

The effects of emotion on pilot decision-making: A neuroergonomic approach to aviation safety

Mickael Causse, Frédéric Dehais, Patrice Péran, Umberto Sabatini, Josette Pastor

▶ **To cite this version:**

Mickael Causse, Frédéric Dehais, Patrice Péran, Umberto Sabatini, Josette Pastor. The effects of emotion on pilot decision-making: A neuroergonomic approach to aviation safety. Transportation Research Part C: Emerging Technologies, 2013, vol. 33, pp. 272-281. ⟨10.1016/j.trc.2012.04.005⟩. ⟨hal-00998693⟩

HAL Id: hal-00998693

https://hal.science/hal-00998693v1

Submitted on 2 Jun 2014

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization



Open Archive Toulouse Archive Ouverte (OATAO)

OATAO is an open access repository that collects the work of Toulouse researchers and makes it freely available over the web where possible.

This is an author-deposited version published in: http://oatao.univ-toulouse.fr/
Eprints ID: 11596

To link to this article: DOI: 10.1016/j.trc.2012.04.005
URL: http://dx.doi.org/10.1016/j.trc.2012.04.005

To cite this version: Causse, Mickael and Dehais, Frédéric and Péran, Patrice and Sabatini, Umberto and Pastor, Josette *The effects of emotion on pilot decision-making: A neuroergonomic approach to aviation safety.* (2013) Transportation Research Part C: Emerging Technologies, vol. 33. pp. 272-281. ISSN 0968-090X

Any correspondence concerning this service should be sent to the repository administrator: staff-oatao@inp-toulouse.fr

The effects of emotion on pilot decision-making: A neuroergonomic approach to aviation safety

Mickaël Causse [a,b,c,*], Frédéric Dehais [a], Patrice Péran [b,c,d], Umberto Sabatini [d], Josette Pastor [b,c]

[a] Centre Aéronautique et Spatial ISAE-SUPAERO, Université de Toulouse, 10 avenue E. Belin, 31055 Toulouse Cedex 4, France
[b] Inserm, Imagerie cérébrale et handicaps neurologiques UMRS 825, F-31059 Toulouse, France
[c] Université de Toulouse, UPS, Imagerie cérébrale et handicaps neurologiques UMRS 825, CHU Purpan, Place du Dr Baylac, F-31059 Toulouse Cedex 9, France
[d] Radiology Department, IRCCS Santa Lucia Foundation, via Ardeatina 306, Rome 00149, Italy

ARTICLE INFO

Keywords:
Human factors
Aviation
Plan continuation error
Decision making
Emotion
Neuroergonomics
Neuroeconomics

ABSTRACT

Emotion or stress can jeopardize decision-making relevance and cognitive functioning. In this paper we examine plan continuation error (PCE), an erroneous behavior defined as a "failure to revise a flight plan despite emerging evidence that suggests it is no longer safe" (Orasanu et al., 2001). Our hypothesis is that negative emotional consequences attached to the go-around decision provoke a temporary impairment of the decision-making process and favor PCE. We investigated this hypothesis with a simplified landing task in which two possible contributors to those emotions, namely the uncertainty of a decision outcome and the reward/punishment, associated to the outcome were manipulated. A behavioral experiment ($n = 12$) and a second one ($n = 6$) using functional magnetic resonance imaging (fMRI) were conducted. Behavioral results of both studies showed the effectiveness of the financial incentive to bias decision making toward a more risky and less rational behavior from a safety point of view. Neuroimaging data showed that the PCE behavior was underpinned by the contribution of brain circuitry of emotion and reward during the decision-making process. Taken together, behavioral and fMRI result support the hypothesis that PCE can be provoked by a temporary impairment of rational decision-making due to the negative emotional consequences attached with the go-around.

1. Introduction

Approach and landing are critical flight phases that require formalized sequences of actions (e.g. to lower the gear down, to extend the flaps) and to follow an arrival procedure through several waypoints. Uncertainty, a worsening factor since it generates psychological stress, deleterious to piloting activity (Katsis et al., 2010), can be high during landing. According to the legislation, hazardous conditions (e.g. unstabilized approach, vehicles on the runway, strong crosswind or wind shear) require to go-around to perform a new safe attempt or to divert to another airport. The go-around decision-making rules follow legal guidelines that are adapted by aircraft manufacturers in their operating manual (e.g. crosswind limitation, use of autopilots, etc.) and airport authorities (decision gates, speed envelopes, sink rates, etc.). In addition, pilots should use their own judgment and may decide to perform a go-around at any time. A study conducted by MIT (Rhoda and Pawlak, 1999) has demonstrated that in 2000 cases of approaches under thunderstorm conditions, two aircrews out of three keep on landing in spite of adverse meteorological conditions. This phenomenon called plan continuation error (PCE) (Orasanu et al., 2001) also exists in general aviation. Indeed, the BEA (the French Accident Investigation Bureau) revealed that this pilots' trend to land (the get-home-itis syndrome) have been responsible for more than 41.5% of casualties in general aviation (BEA, 2000).

* Corresponding author at: Centre Aéronautique et Spatial ISAE-SUPAERO, Université de Toulouse, 10 avenue E. Belin, 31055 Toulouse Cedex 4, France.
E-mail addresses: Mickael.causse@isae.fr (M. Causse), Frederic.dehais@isae.fr (F. Dehais), patrice.peran@inserm.fr (P. Péran), u.sabatini@hsantalucia.it (U. Sabatini), josette.pastor@inserm.fr (J. Pastor).

Many experiments have addressed the difficulty for pilots to revise their flight plan and several cognitive and psychosocial explanatory hypotheses have been put forward such as weather related change blindness (Muthard and Wickens, 2003), reduced updating abilities in working memory (Causse et al., 2011b,c; Ebbatson et al., 2007), task commitment issues and psychological stress (Dehais et al., 2011, 2012) or poor risk assessment (O' Hare and Smitheram, 1995; Wiegmann et al., 2002; Wiggins and O'Hare, 1995). Another contributing factor to PCE may reside in the large range of aversive consequences associated with the decision to go-around (Causse et al., 2011a). Indeed, a go-around can generate a psychological stress and/or a high uncertainty in the crew and the passengers, and it may lead to difficulties to reinsert into the landing pattern. For instance, Bonner and Wilson (2002) found that reported subjective mental workload and heart rate (physiological index of mental stress) were higher during go-around in comparison to others flight segments. This is a quite rare event and pilots lack pre-programmed responses whereas the flight plan must be rapidly updated. Moreover, a go-around has important economic consequences for the airline due to extra fuel consumption. One now-defunct airline used to pay passengers one dollar for each minute their flight was late until a crew attempted to land through a thunderstorm and crashed (Nance, 1986). According to Orasanu and colleagues (2001), airlines also emphasize fuel economy and getting passengers to their destinations rather diverting the flight, perhaps inadvertently sending mixed messages to their pilots concerning safety versus productivity. Those blurred messages create conflicting motives, which can affect unconsciously pilots' risk assessments and the course of action they choose.

