THE IN-FLIGHT AFFECTIVE BRAIN: DECISION MAKING UNDER UNCERTAINTY AND SAFETY IMPLICATIONS IN AVIATION

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Understanding the relation between motivation and pilot impulsive decision-making is extremely important in the context of aviation human factors. One way to operationalize motivation is by presenting participants with different reinforces, either primary (e.g. food rewards) or secondary (e.g. financial incentives, arguably playing a crucial role in in-flight decision-making). To establish the role that different reward systems play in decision-making, we tested the extent to which distinct brain regions are sensitive to the reinforcement content. Combining a neuro-economics approach with a voxel-based lesion method, we found that distinct regions within orbito-frontal cortex (OFC) are differentially involved in impulsivity decisions based on the reinforcement type. In contrast, lesions in dorsolateral prefrontal cortex (DLPFC) were not associated with such decisions. These results suggest a distinction between reward types at the neural level, and thus emphasize the importance of investigating how different reinforces can affect flight activity especially in pilot impulsive, risk-taking behavior.

Most flight accidents occur during arrival, even though this flight phase represents only 4% of overall flight time (Boeing, 2005). One potential reason for this is pilot risky decision-making. In 2,000 cases of approaches under thunderstorm conditions studied, two aircrews out of three kept on landing in spite of adverse meteorological conditions, instead of going-around to perform a new attempt to land more securely or to divert to another airport (Rhoda & Pawlak 1999). Many factors might account for the difficulty for pilots to revise their flight plan given adverse weather conditions (Goh & Wiegmann 2002). The decision to go-around might incur a broad range of strong negative emotional consequences, as a go-around decision increases uncertainty and level of stress. Moreover, a go-around has important financial consequences for the airlines, resulting in airlines emphasizing fuel economy and getting passengers to their destinations rather than diverting the flight (Orasanu, 2001). Thus, the airlines might inadvertently send implicit messages to their pilots and these blurred messages might create conflicting motives, which can affect pilots' risk assessments and the course of action they choose. Together, all these emotional pressures could negatively impact pilots' rational decision-making.

As in the aviation context, everyday decisions are often made in the presence of risk and uncertainty. Risk refers to multiple possible outcomes, both positive and negative, that could occur with well-defined or estimable probabilities (Stearns 2000). In the field of neuro-economics, 'risk' refers to monitoring potential monetary outcomes (Tom et al. 2007). Studies exploring the effects of risk on cognition in the form of monetary reward or punishment highlighted that financial incentives can bias working memory and object recognition (Taylor et al. 2004). As reward/punishment manipulation may interfere both with cognition and emotion, one might expect similar

effect in pilots placed in a conflict situation between systems of punishment (extra fuel consumption, fatigue caused by a second landing attempt etc.) and reward (bring passengers without delay).

The current study aims to explore the mechanisms underlying conflict in reward and its impact on decision-making. We adopted a voxel-based lesion symptom mapping (VLSM) approach (Bates et al. 2003) to investigate the relationship between the amount of brain tissue damage and the extent to which decision-making is affected by different types of reinforcement. Prior studies of the neural correlates of risk in the context of financial decision-making suggest that estimating monetary gains and losses involves activity in multiple brain areas (e.g. Huettel et al. 2006) including different regions within prefrontal cortex, particularly orbitofrontal cortex (OFC) and dorsolateral prefrontal cortex (DLPFC). DPLFC is involved in higher cognitive processes, such as reasoning, whereas OFC is involved in emotional processes, primarily modulating the anticipation of regret linked with financial loss (Coricelli et al. 2005). Further, neuroimaging studies found dissociation in the type of rewards activating specific sub-regions of OFC: erotic stimuli preferentially activated the posterior portion of the OFC whereas monetary gains activated the anterior lateral part of OFC (Sescousse et al., 2010; 2013). Given that posterior OFC is phylogenetically and ontogenetically older than anterior OFC, this might reflect differential processing of rewards based on their evolutionary significance.

We aimed to establish the extent to which distinct brain regions within the OFC show a differential sensitivity to the content of reinforcement. In this lesion-defined approach, behavioral performance is accounted by the amount of missing voxels derived from various groups of patients with lesions varying in location and extent (Bates et al. 2003). This may reveal whether the absence of a given brain region (e.g. OFC) can explain variation in behavioral performance (e.g. impulsivity). Notably, the VLSM method does not require patients to be grouped by either lesion site or behavioral cutoff, but instead makes use of continuous behavioral and lesion information. We selected patients with brain lesions located in the OFC cortex (OFg), patients with brain lesions located outside the frontal cortex (non-OFg), and healthy participants (CnTg). All participants were tested with the Delay Discounting (DD) paradigm that allows measuring impulsivity in decision-making by asking participants to choose between either a fixed amount of a reward that could be received immediately or a greater amount of reward that could be received after a specific delay. We administered the DD paradigm with two types of rewards: primary (food) and secondary (monetary). Based on the notion of a reward-based functional dissociation within the OFC, our hypothesis was that a higher amount of brain damage (in terms of missing voxels) involving the anterior OFC would result in a more impulsive behavior in the money-related task, whereas a greater damage involving the posterior OFC would result in a more impulsive behavior in the food-related task.

