illustration of a trial in Experiment 1

horizontal electrodes) were placed around the eyes to record the electrooculogram (EOG). The data were sampled at a frequency of 512 Hz. Two additional electrodes placed close to Cz, the Common Mode Sense [CMS] active electrode and the Driven Right Leg [DRL] passive electrode, were used to form the feedback loop that drives the average potential of the participant as close as possible to the AD-box reference potential (Metting van Rijn et al. 1990). Skin–electrode contact, obtained using electro-conductive gel, was monitored, keeping voltage offset from the CMS below 20 mV for each measurement site. All the signals were (DC) amplified and digitalized continuously with a sampling rate of 512 Hz with an anti-aliasing filter with 3 dB points at 104 Hz (fifth-order sinc filter); no high pass filtering was applied online. The triggering signals to each video onset were recorded on additional digital channels. EEG data were analyzed using EEGLAB v.13.6.5b open source software (Delorme and Makeig 2004) on Matlab 2017a. First, EEG signals were band-pass filtered between 0.1 and 40 Hz. An independent component analysis was performed to isolate eye blinks and movements related to artifacts that have been subsequently subtracted to the signal. A visual inspection of the data was conducted to reject residual artifacts intervals. Data were segmented into epoch from − 1000 to 3000 ms.

The alpha rhythm desynchronization was analyzed in order to assess the allocation of attentional resources of participants to the two alarms. It was measured in the 0–3000 ms time window at parieto-occipital sites where the desynchronization was maximal based on visual analysis. These electrodes were then grouped into three clusters (left cluster: PO7/PO3/O1; central cluster: Pz/POz/Oz; right cluster: PO8/PO4/O2) aiming at investigating potential laterality effects. The desynchronization of both mu (i.e., motor alpha, 8–12 Hz) and beta (13–25 Hz; Babiloni et al. 2002) rhythms were also measured at central sites (i.e. C3 and C4; Stancák and Pfurtscheller 1996) to assess the activity of the mirror neuron system in response to the two alarms. The event-related spectral perturbations (ERSPs) were assessed in the 0–3000 ms time window for the mu rhythm and in the 300–1300 ms time window for the beta rhythm. A baseline correction (− 500 to 0 ms) was applied to the alpha, the mu and the beta powers, as presented in the following equation:

$$Power = 10.\log_{10}\left(mean\left(ERSP\ amplitude_{window\ of\ interest}\right)^2\right) - 10.\log_{10}\left(mean\left(ERSP\ amplitude_{baseline}\right)^2\right)$$

Procedure

Participants were installed in a dark and quiet room, at 85 cm from the computer screen. They were equipped with a 64-electrode EEG headset. Participants were instructed to watch the alarms. As we wanted to ensure that the activity of the mirror neuron system reflected the facilitation of the motor preparation and not the hand movement performance, participants were asked not to respond to the alarms. The current "Pull up" alarm, the enlarged "Pull Up" alarm, and the "Pull Up" video were each presented 30 times in a row, the order of presentation being counterbalanced between participants. A fixation cross was presented for 1 s, followed by the alarm (2.8 s) and a 2-s black screen (see Fig. 2). In order to facilitate EEG processing and limit ocular artifacts, participants were asked to avoid blinking during the presentation of the alarms.

Data Analysis

A 3 × 3 (Cluster [left cluster: PO7/PO3/O1; central cluster: Pz/POz/Oz; right cluster: PO8/PO4/O2] x Alarm [current "Pull Up"; enlarged "Pull Up"; "Pull Up" video]) two-way ANOVA was performed to examine alpha rhythm power at parieto-occipital sites. Two additional 2 × 3 (Electrode [C3; C4]) x Alarm [current "Pull Up"; enlarged "Pull Up"; "Pull Up" video]) two-way ANOVAs were conducted on both mu and beta rhythm powers at central sites. Bonferroni post-hoc tests were carried out to further examine significant effects ($\alpha = 0.05$).