In a landing phase, decision-making processes are generally based upon rational elements like the maximum crosswind speed for a given aircraft. However, emotional pressures can alter the rational reasoning by shifting decision-making criteria from safety rules to subjective ones (aversion to negative emotion). Indeed, experiencing an emotion has an ambiguous role in decision making. It can trigger unconscious processes useful to decision making, in particular when the uncertainty is high (Damasio, 1994). However, emotion or stress can also jeopardize decision-making relevance and cognitive functioning, in particular during complex tasks that involve higher cognitive abilities like executive functions, mainly but not only, implemented in the dorsolateral prefrontal cortex (DLPFC) (Schoofs et al., 2009). Abelson and Clarke (1963) were the firsts to oppose reason-based "cold cognition" to emotionally influenced "hot cognition". In this perspective, hot cognition integrates the influence of affect, for example during reasoning. Many authors have since confirmed the existence of a shift from rational cold reasoning to emotional hot reasoning and its cerebral underpinning has been demonstrated (Mitchell and Phillips, 2007). Neuroscientists commonly use such distinction in studies that examine relationships between cognitive and emotional processes. For instance, Goel and Dolan (2003) have explored the neural network involved in cold reasoning versus hot reasoning. In their experiment, participants had to solve syllogisms during an fMRI experiment. Half of the syllogism verbal content was neutral (cold) whereas the other half was emotionally salient (hot). Hot reasoning resulted in enhanced activation in ventromedial prefrontal cortex (VMPFC) whereas cold reasoning resulted in enhanced activity in DLPFC, highlighting that different regions are recruited during decision making according to the emotional state of participants. Such a cerebral shift may affect performance, accuracy of decision making and or reasoning (Simpson et al., 2001).

Neuroeconomics has widely studied the influence of emotional factors, such as incentive, on economic decision-making under uncertainty and its underlying neural bases. Monetary incentive is widely used since it is a good mean to reproduce real life emotions. Indeed, financial reward is associated with neuronal activities in the same regions that respond to emotions and primary reinforcers (Elliott et al., 2003). Taylor et al. (2004) highlighted the efficiency of financial incentive to bias cognitive processes such as short-term memory and object recognition. Therefore a parallel could be drawn between neuroeconomics experimental situations and pilots facing a conflict between expected punishments (extra fuel consumption, fatigue caused by a second landing attempt, etc.) and rewards (bring passengers without delay).

We adopted a neuroergonomics approach (Parasuraman and Rizzo, 2007; Sarter and Sarter, 2003) and developed an experimental paradigm inspired from neuroeconomics brain imaging protocol to investigate the impact of the emotional cost of a go-around on decision-making during a plausible landing-decision situation. Neuroimaging data were collected to bring objective clues on the cognitive and emotional processes involved in PCE. Our overall hypothesis is that, besides cognitive and psychosocial factors, a large range of strong negative emotional consequences attached to the go-around decision provokes a temporary impairment of the decision-making process and favors PCE. We explored two possible sources of the negative emotions: the uncertainty of the decision outcome and the reward or punishment associated to the outcome. Reward should elicit an emotional response that could interfere with rational decision-making and the emotional bias should increase with uncertainty (Katsis et al., 2010). We investigated our hypothesis in two experiments in which reward and uncertainty were manipulated. Both experiments used the same simplified landing task. In the next section, we describe participants' characteristics and the experimental paradigm of both behavioral and fMRI experiments. Experimental results are detailed in Section 3 and they are discussed in Section 4.

2. Methods

2.1. Participants

Two separate experiments were conducted with non-pilots. 12 healthy participants were recruited from the local population to participate to the behavioral experiment (mean age = 28, *SD* = 3.69). In addition, six other healthy participants (mean age 24, SD = 1.26) performed the same experiment within the fMRI. Pilots have years of training and their decisions

are based upon an important operational knowledge. However, we considered that the binary decision-making process involved in landing decision without external visibility (mainly based on rhombuses' positions) is quite generic and simple (even if some other information can be considered in real situation, like altitude) and should be very similar in non-pilots. All participants were right handed as measured by the Edinburgh handedness inventory (Oldfield, 1971). A professionally trained clinical psychologist neuropsychologically examined all participants. Due to their influence on decision-making processes, emotional disorders identification was based on impulsivity and anxiety assessment with the Barratt Impulsiveness Scale (BIS-10) (Patton et al., 1995) and the Spielberger state anxiety inventory (STAI Y-A) (Spielberger, 1983). In all participants, impulsivity and anxiety traits level were within a normal range (respectively, mean impulsivity = 63.5, *SD* = 9.91; mean state anxiety = 41.14, *SD* = 4.67). The experiment was approved by the local ethics committee and an informed consent was obtained before participation. Participants were paid for participating and were told that they would earn earned extra money according to their performance during the task. Eventually, they all received the same maximal amount of money for their participation at the end of the experiment.

2.2. Behavioral experiment

We used a 2 × 2 factorial design crossing two independent variables, the financial incentive and the uncertainty. The task was based on 480 × 480 pixels simplified reproduction of a real flight instrument, the ILS (Instrument Landing System). This instrument mainly supports the pilot's decision-making during landing without external visibility. Since the automation of the flight desk, the pilot's activity mainly aims at monitoring the embedded systems and not at controlling manually the flight itself. It is particularly true during the landing phase where pilots perform automatic landing and focus on Go/No–Go decision-making. Indeed when pilots decide to go-around, the first major action is to push the throttle to trigger the automated go-around maneuver. In a second time, the go-around initiates a missed approach procedure, an optional flight segment that is depicted in the flight plan (altitude to reach, heading, etc.).