Materials and Methods

Participants

Participants comprised of 37 individuals: 11 patients with lesions involving the OFC (OFg; mean age 59.27 DS ± 10.71; mean education in years 9.45 DS ± 4.23; 7 females) located either in the anterior (involving BA 10; mean missing voxels = 1,020 N = 5) or the posterior part (involving BA 11 and 13; mean missing voxels = 1,126 N = 6), 9 patients with lesions located outside the frontal cortex (non-OFCg; mean age 50.22 DS ± 11.39; mean education in years 10.78; DS ± 3.93; 6 females) and 17 healthy controls (CnTg; mean age 53.12 DS ± 13.61; mean education in years 13.11 DS ± 5.48; 8 females). The three groups did not significantly differed for age, education and lesion extension (all $p_s > 0.05$).

Experimental paradigm and procedure

Participants were requested to choose between a fixed amount of a reward that could be received immediately and a greater amount of reward that could be received after a specific delay. The nature of the reward changed across sessions: one session assessed DD for money, whereas the other one assessed DD for food. Delays used for the money session were based on Peters & Büchel (2009) – i.e. 6 hours, 1 day, 7 days, 30 days, 90 days, 180 days. Since food reward, by its nature, cannot be delayed over long period of time, we used shorter intervals for the food condition than the money condition. Based on a pilot study (unpublished), the following delays were adopted: 30 min, 90 min, 3 hours, 10 hours, 1 day, 7 days. Participants were told that the compensation for their participation would be based on a raffle performed at the end of the study, in which a trial would have been chosen at random and delivered to them. Participants were tested individually. Two behavioral experimental sessions - one

with primary (food) and one with secondary (money) rewards were performed. The session order was counterbalanced across subjects. The total duration of the experimental session was about 30 minutes.

Data analysis

Behavioral data. For each task, the rate at which the subjective value (SV) of a reward decays with delay (TD rate) was assessed through the discounting parameter (k) (Rachlin et al., 1991; Green and Myerson, 2004). The hyperbolic function SV = $1/(1+k$D), where SV = subjective value (expressed as a fraction of the delayed amount), and D = delay, was fit to the data to determine the k constant of the best fitting TD function, using a nonlinear, least-squares algorithm. The larger the value of k, the steeper the discounting function, the more participants are inclined to choose small-immediate rewards over larger-delayed rewards. The hyperbolic K constants were normally distributed after log-transformation (Kolmogorov-Smirnov $d < 0.19$, $p > 0.1$ in all cases) therefore allowing the use of parametric statistical tests.

Lesion localization and quantification. To identify patients' lesion, a high-resolution T1-weighted anatomical image (TR, 9.9 ms; TE, 4.6 ms; 170 sagittal slices; voxel size, 1x1x1) was acquired with a Philips Intera system at 3 T. In order to automatically identify patients' lesions avoiding to trace them manually, MRI scans acquired from 100 healthy participants (not included in the actual CnTg) divided in two subgroups based on gender (male subgroup: N = 50; mean age = 34.16; mean education = 15.96; female subgroup: N = 50; mean age = 42.6; mean education = 15.16) were used. To control for gender effect, each patient was compared with the appropriate gender subgroup. Lesion data from 20 patients belonging to the OFg (N = 11) and the non-OFg (N = 9) were analyzed. Matlab 7.1 (Mathworks Inc., MA, USA) and SPM12 (Wellcome Trust Centre for Neuroimaging, London, UK) software were used for *pre-processing*. This included the following steps: segmentation, template creation, normalization, modulation and smoothing. The number of voxels lost was calculated using xjView (http://www.alivelearn.net/xjview) for the following Broadmann areas (BA 10, BA 11, BA 13, BA 46, BA 47).

Statistical analysis. A hierarchical regression analysis (forward stepping) was then conducted separately for food and money conditions in order to determine the variance explained in the dependent variables (the log-transformed K constants for food and money tasks) with the missing voxels computed in BA 10, BA 11, BA 13, BA 46, BA 47 and sex as predictors. In order to correct for lesion extension, each BA value reflected the percentage of missing voxels computed out of the total missing voxels due to the lesion. For all performed analysis, p < .05 was considered to be statistically significant.

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Results

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Our hypothesis was that a brain damage predominantly located in the anterior OFC would result in a selective impairment in performing the money-related task, while a brain damage predominantly located in the posterior OFC would result in a selective impairment in performing the food-related task. To this end, missing voxels due to brain lesions located in different Regions of Interest (ROIs) within OFC and DLPFC were computed in order to see whether a greater amount of tissue damage involving the anterior/posterior part of OFC correlates with a more impulsive behavior in the DD task for money and food, respectively.