Results

Results from the three above described ANOVAs were not significant ($F < 1$, $p > 0.05$). However, they were some limitations in comparing the current "Pull Up" to the two new alarms. Indeed, the current alarm inscription is displayed in the middle of the PFD while the new alarms were displayed at the bottom of it, making their brain signatures difficult to compare. We thus conducted a second set of exploratory analyses. We removed the current "Pull Up" from this ANOVA model and focused on the comparison between the enlarged "Pull Up" and the "Pull Up" video. We present below the results of the new three ANOVAs.

Alpha desynchronization. The analysis revealed a significant main effect of the alarm [F (1, 24) = 24.93, $p < 0.001$, $\eta p^2 = 0.51$; Fig. 3], with a greater alpha desynchronization in response to the "Pull Up" video ($M = -15.14$ dB ± 1.49) than to the enlarged "Pull Up" ($M = -13.52$ dB ± 1.78, $p < 0.001$). The main effect of cluster [F (2, 48) = 1.58, $p = 0.20$, $\eta p^2 = 0.07$] and the Cluster x Alarm interaction [F (2, 48) = 0.21, $p = 0.81$, $\eta p^2 = 0.01$] were not significant.

Mu desynchronization. The analysis revealed a significant main effect of the alarm [F (1, 24) = 13.38, $p < 0.001$, $\eta p^2 = 0.36$; Figs. 4 and 5a], with a greater desynchronization in response to the "Pull Up" video

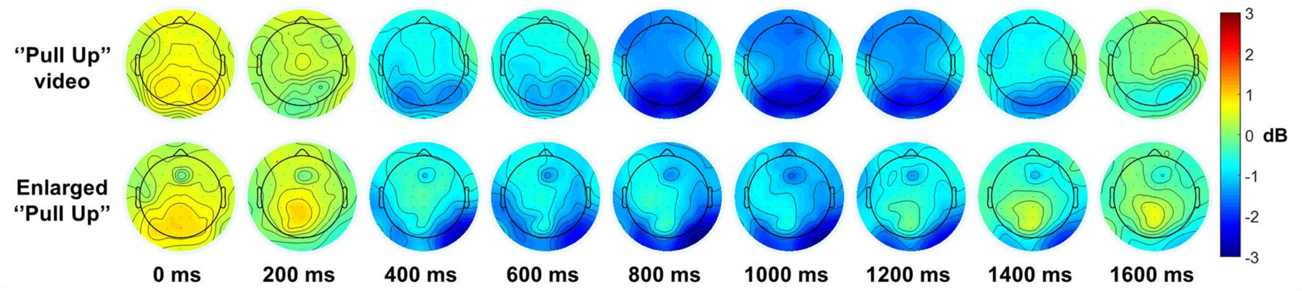

Fig. 3 Time–frequency scalp maps for the alpha rhythm (8–12 Hz) in response to the "Pull Up" video (upper row) and the enlarged "Pull Up" (lower raw). The blue color represents the desynchronization of the alpha rhythm, the darker the blue, the greater the desynchronization. The significant difference in alpha rhythm was significant in the time window of the whole epoch (i.e. 0–3000 ms). Here, we present only the time window where the desynchronization was maximal. Higher alpha rhythm desynchronization for the "Pull Up" video is particularly visible in the figure between 800 and 1200 ms