Participants were instructed that they were flying an airplane that had reached the decision altitude (the point of the approach where the pilot must decide if the flight has to be aborted or not) and that, like pilots, they were allowed to abort the landing if they believed that landing was unsafe. Decisions were based on two elements of the ILS: the localizer and the glide slope, which provide lateral and vertical guidance to adjust the trajectory of the aircraft to land on the runway. This information was given by two rhombuses, like in real aircraft, displayed below and on the right of the artificial horizon (Fig. 1). Participants were instructed that the landing was safe when both rhombuses were close to the center of their axes and that the farthest from the center the rhombuses were, the higher the risk of crash was. Indeed, they were told that the rhombuses'

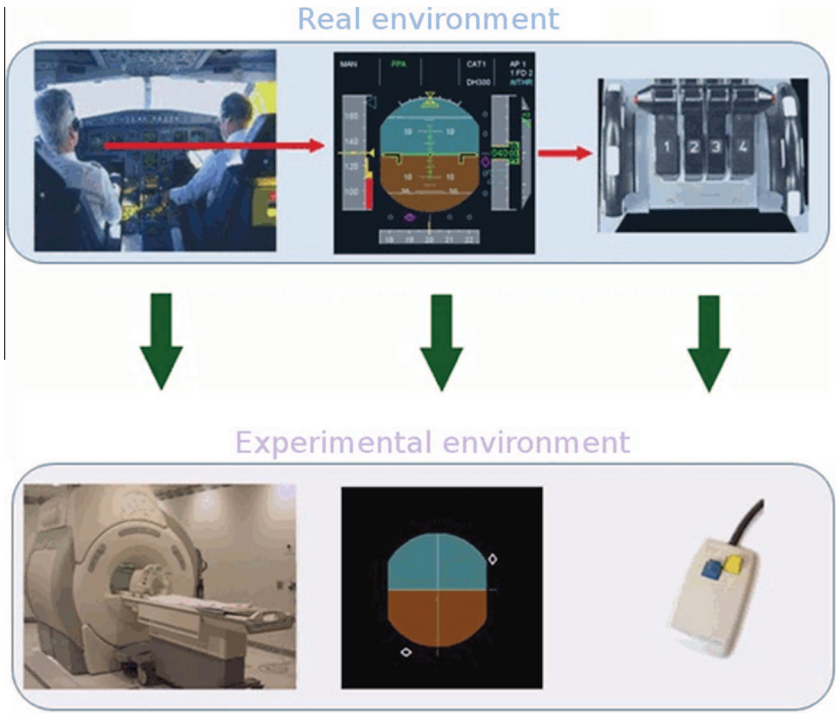


Fig. 1. Simplified reproduction of the decision-making environment during the landing phase. In the upper part, the real flight environment. From left to right: the cockpit, the main instrument with ILS and the throttle. In the bottom part, the fMRI environment. From left to right: the fMRI, the simplified instrument that supports decision making with the two rhombuses of the ILS (in white) and the response pad that allowed the Go–No–Go decision.

positions represented the vertical/lateral current position of the aircraft regarding an ideal approach flight-path. During unstabilized approach, events may be strongly unpredictable and results of actions cannot be well anticipated. In our study, we reproduced this uncertainty thanks to the level of ambiguity of the information provided by the instrument. Stimuli that supported the landing decision were manipulated according to two level of uncertainty: low and high (Fig. 2). When the rhombuses were in "fuzzy" positions (i.e. in between a straight go-around and a safe landing), the decision consequence (accuracy and/or financial outcome) became unpredictable, which generated uncertainty. In the low-uncertainty condition, decision making was quite simple as the rhombuses' positions were not ambiguous: either the rhombuses were very far from the centers of their axes, requiring a go-around (likelihood of successful landing: 0%), either they were very close from the centers of their axes, requiring a landing acceptance (likelihood of successful landing: 100%). In the high-uncertainty condition, decision making was complex as the rhombuses' positions were ambiguous (i.e. borderline, not very far, and not very close from the center of their axes). In this latter condition, the uncertainty was maximal as the likelihoods (unknown by the participants) of successful landing or crash were equal (50%). Within a run, there was no repetition of a same rhombus pattern.

Two types of runs were presented during the experiment: neutral and financial (Fig. 3). For each trial, participants indicated their choice (Go/No–Go) by pressing a button on the response pad. After each response, the participants received a feedback that informed on the response accuracy (OK, for a successful landing or a justified go-around; NO, for an erroneous decision to land or an unjustified go-around). During the financially motivated condition, the emotional consequences associated with a go-around were simulated by a payoff matrix. This matrix was designed to bias responses in favor of landing acceptance. A go-around was systematically punished by a financial penalty. The penalty was less important (−2€) when the go-around was justified (in the case where rhombuses were clearly too far from their centers) than when it was unjustified (−5€). This systematic punishment of the decision to go-around artificially reproduced the systematic negative consequences encountered in real life after this decision. A successful landing was rewarded (+5€) whereas an erroneous decision to land was punished (−2€).

The fact that the erroneous decision to go-around was more punished than the erroneous decision to land may appear counterintuitive but the payoff matrix was set up in this way for two reasons. Firstly, in real life, pilots know that crash and overrun are rather unlikely events whereas the negative consequences associated with a go-around are systematic. The analysis of unstabilized approach events confirms that they rarely lead to an accident in spite of frequent risk-taking (Rhoda and Pawlak, 1999). As a consequence, the expected value (EV) of a landing decision has to remain positive in the experimental design to reproduce this psychological aspect. Secondly, the detection of the cerebral activation would have been difficult with a too low number of repetitions of the same condition (i.e. a decision to land that provokes a crash).

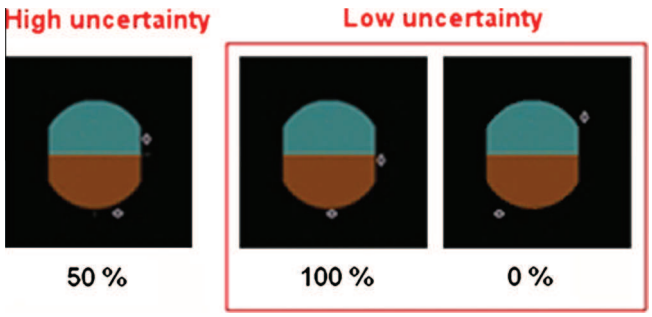


Fig. 2. Categorization of the level of uncertainty according to the rhombuses positions. The rhombuses positions were counterbalanced to avoid laterality effects. The order of presentation of the stimuli was randomized.