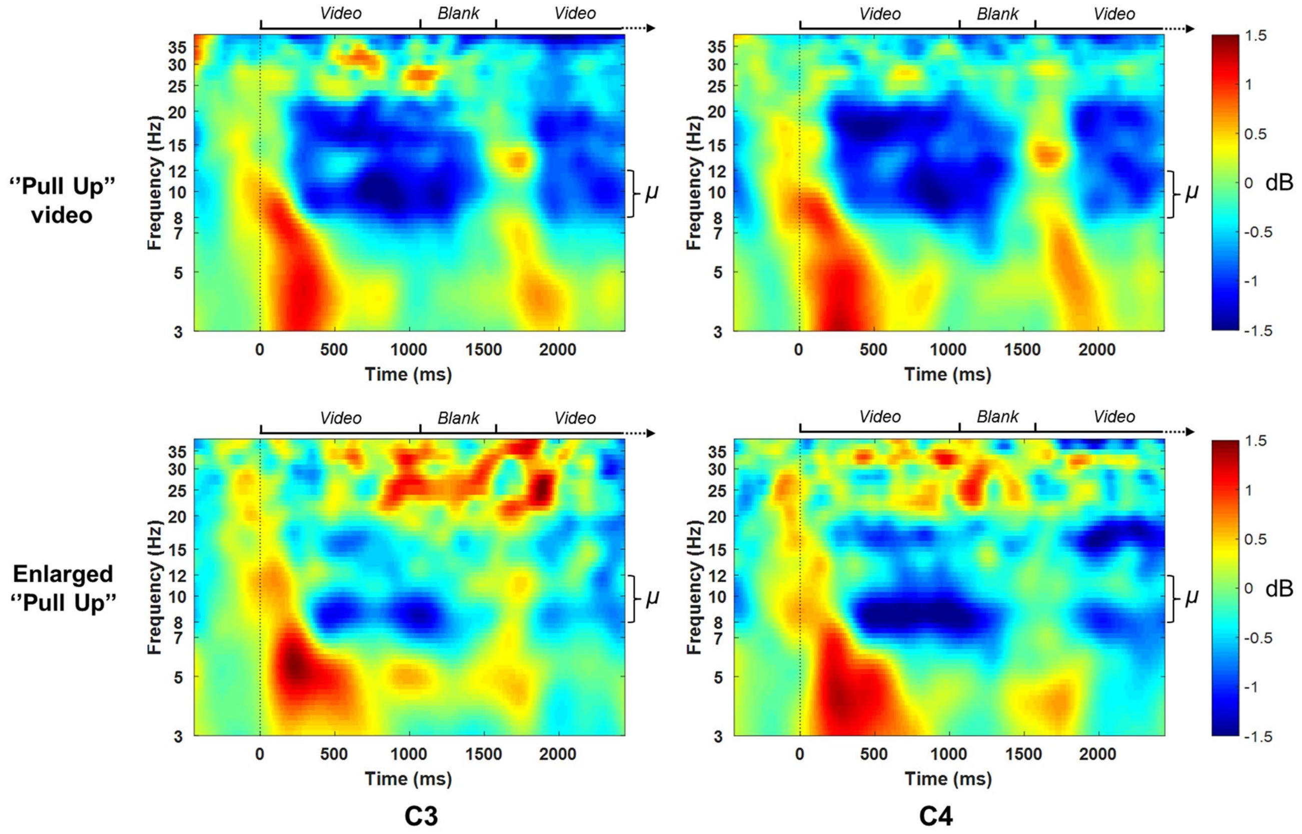

Fig. 4 Time–frequency maps in response to the "Pull Up" video (upper row) and the enlarged "Pull Up" (lower raw) on C3 (left column) and C4 (right column) electrodes. The whole epoch (0–3000 ms) was composed of two consecutive videos for each stimulus. The blue color represents the desynchronization of the rhythms, the darker the blue, the greater the desynchronization. Greater rhythm desynchronizations for the "Pull Up" video are particularly visible in the figure for both alpha (8–12 Hz) and beta (13–25 Hz) bands

($M = -15.39$ dB ± 1.34) than to the enlarged "Pull Up" ($M = -14.16$ dB ± 1.95, $p < 0.005$). Results revealed no significant main effect of electrode [F (1, 24) = 2.51, $p = 0.13$, $\eta p^2 = 0.09$] nor Electrode x Alarm interaction [F (1, 24) = 0.01, $p = 0.93$, $\eta p^2 = 0.00$].