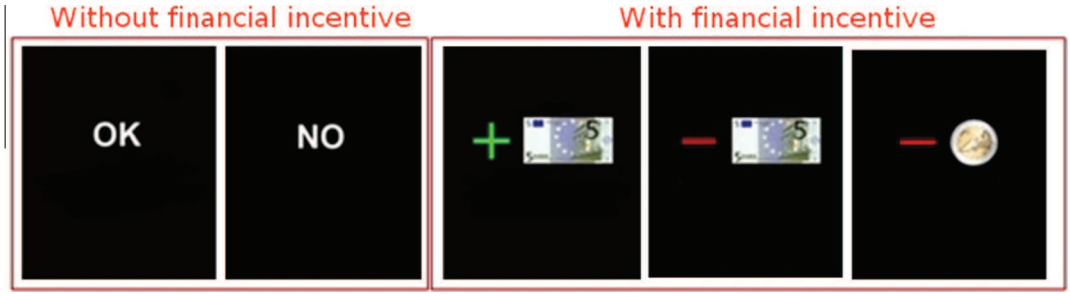


Fig. 3. The various feedbacks displayed after each decision making. During the neutral condition, only the accuracy feedback was delivered (OK/NO). During the financially motivated condition, the financial consequences (reward/punishment) were also displayed, after the accuracy feedback.

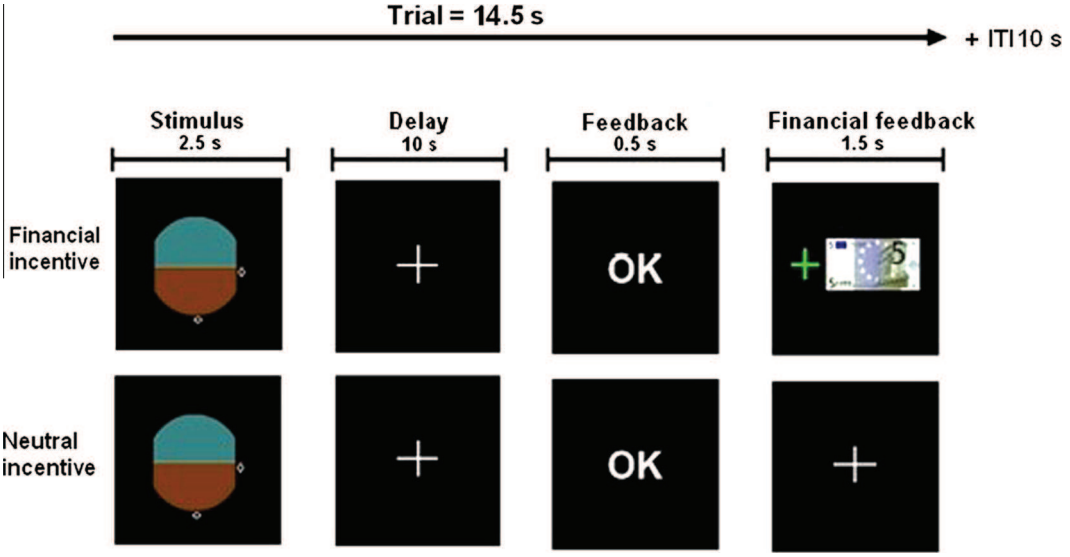


Fig. 4. Diagrammatic illustration of the experimental design. The two types of experimental runs (neutral and financially motivated) are showed.

The low signal-to-noise ratio of fMRI requires a great number of repetitions of stimuli under the same condition. For this reason, we choose to apply a low punishment for erroneous landings rather than diminishing their likelihood of occurrence and administrating a very high punishment when it happened (which would have been closer to real life where crashes are rare but have immeasurable costs). To summarize, the expected value of the gain/loss after the decision to land was positive $((0.5 \times 5€) - (0.5 \times -2€) = +1.50€)$, whereas it was clearly negative after the decision to go-around $((0.5 \times -2€) + (0.5 \times -5€) = -3.50€)$. Our goal was not to monetize precisely the cost of a go-around, since such a calculation would be quite complex to perform. Monetary incentive simply allowed reproducing the conflicting positive/negative emotional consequences attached with the landing decision. The values of gains and losses were chosen to be plausible for the participants, as they were told that they would be rewarded according to them.

At the end of each run, a global feedback indicated the percentage of correct responses, the ''safety score''. Moreover, at the end of the financially motivated run only, another feedback indicated the cumulative amount of money gain or loss, the ''financial score''. These two scores are conflicting since the optimization of the ''financial score'' can only be obtained at the expense of the ''safety score'' as it necessarily implies a dangerous increase of the landing acceptance rate. Eventually, participants were explained that, as in real life, taking into account the flight safety was essential in the experiment.

Stimulus display and data acquisition were done with Cogent 2000 v125 (a software environment for functional brain mapping experiments that allows presenting scanner-synchronized stimuli) running under Matlab environment (Matlab 7.2.0.232, R2006a, The MathWorks, USA). Each trial (see Fig. 4) consisted in the display of the stimulus (2.5 s) during which the participant performed the decision making thanks to a response pad, followed after a delay (10 s) by the feedback informing of the accuracy of the response (0.5 s). During the financially motivated condition only, the financial outcome, contingent of the participants' response, was displayed during 1.5 s. An inter-trial interval (10 s) was introduced (an amount of time between the end of the feedback display and the display of the next stimulus). Before the experiment, participants performed two runs (neutral and financial) to become familiar with the task and the payoff matrix.