Beta desynchronization. The analysis revealed a significant main effect of the alarm [F (1, 24) = 5.56, $p < 0.05$, $\eta p^2 = 0.19$; Figs. 4 and 5b], with a greater desynchronization in response to the "Pull Up" video ($M = -6.76$ dB ± 1.52) than to the enlarged "Pull Up" ($M =$

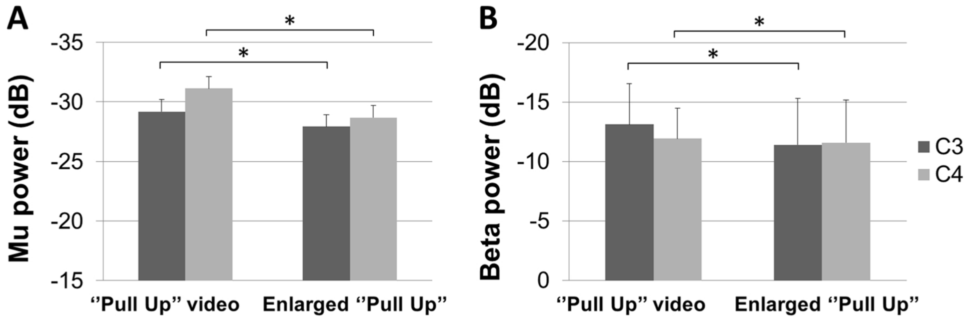

Fig. 5 **a** Mu rhythm power and **b** Beta rhythm power in response to the "Pull Up" Video and the enlarged "Pull Up" alarms. Errors bars represent standard errors

−5.75 dB ± 1.85, $p < 0.05$). Results revealed no significant main effect of electrode [F (1, 24) = 1.41, $p = 0.25$, $\eta p^2 = 0.05$] nor Electrode x Alarm interaction [F (1, 24) = 0.43, $p = 0.52$, $\eta p^2 = 0.02$].

Experiment 2—Flight Simulator Study

Material and Methods

Participants

The same 25 participants who participated in the first experiment also took part in the second one.

Ethics Statement

The present study was carried out in accordance with the recommendations of CERNI no. 2018–107, the Research Ethics Committee of the University of Toulouse (France). All subjects gave written informed consent in accordance with the Declaration of Helsinki.

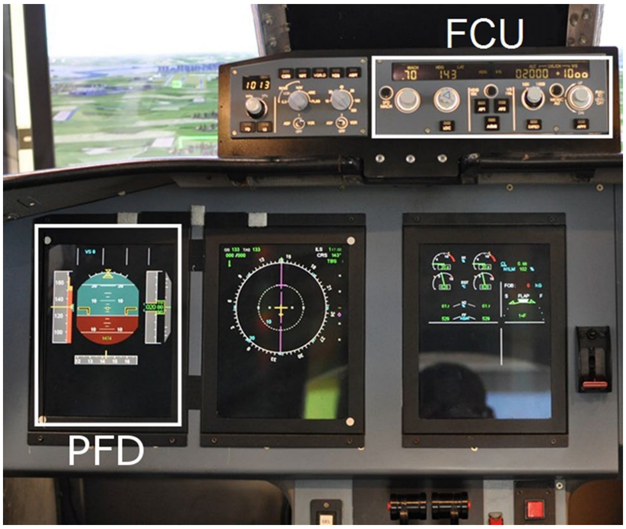

Fig. 6 Cockpit of the Airbus A320 flight simulator at ISAE-SUPAERO with the PFD on the left screen and the FCU on the top

Material

Flight Simulator. The experiment was carried out in the PEGASE A320 flight simulator at ISAE-SUPAERO (French Aeronautical Engineering School, Toulouse, France). During the flight scenario, the participants mainly monitored the PFD that displays flight parameters such as altitude, speed, attitude indicator, and heading. The Flight Control Unit (FCU) was also used for the interactions with the autopilot and the auto-throttle (see Fig. 6).

"Pull Up" alarms. The same alarms as experiment 1 were presented in the PFD. The current "Pull Up" inscription was displayed on the attitude indicator of the PFD (Arial font size 18). The "Pull Up" alarm with an enlarged inscription (i.e., enlarged "Pull Up") was displayed on the bottom part of the PFD (Arial font size 85 corresponding to an 18-fold increase in size). The video of the hand gesture was also displayed on the bottom part of the PFD. The gesture video lasted 1.15 s and was presented six consecutive times with a 0.5 s black screen between each repetition of the video (6 gesture videos of 1.15 s + 6 black screens of 0.5 s = 9.9 s). The three versions of the GPWS alarm were randomly presented three times each for approximately 10 s. The "Pull Up" procedure was simplified (i.e. participants were not required to move the thrust lever), thus the video did not show the application of the maximum thrust. As in experiment 1, the auditory component of the GPWS alarm was turned off to prevent potential interaction effects between the auditory modality and the visual modality of the alarm.

Fillers. In order to prevent participants from responding automatically each time a stimulus was displayed on the PFD, three different fillers for which no response was expected were also presented to the participants. These three fillers were designed to be as similar as possible to the three alarms of interest. The first filler was a 1 Hz-blinking "Jump" inscription on the PFD, similar to the current "Pull Up" alarm (see supplementary Figure A). The second filler was an enlarged 1 Hz-blinking "Jump" inscription displayed on the bottom of the PFD, similar to the enlarged "Pull Up" (see supplementary Figure B). The third filler was a video of a jump with similar characteristics as the "Pull Up" video (i.e., the jump lasted 1.15 s and was presented six times with a black screen of 0.5 s between each jump; see supplementary Figure C). Fillers stimuli were randomly presented three times each for approximately 10 s, as the three alarms of interest.

Procedure

Participants were comfortably installed in an experimental room and asked to fill two questionnaires: an information questionnaire (age, license issue date, total flight hours, etc.) and the Edinburgh Handedness Inventory (Oldfield 1971) designed to assess the dominance of a person's right or left hand in everyday activities. After that, participants took place in the A320 flight simulator to perform a 30-minute cruise flight from Lyon to Toulouse with the autopilot set (speed: 265 knots, heading: 237°, altitude 15,500 feet). Participants took as much time as necessary to familiarize themselves with the simulator before the beginning of the experiment. The three versions of the alarms were presented to the participants as many times as desired, so they could get acquainted with the stimuli before the experiment started. Participants were asked to apply a simplified Pull-Up maneuver (i.e., pull back the stick frankly a few seconds, then release it, and re-engage the autopilot) as soon as they would detect one of the alarms of interest. There were also instructed to ignore the fillers. Several means were used to prevent the participants from fixing their attention on the PFD only. They were told that some traffic could appear on their flight route, thus they had to monitor the external environment (i.e., the cockpit windows). Moreover, a 300-foot thick layer of clouds was set at an altitude of 12,500 feet in order to reduce the visibility and to reinforce the need to actively monitor the external environment. Participants were also distracted by random disengagement of the autopilot and the auto-throttle. They were instructed to reactivate these instruments by pushing the appropriate buttons on the FCU, as soon as they detected the disengagement. All events (i.e., alarms, fillers and autopilot/auto-throttle disengagements) occurred every 20 to 25 s.

Data Analysis

The reaction times of the participants (i.e. the time between the onset of the "Pull Up" alarm and the initiation of the pullback movement) were assessed for the three types of alarms. Statistical analyses were performed using Statistica 10 ©. A one-way (Alarm [Current "Pull Up"; enlarged "Pull Up"; "Pull Up" video]) ANOVA was conducted on the mean reaction times. Bonferroni post-hoc tests were carried out to further examine significant effects ($\alpha < 0.05$). We also counted two types of errors committed by the participants: omission errors (i.e., the participants did not respond to a "Pull Up" alarm) and commission errors (i.e., responses to the filler alerts that should have been ignored; Falkenstein et al. 1999).