2.3. Functional magnetic resonance imaging experiment

The experiment was conducted at the neuroimaging laboratory of the Santa Lucia Foundation (Roma). All the data were acquired in a single session on a 3 T Allegra scanner (Siemens Medical Solutions, Erlangen, Germany) with a maximum gradient strength of 40 mT/m, using a standard quadrature birdcage head coil for both RF (Radio Frequency) transmission and RF reception. The fMRI data were acquired using a gradient echo-EPI (Echo Planar Imaging), with 38 axial slices with a voxel size of $3 \times 3 \times 3.75$ mm^3 (matrix size 64×64; FOV (Field Of View) 192×192 mm^2) in ascending order. The acquisition time was 2.47 s/65 ms/slice. Data analysis was performed within SPM8 analytic package (Statistical Parametric Mapping 8, Wellcome Department of Cognitive Neurology, London, UK). The data were sinc-interpolated in time and re-aligned to the first acquired volume to correct head motion. A mean functional image volume was constructed for each subject from the realigned image volumes. This mean image was spatially normalized to a Montreal Neurological Institute (MNI) EPI template with affine registration followed by nonlinear transformation. The normalization parameters determined for the mean functional volume were then applied to the corresponding functional image volumes for each subject. Spatial normalization of neuroimaging data is a standard step when assessing group effects. All participants' brain images were warped to a stan-

dard space (MNI space, which is the average of 152 normal MRI scans) to match a comparable standard size, orientation and shape. This allows identifying activated brain structures independently from individual differences in the size and overall shape of the brain. Finally, images were smoothed with an isotropic 8-mm full-width-half-maximum Gaussian kernel to correct for remaining inter-subject anatomy variability. For reporting, MNI coordinates were converted into Talairach (TAL) space (another widely used standard space) using Wake Forest University Pickatlas (WFU-Pickatlas, version 2.4) (Maldjian et al., 2004). Talairach atlas Anatomical regions were identified using the Talairach Daemon Client, version 2.2.4. The Talairach Daemon gives Talairach Atlas labels (i.e. anatomical region labels) for a given x, y, z coordinate and allows to identify anatomical regions with a specified tolerance (3 mm^3 in our analysis). The fMRI design was identical to that of the behavioral study except that the delay between the stimulus and the feedback (6–10 s) and that the inter-trial intervals were variables (3–9 s) for neuroimaging technical requirements. We focused our investigations on the decision making cerebral processes. The hemodynamic response measured by fMRI (i.e. related to the neural activity) peaks at 4–6 s and lasts over 10 s. The long variable delay before the feedback allowed us to dissociate the hemodynamic signal associated with the stimulus (the decision making) from the signal associated with the reward expectancies during the delay (the expectancies of a reward/punishment also generates a cerebral activity). The training session was identical to the behavioral task one.

3. Results

3.1. Statistical analysis

We examined two different behavioral dependant variables: percentage of landing acceptance and reaction times (RTs). The percentage of landing acceptance gave a direct indication on the behavioral shift generated by the financial incentive. We also analyzed RTs to confirm that ambiguous stimuli generated a high uncertainty. This higher level of uncertainty should provoked longer RTs before reaching a decision in comparison to non-ambiguous stimuli. This was an important issue as the effects of emotion on decision making are particularly obvious during complex tasks with high uncertainty. All behavioral data were analyzed with Statistica 7.1 (© StatSoft). The Kolmogorov–Smirnov goodness-of-fit test showed that data distribution was not normal; therefore we used non-parametric tests. The effects of the stimulus type (neutral or financial) and the level of uncertainty (low or high) on our dependant variables, the percentage of landing and RTs, were examined thanks to Friedman's ANOVA.

Presented preliminary analyses focused on the decision-making processes, at the time of the stimulus (instrument with rhombuses) display. To analyze the brain regions that were more activated during the neutral stimuli, the following contrast was performed: [Low uncertainty + High uncertainty, Neutral] minus [Low uncertainty + High uncertainty, Financial]. The opposite contrast, [Low uncertainty + High uncertainty, Financial] minus [Low uncertainty + High uncertainty, Neutral] was performed to examine brain regions that were more activated during the financially motivated condition. These analyses are based on one sample t-test. Neuroimaging results are presented in table 1 (i.e. 3D coordinates, z-value and cluster size k).

3.2. Behavioral results

The mean total amount won was positive (13.75€, $SD = 11.15$) and confirmed that the reward/punishment system has oriented decision making toward economic optimization as decision that would have been oriented only toward safety (systematic go-around in case of uncertainty) would have lead participants to get a negative outcome (−70€). Indeed, in response to the asymmetric payoff matrix, participants demonstrated a significant shift in the likelihood of accepting landings when uncertainty was high. More precisely, the Friedman's ANOVA showed that under high uncertainty, the mean percentage of landing acceptance increased in response to the financial incentive, from 30.71% ($SD = 11.83$) to 69.88% ($SD = 27.15$) ($\chi^2(12,1) = 9.00$; $p = .002$), see Fig. 5.

The Friedman's ANOVA also revealed an overall effect of uncertainty (both types of incentive included). Ambiguous stimuli generated longer mean RTs than non-ambiguous ones ($\chi^2(12,1) = 18.0$, $p < .001$), see Fig. 6. In addition, there was

Table 1
Brain area and Brodmann number, Talairach 3D coordinates (anatomical identification), Z-score (Gaussian normalized t-statistics, it gives an indication on the level of activation) and cluster sizes (k) of the activated anatomical structures for both contrasts, neutral minus financial and financial minus neutral. Cluster size refers to the number of activated voxels in each region. All activations were significant at threshold $p < .001$ uncorrected. Bilateral regions of the VMPFC (BA11) were found to be more activated when the task was performed with the financially motivated condition in comparison to the neutral condition. On the opposite, the right DLPFC (46) was more activated during the neutral condition in comparison to the financially motivated condition.

Brain area (BA)	Neutral minus Financial Talairach coordinates					Brain area (BA)	Financial minus Neutral Talairach coordinates				
	x	*y*	*z*	*Z*-score	*k*		*x*	*y*	*z*	*Z*-score	*k*
Frontal						Frontal					
DLPFC (BA46)	53	36	19	2.35	22	VMPFC (BA11)	−12	42	−24	2.33	21

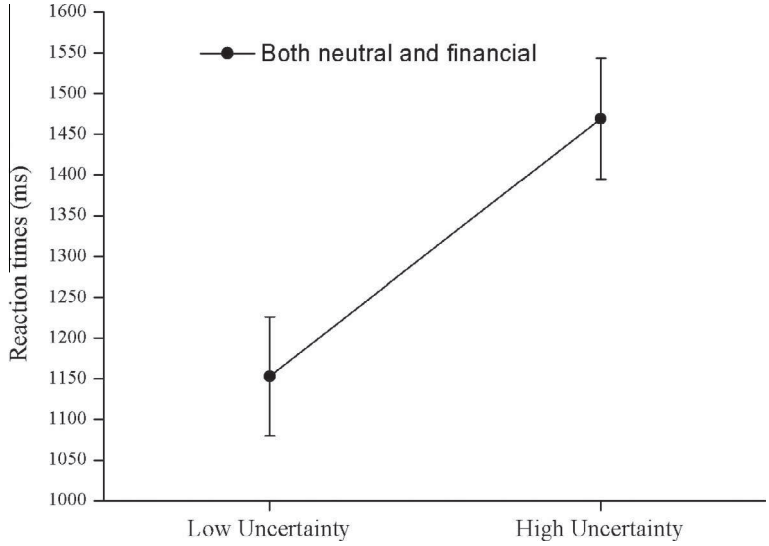


Fig. 5. Reaction times (in ms) according to the level of uncertainty (low and high) for both types of stimuli (neutral and financial).

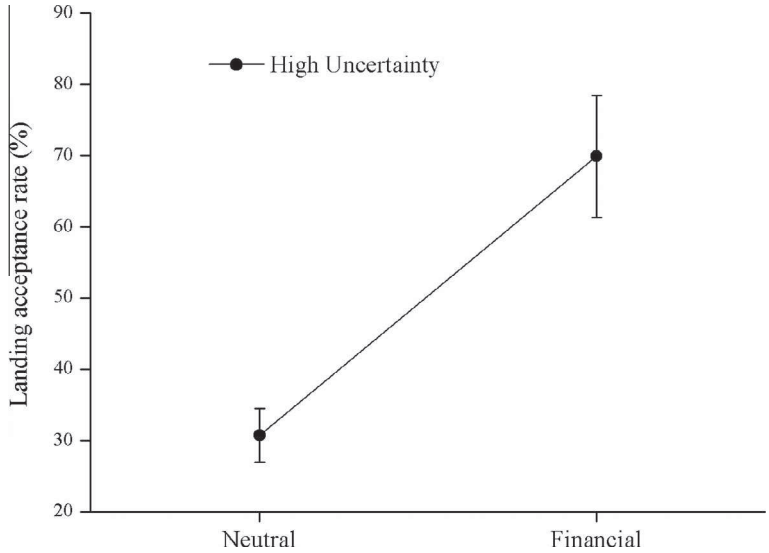


Fig. 6. Percentage of landing acceptance according to both type of incentive (Neutral and Financial) during high uncertainty stimuli only (50%). Whereas participants demonstrated a conservative behavior during the neutral condition (below 50% of landing acceptance) they made more risky decision during the financially motivated condition (far beyond 50% of landing acceptance).

an interaction between the type of stimuli and the level of uncertainty. When uncertainty was high, RTs where shorter during financially motivated condition in comparison to the neutral condition ($\chi^2(12,1) = 8.00$, $p = .004$).

3.3. fMRI results

The six participants that performed the task in the scanner demonstrated behavioral results that were coherent with the previous larger behavioral group. The financial incentive generated a shift in the likelihood of accepting landings under high uncertainty ($\chi^2(6,1) = 15.00$; $p < .001$), from 45.83% ($SD = 16.63$) in the neutral condition to 65.83% ($SD = 7.37$) of landing acceptance in the financially motivated condition. Moreover, RTs were longer when the uncertainty was high ($\chi^2(6,1) = 6.0$; $p < .001$). We also found an interaction between the type of stimuli and uncertainty: when uncertainty was high, RTs where shorter during financially motivated condition in comparison to the neutral condition ($\chi^2(6,1) = 6.25$; $p = .012$).

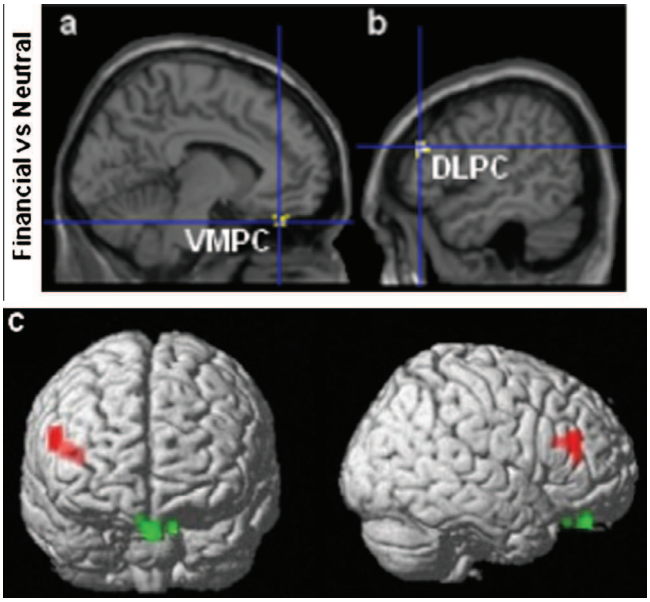


Fig. 7. (a) Bilateral VMPFC activations (BA11) during stimuli display for financially motivated condition minus neutral condition. (b) Right DLPFC activation (BA46) during stimuli display for neutral condition minus financially motivated condition (c) global view for both contrasts. Effects of financial incentive are displayed in green; effects of neutral condition are displayed in red ($p < 0.001$; cluster > 15). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

We investigated brain regions that were involved during decision making, depending on the type of stimuli. The first contrast [Low uncertainty + High uncertainty, Neutral] minus [Low uncertainty + High uncertainty, Financial] revealed that cold decision-making activated right DLPFC (Brodmann area[1] 46; $p < .001$; cluster size = 22). Our main interest in this study was to examine which regions were more activated during hot decision-making. We then performed a second contrast [Low uncertainty + High uncertainty, Financial] minus [Low uncertainty + High uncertainty, Neutral] to analyze decision making during the financially motivated condition. We found that hot decision-making increased activity in bilateral VMPFC (Brodmann area 11; $p < .001$; cluster size = 21) (Fig. 7). An additional analysis examining the effects of the financial incentive only during high uncertainty stimuli [High uncertainty, Financial] minus [High uncertainty, Neutral] gave coherent results with larger bilateral VMPFC activations (larger cluster size) than the previous analysis that included both levels of uncertainty (Brodmann area 11; −3, 47, −11; $p < .001$; cluster size = 30; $Z = 3.14$).