Results

The analysis revealed a significant main effect of the alarm [F (1, 48) = 28.89, $p < 0.001$, $\eta p^2 = 0.55$]. Bonferroni's post-hoc analysis revealed that participants were longer to react to the current "Pull Up" alarm ($M = 2.89$ s ± 1.36; see Fig. 7) than to both the "Pull Up" video ($M = 1.60$ s ± 0.31, $p < 0.001$) and the enlarged "Pull Up" ($M = 1.47$ s ± 0.30, $p < 0.001$). Reaction times to the "Pull Up" video and the enlarged "Pull Up" were not significantly different ($F < 1$, $p = 1.0$). Only one participant committed an omission error, missing a current "Pull Up" alarm. No omission errors were found for the two other "Pull Up" alarms. Nine participants made one commission error and one participant made two commission errors in reaction to the small "Jump" filler alarm. One participant made one commission error in reaction to the enlarged "Jump" filler alarm. No commission error was observed in reaction to the "Jump" filler video.

Discussion

The starting point of this study was that mirror neuron based alarms could help improve human reactions and contribute to mitigating the dramatic consequences of human errors in transportation (Parker et al. 1995; World Health Organization 2013). Poor human reactions are not restricted to aviation, for example, the literature shows that 53% of train accidents (Reinach and Gertler 2002; Reinach and Viale 2006) and 76–95% of road transport accidents are at least partly attributable to human error (Elgarov 1995; Sabey 1983).

The mirror neuron system is believed to play a key role in understanding and imitating actions, suggesting that videos of hand gestures could facilitate the initiation of critical motor actions. In this sense, an alarm based on the mirror neuron system functioning could potentially be an efficient solution to display an action to be performed urgently. The aim of the present aviation study was twofold: (1) investigating whether hand gesture videos (i.e., a hand pulling back the sidestick) can activate brainwave frequencies related to the mirror neuron system; (2) determining whether enhancing of the visual characteristics of the "Pull Up" alarm could improve pilots' response times.

A first experiment was conducted to compare the brain signatures of the three alarms: the "Pull Up" alarm currently used in the operational cockpits and two visually-enhanced

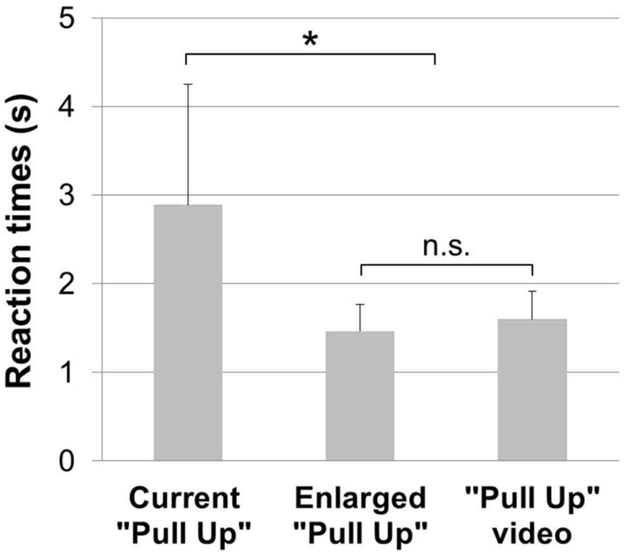

Fig. 7 Reaction times to the current "Pull Up" alarm, the enlarged "Pull Up", and the "Pull Up" video. Errors bars represent standard errors