4. Discussion

Our hypothesis was that a large range of strong negative emotional consequences attached to the go-around decision provokes a temporary impairment of the decision-making process and favors PCE. To better understand the underlying neural mechanisms, we designed a brain imaging protocol where financial incentive and uncertainty were manipulated while participants were performing a landing decision task. The behavioral results were in accordance with our expectations. The uncertainty level generated two types of decision-making: when the rhombuses positions were non-ambiguous, all participants reported that the decision was straightforward. On the contrary, when the rhombuses positions were ambiguous they tried hard to find a rule. These assertions were supported by longer RTs when the ambiguity was high. Such results were predictable and suggest that low uncertainty stimuli were easily categorized and that high uncertainty stimuli tended to provoke a more difficult decision-making.

Moreover, the payoff matrix encouraged participants to avoid financial loss and maximize their monetary reward and biased their response criterion from safety to economic considerations. The volunteers showed a significant shift in the response criterion and a trend to increase their landing acceptance rate under the influence of the financial incentive. Whereas their behaviors were rather conservative in the neutral condition, they made more risky decisions during the financially motivated condition to avoid the risk of a penalty in the case of go-around. This effect was particularly true when the uncertainty was high. In addition, concerning stimuli with high uncertainty only, RTs were shorter during the financially motivated condition, showing more compulsive and reward-weighted decision-making. These results were quite comparable

[1] Brodmann area, defined and numbered by the German anatomist Korbinian Brodmann, are structurally distinguishable and presumably functionally distinct regions into which the cortex of each cerebral hemisphere can be divided.

to those of the neuroeconomics study conducted by Taylor Taylor et al. (2004) where monetary incentive and task complexity negatively impacted performances to a short-term memory task and increased the number of false items recognition.

Our preliminary neuroimaging results suggest that the payoff matrix biased emotionally decision making. Indeed, the change in decision-making criterion entailed by the financial incentive was subserved by a shift from a cerebral region dedicated to reasoning, the DLPFC, to a region involved in emotional processing, the VMPFC. It should be noted that an additional analysis that focused on financial incentive effect during high uncertainty stimuli only, gave coherent results with even larger bilateral VMPFC activations than the analysis that considered overall financial incentive effect (both type of uncertainty included). These outcomes confirmed the hypothesized emotional and cognitive subdivisions within the prefrontal cortex (Goel and Dolan, 2003). Cold decision-making appeared to be more analytic and safety oriented whereas hot decision-making was associated with a search for reward at the expense of safety. Taken together, our results are coherent with the neuroscientific literature that shows that the reciprocal influence of cognition and emotion are meditated by specialized brain subdivisions (Mitchell and Phillips, 2007; Simpson et al., 2001). We are aware that our simplified landing situation, due to fMRI requirements, was far from a real flight situation. Moreover a strong limitation of this study is the limited sample of non-pilots participants. However, a similar experiment, where physiological measurements were performed in 19 pilots, demonstrated the same response pattern: an increased number of landing acceptance during the financially motivated condition when uncertainty was high (Causse et al., 2011a). Moreover, the physiological results showed that heart rate was higher during the financially motivated condition in comparison to the neutral condition, demonstrating that the financial incentive provoked a substantial emotional arousal. Eventually, though the human and economical consequences of our simplified landing task had nothing to compare with real flight issues, the payoff matrix designed to reproduce the negative emotional consequences linked with the decision to go-around was efficient enough to provoke risky behavior such as PCE. The gap between reality and laboratory exists in every fMRI experiment that examines the relationship between emotion and cognition. Nevertheless such an approach with simplified situations was initiated by neuroeconomics and has provided new theoretical issues for behavioral economy. Whereas neuroimaging results can be more conclusive (and extrapolated to real-life situation) in less context-dependant neural processes, for instance like those involved in reading, emotional related neural processes are more difficult to apprehend and generalization to everyday life is sometime quite questionable. However we assume that this controlled laboratory experiment involved quite generic processes related to emotional influence on decision making and brings a part of explanation concerning risky decision-making observed in pilots when facing uncertainty and emotional pressures.

The shift from cold to hot decision-making offers interesting theoretical prospects for aviation safety. At least in part, PCE could be the result, of the different aversive negative consequences associated with the go-around decision, such as the financial cost for the company. Despite its limitations, the present study confirms the interest of merging cognitive neurosciences with cognitive ergonomics (Sarter and Sarter, 2003) within a neuroergonomics approach (Parasuraman and Rizzo, 2007) to refine the underlying mechanisms of human error (Fedota and Parasuraman, 2010). Very few studies have used fMRI means in aviation safety. Despite limits in terms of task realism, such a technique presents an excellent spatial resolution and allows observing precisely which brain regions, and as a consequence which cognitive processes, are involved during specific complex human tasks. In addition, the use of image-processing techniques such as independent component analysis (Calhoun et al., 2005; Meda et al., 2009) is expected to allow more dynamic and ecological protocols in the future. Moreover, less spatially accurate but less invasive methods such as magneto-encephalography (Fort et al., 2010), electro-encephalography (Dussault et al., 2005) or near infra-red spectroscopy (Takeuchi, 2000) has to be considered as they allow experiments in more realistic situations, for instance in full flight simulators.

References

Abelson, R., Clarke, D.D., 1963. Computer simulation of ‘‘hot’’ cognition. In: Tomkins, S., Messick, S. (Eds.), Computer Simulation and Personality: Frontier of Psychological Theory. Wiley, New York.

BEA, 2000. Objectif: Destination. Technical Report, Bureau Enquête Analyse.

Bonner, M.A., Wilson, G.F., 2002. Heart rate measures of flight test and evaluation. The International Journal of Aviation Psychology 12 (1), 63–77.

Calhoun, V., Carvalho, K., Astur, R., Pearlson, G., 2005. Using virtual reality to study alcohol intoxication effects on the neural correlates of simulated driving. Applied Psychophysiology and Biofeedback 30 (3), 285–306.

Causse, M., Baracat, B., Pastor, J., Dehais, F., 2011a. Reward and uncertainty favor risky decision-making in pilots: evidence from cardiovascular and oculometric measurements. Applied Psychophysiology and Biofeedback 36 (4), 231–242.

Causse, M., Dehais, F., Arexis, M., Pastor, J., 2011b. Cognitive aging and flight performances in general aviation pilots. Aging, Neuropsychology, and Cognition 18 (5), 544–561.

Causse, M., Dehais, F., Pastor, J., 2011c. Executive functions and pilot characteristics predict flight simulator performance in general aviation pilots. The International Journal of Aviation Psychology 21 (3), 217–234.

Damasio, A., 1994. Descartes’ Error: Emotion, Reason, and the Human Brain. Grosset/Putnam, New York.

Dehais, F., Causse, M., Tremblay, S., 2011. Mitigation of conflicts with automation. Human Factors: The Journal of the Human Factors and Ergonomics Society 53 (5), 448–460.

Dehais, F., Causse, M., Vachon, F., Tremblay, S., 2012. Cognitive conflict in human–automation interactions: a psychophysiological study. Applied Ergonomics 43 (3), 588–595.

Dussault, C., Jouanin, J.C., Philippe, M., Guezennec, C.Y., 2005. EEG and ECG changes during simulator operation reflect mental workload and vigilance. Aviation, Space, and Environmental Medicine 76 (4), 344–351.

Ebbatson, M., Harris, D., Jarvis, S., 2007. Crosswind landings in general aviation: a modified method of reporting wing information to the pilot. The International Journal of Aviation Psychology 17 (4), 353–370.

Elliott, R., Newman, J., Longe, O., Deakin, J., 2003. Differential response patterns in the striatum and orbitofrontal cortex to financial reward in humans: a parametric functional magnetic resonance imaging study. Journal of Neuroscience 23 (1), 303.

Fedota, J.R., Parasuraman, R., 2010. Neuroergonomics and human error. Theoretical Issues in Ergonomics Science 11 (5), 402–421.
Fort, A., Martin, R., Jacquet-Andrieu, A., Combe-Pangaud, C., Foliot, G., Daligault, S., et al, 2010. Attentional demand and processing of relevant visual information during simulated driving: a MEG study. Brain Research 1363, 117–127.
Goel, V., Dolan, R., 2003. Reciprocal neural response within lateral and ventral medial prefrontal cortex during hot and cold reasoning. Neuroimage 20 (4), 2314–2321.
Katsis, C., Goletsis, Y., Rigas, G., Fotiadis, D., 2010. A wearable system for the affective monitoring of car racing drivers during simulated conditions. Transportation Research Part C: Emerging Technologies 19 (3), 541–551.
Maldjian, J.A., Laurienti, P.J., Burdette, J.H., 2004. Precentral gyrus discrepancy in electronic versions of the Talairach atlas. Neuroimage 21 (1), 450–455.
Meda, S.A., Calhoun, V.D., Astur, R.S., Turner, B.M., Ruopp, K., Pearlson, G.D., 2009. Alcohol dose effects on brain circuits during simulated driving: an fMRI study. Human Brain Mapping 30 (4), 1257–1270.
Mitchell, R., Phillips, L., 2007. The psychological, neurochemical and functional neuroanatomical mediators of the effects of positive and negative mood on executive functions. Neuropsychologia 45 (4), 617–629.
Muthard, E.K., Wickens, C.D., 2003. Factors that mediate flight plan monitoring and errors in plan revision: planning under automated and high workload conditions. In: Paper Presented at the 12th International Symposium on Aviation Psychology. Wright State University, OH.
Nance, J., 1986. Blind trust: How Deregulation has Jeopardized Airline Safety and What You Can Do About It. William Morrow and Co., New York.
O' Hare, D., Smitheram, T., 1995. "Pressing on" into deteriorating conditions: an application of behavioral decision theory to pilot decision making. The International Journal of Aviation Psychology 5 (4), 351–370.
Oldfield, R., 1971. The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia 9 (1), 97–113.
Orasanu, J., Ames, N., Martin, L., Davison, J., 2001. Factors in aviation accidents: decision errors. In: Salas, E., Klein, G.A. (Eds.), Linking Expertise and Naturalistic Decision Making. Lawrence Erlbaum Associates, Mahwah, NJ, pp. 209–225.
Parasuraman, R., Rizzo, M., 2007. Neuroergonomics: The Brain at Work. Oxford University Press, USA.
Patton, J.H., Stanford, M.S., Barratt, E.S., 1995. Factor structure of the Barratt impulsiveness scale. Journal of Clinical Psychology 51 (6), 768–774.
Rhoda, D., Pawlak, M., 1999. An Assessment of Thunderstorm Penetrations and Deviations by Commercial Aircraft in the Terminal Area. Massachusetts Institute of Technology, Lincoln Laboratory, Project Report NASA/A-2, 3.
Sarter, N., Sarter, M., 2003. Neuroergonomics: opportunities and challenges of merging cognitive neuroscience with cognitive ergonomics. Theoretical Issues in Ergonomics Science 4 (1), 142–150.
Schoofs, D., Wolf, O., Smeets, T., 2009. Cold pressor stress impairs performance on working memory tasks requiring executive functions in healthy young men. Behavioral Neuroscience 123 (5), 1066–1075.
Simpson, J., Snyder, A., Gusnard, D., Raichle, M., 2001. Emotion-induced changes in human medial prefrontal cortex: I. During cognitive task performance. Proceedings of the National Academy of Sciences, 98 (2), 683.
Spielberger, C.D., 1983. Manual for the State-Trait Anxiety Inventory (STAI). Consulting Psychologists Press, Palo Alto, CA.
Takeuchi, Y., 2000. Change in blood volume in the brain during a simulated aircraft landing task. Journal of Occupational Health 42 (2), 60–65.
Taylor, S., Welsh, R., Wager, T., Luan Phan, K., Fitzgerald, K., Gehring, W., 2004. A functional neuroimaging study of motivation and executive function. Neuroimage 21 (3), 1045–1054.
Wiegmann, D.A., Goh, J., O'Hare, D., 2002. The role of situation assessment and flight experience in pilots' decisions to continue visual flight rules flight into adverse weather. Human Factors: The Journal of the Human Factors and Ergonomics Society 44 (2), 189–197.
Wiggins, M., O'Hare, D., 1995. Expertise in aeronautical weather-related decision making: a cross-sectional analysis of general aviation pilots. Journal of Experimental Psychology: Applied 1 (4), 305.