versions of the "Pull Up" alarm. The latter consisted of an enlarged "Pull Up" inscription and a video of the "Pull Up" gesture ("mirror alarm") to perform in response to the GPWS alarm. Participants passively observed (i.e., no action was expected in response to the alarms) the current "Pull Up" inscription, the enlarged "Pull Up" inscription, and the "Pull Up" video, displayed 30 times each on a computer screen. This experiment was conducted under controlled conditions (i.e. in an experimental room) in order to guarantee a good EEG signal-to-noise ratio. The first round of analysis comparing all three alarms failed to reach significance. At the difference of the enlarged "Pull Up" inscription and the "Pull Up" video that were displayed alone, the current "Pull Up" alarm was embedded in the PFD, where other flight information (i.e., including words) is also displayed. Many studies have shown that written stimuli can trigger a response of the mirror neuron system (Baumgaertner et al. 2007; Hauk et al. 2004; Kemmerer et al. 2008; Kemmerer and Gonzalez-Castillo 2010; Pulvermüller et al. 2001; Skipper et al. 2006). This difference in the visual environment may have artificially enhanced the brain response to the current "Pull Up" alarm. A second set of exploratory analysis excluding the current "Pull Up" alarm revealed greater alpha desynchronizations at parieto-occipital sites in response to the "Pull Up" video than to the enlarged "Pull Up" alarm. Previous studies have shown that alpha desynchronizations reflect the allocation of attentional resources to a stimulus (Fink et al. 2005; Keil et al. 2006; Klimesch 2012; Klimesch et al. 1998; Ray and Cole 1985), suggesting that the "Pull Up" video caught more efficiently the attention of the participants than the enlarged "Pull Up" inscription. This result is in line with previous studies showing that motion stimuli attract more attention than static stimuli (e.g., Abrams and Christ 2003). Second, this exploratory analysis revealed greater desynchronizations of mu and beta rhythms at central sites (i.e., C3 and C4) in response to the "Pull Up" video than to the enlarged "Pull Up" inscription. Both mu and beta desynchronizations were found to reflect the activity of the mirror neuron system in response to the observation and/or the execution of a movement (e.g. Babiloni et al. 2002; Muthukumaraswamy et al. 2004; Nam et al. 2011). While some previous studies showed that written action verbs activate the mirror neuron system (e.g. Baumgaertner et al. 2007; Callan et al. 2003; Kemmerer et al. 2008; Kemmerer and Gonzalez-Castillo 2010; Skipper et al. 2006), the present study suggests that the mirror neuron system may be more strongly activated by a gesture video (i.e. "Pull Up" video) than by the corresponding written action verb (i.e. enlarged "Pull Up" inscription). Despite possible contamination of the mu rhythm by the occipital alpha rhythm (Hobson and Bishop 2016), the observed beta rhythm desynchronization on the central areas supports the idea that the mu desynchronization mainly resulted from the mirror neuron system activity. Taken together, the electrophysiological results of the first experiment might support the assumption that the "Pull Up" video attracts more the pilots' attention (i.e. greater alpha desynchronization) and elicits greater motor preparation and pre-activation of the gesture (i.e. greater mu and beta desynchronizations at central sites; Fadiga et al. 1995) in comparison to the enlarged "Pull Up" inscription.

The second experiment was conducted in a flight simulator and aimed at measuring the participants' reaction times to the same three alarms. While performing a flight scenario, participants were instructed to pull back the stick in response to these three "Pull Up" alarms, each time they were displayed in the PFD. Three filler stimuli that had to be ignored were also presented to the participants in order to prevent automatic responses to any stimulus displayed on the PFD. These fillers consisted of "Jump" stimuli sharing similar characteristics with the three "Pull Up" alarms of interest: one small "Jump" inscription, one enlarged "Jump" inscription and one "Jump" video. The results of this second experiment revealed various errors of commission (Falkenstein et al. 1999) in reaction to the "Jump" inscription. This result is a first indication that a small inscription embedded in the PFD is not optimal to indicate the requested action. The results also revealed that enhancing the visual component of the alarm improved the responses to the "Pull Up" alarm (i.e., faster reaction times). While it took the participants around 3 seconds to react to the current "Pull Up" alarm, the reaction times to the two visually enhanced "Pull Up" alarms were below 2 seconds. These shorter reaction times are encouraging as in some cases the time available to react is very limited, for instance when the descent rate of the aircraft is low, the GPWS alerts are delayed (Kuchar 2001). Increasing the size of the area in which the alarm was displayed from 0.5 to 30% of the PFD screen appears to have improved the saliency of the alarm and consequently accelerated the alarm detection process (Busch et al. 2004). This result suggests that enhancing the visual component of the GPWS alarm could improve pilots' reactions in case of an imminent collision with the ground and may help prevent CFIT accidents. Yet, unexpectedly, the results revealed no significant difference in reaction time between the enlarged "Pull Up" inscription and the "Pull Up" video, making it difficult to determine which of the two visual enhancements would be the most effective in a situation of an imminent collision with the ground. The lack of difference in reaction times may be explained by the fact that participants knew that the alarms would be repeatedly displayed in the PFD. This may have led them to pay more attention to the location where the alarms were displayed, possibly contributing to prevent a potential difference in reaction times between the two alarms. Another explanation may be that the flight scenario generated relatively low levels of stress and workload compared to a real imminent collision with the ground. Beyond the overall negative effect of stress and high mental workload on cognition, these factors can also affect reading skills and the processing of written material (Causse et al. 2016; Daneman and Carpenter 1980; Sulpizio et al. 2015). As reacting to mirror alarms does not require decoding complex information nor reading written material, the former might be advantageous when cognitive functions are impacted both by stress and mental workload. Further research is now needed to assess a possible greater efficiency of "mirror alarms" in a context of high stress and/or workload, in which they may specifically trigger faster reactions times than more classical warnings.

The efficiency of this new GPWS alarm should also be evaluated with professional pilots. Moreover, in the present study, we focused on the visual component of the GPWS alarm, and its auditory component was removed. In order to confirm and consolidate the results of the present study, the efficiency of mirror alarms should be investigated when associated with the auditory component of the current GPWS alarm. Previous studies have shown that action sounds can also activate the mirror neuron system (Kohler et al. 2002) and that some specific neurons called audiovisual mirror neurons respond to actions, independently of whether the latter are performed, heard or seen (Cook, 2012; Keysers et al. 2003). Multimodal stimuli are also generally better perceived and trigger faster reactions in pilots (e.g. Colcombe and Wickens 2006). Thus, presenting a gesture alarm with both visual (i.e. gesture video) and auditory components could further improve pilots' reactions. Moreover, using the operational synthetic voice—familiar to airline pilots—in association with the gesture video may facilitate the transition to this new type of mirror alarms, limiting the risk of a change in habits (Patterson 1982). Future studies could also investigate a combination of text and video as the mirror neuron system was also found to be responsive to the linguistic representation of actions, like written or spoken action verbs (Baumgaertner et al. 2007; Hauk et al. 2004; Kemmerer et al. 2008; Kemmerer and Gonzalez-Castillo 2010; Skipper et al. 2006).

Conclusion and Perspectives

The current study investigated whether mirror neuron based alarms may be useful in situations where accurate and fast reactions are required to handle emergency situations. We found mixed results. The brain signatures of the two visually enhanced alarms' observed during exploratory analysis could suggest that the mirror alarm may: (1) better capture the pilots' attention (i.e., greater alpha desynchronization) and (2) improve motor preparation (i.e. greater mu and beta desynchronizations) compared to the enlarged "Pull Up" inscription. However, these preliminary results should be taken with caution and should be replicated using three perfectly comparable alarms. In the flight simulator, both enhanced "Pull Up" alarms improved the response (i.e. faster reaction times) compared to the current "Pull Up" alarm. No reaction time difference was found between the mirror alarm and the enlarged "Pull Up" inscription. Thus we cannot conclude that mirror alarm could be more effective in case of an imminent collision with the ground than written action verbs. However, we can confirm that a more salient "Pull Up" alarm would be desirable to trigger fast reactions in pilots in case of emergencies. In conclusion, very few studies examined the properties of the human mirror neuron system in the aeronautics field (Callan et al. 2012) and this work is probably the first to examine its potential for new alarm systems (with the exception of the preliminary studies of Causse et al. 2012b). Our results are far from being definitive. We encourage additional studies to better understand how and when mirror alarms could be used with significant benefits. If their benefit was confirmed and better understood in future experiments, such alarms might also be used in autonomous vehicles to help drivers take control of the car after a long period of inactivity. Applications of this type of alarms could also be imagined in emergency medicine (Brennan et al. 1991; Wears and Leape 1999) or in the military field, to name a few.

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