For the DD task with food as reward, the hierarchical regression analysis showed that the K constant was explained by three ROI predictors: missing voxels in BA 11 (t = 2.27 β = 0.50 p < 0.03), BA 46 (t = - 2.75 β = - 0.53 p < 0.01) and BA 13 (t = 0.47 β = 0.09 p > 0.6) with overall regression model ($F_{(3, 33)}$ = 3.52, p < 0.03, R = 0.49, R^2 = 0.24) accounting for 24.25% of the variance. To estimate the independent contribution of each BA above and beyond the variance accounted for by the other ones, semi-partial correlation coefficients were calculated for each predictor. Only the correlations between the K constant and the missing voxels in BA 11 and BA 46 were significant (see Table 1). Note, though, that whereas the BA 11 was positively correlated, BA 46 was negatively correlated (see discussion).

Table 1.
Semi-partial correlations between predictors and K constants obtained for the Delay Discounting task with food as reward.

Predictors	R	R^2	p
BA 10	0.01	0.24	0.948
BA 11	**0.34**	**0.53**	**0.030***
BA 13	0.07	0.29	0.638
BA 46	**- 0.42**	**0.38**	**0.010***
BA 47	0.04	0.58	0.787

For the DD task with money as reward, the hierarchical regression analysis demonstrated that the K constant was explained by three predictors: missing voxels in BA 10 (t = 2.31 β = 0.42 p < 0.03), BA 46 (t = - 2.25 β = - 0.52 p < 0.04) and BA 47 (t = 2.46 β = 0.51 p < 0.02), with the overall regression model accounting for 29.94% of the variance ($F_{(5, 30)}$ = 2.56, $p < 0.05$, R = 0.55, R^2 = 0.30). Semi-partial correlation coefficients for each predictor were calculated, and only the correlations between the K constant and the missing voxels in BA 10, BA 46 and BA 47 were significant (see Table 2). Note, though, that whereas the BA 10 and BA 47 were positively correlated, BA 46 was negatively correlated (see discussion).

Table 2.
Semipartial correlations between predictors and K constants obtained for the Delay Discounting task with money as reward.

Predictors	R	R^2	p
BA 10	**0.35**	**0.29**	**0.028***
BA 11	-0.02	0.66	0.909
BA 13	0.17	0.12	0.281
BA 46	**-0.34**	**0.57**	**0.032***
BA 47	**0.38**	**0.46**	**0.020***

Discussion

This study reports preliminary findings pointing towards a distinctive involvement of different anterior/posterior portions of OFC when performing a decision-making task with primary and secondary rewards. The more the brain damage involves BA 11, the higher the impulsivity towards the food. In contrast, the more the brain damage overlaps BA 10 (and BA 47), the higher the impulsivity towards money. Moreover, the impulsivity showed in the DD task for both food and money was negatively correlated with damage in DLPFC (BA 46, Petrides & Pandya 1999). The current results support the idea that the brain has distinct systems for different reward types, having a direct impact on impulsive decision-making behavior.

Critically, the two types of rewards considered here (money and food) have significant evolutionary differences, which are putatively paralleled at the cerebral level. While food can be considered as primary reward because it has an innate value and satisfy biological needs, money is a secondary reward which appeared recently in human history and whose abstract value needs to be learned by association with primary reinforces. Similarly, this distinction is reflected both phylogenetically and ontogenetically in the brain. The anterior part of the OFC is especially well developed in humans relatively to other non-human primates, and cytoarchitectonically, it is characterized by a granular cell layer, which is thought to be more recent than the agranular and dysgranular layers characteristic of posterior and medial parts of OFC (Wise 2008). Our current results are therefore in line with the idea that motivational factors (in the form of primary/secondary rewards) impact on decision-making is manifested in the brain as a frontal postero-anterior axis of complexity (Kringelbach & Rolls 2004; Sescousse et al. 2013).

The relation between impulsive motivation and decision-making described here is especially relevant in the context of aviation human factors, as it is well established that motivational factors play a crucial role in in-flight decision-making. These factors might include different incentives, such as financial or food rewards. Thus, a parallel

could be drawn with the current results and previous studies that considered a different involvement of frontal regions when participants make in-flight decisions under financial incentives and uncertainty. Emotional, motivational factors have been shown to jeopardize decision-making and cognitive functioning in piloting tasks (Dehais et al. 2003). Notably, emotion has a fundamental role in rational decision-making, especially in risk assessment of situations with high uncertainty (Damasio 1994). A series of studies using a simplified landing task in a simulated flight environment have shown that financial incentive biases decision-making towards a more risky and hazardous landing behavior (Causse et al. 2010; 2013). Critically, such risky behavior was associated with activity in cortical reward circuits including OFC. In contrast, a decision to land in an emotionally neutral condition (i.e. no financial incentive) resulted in enhanced activity in DLPFC. Overall, these findings showed that a shift occurs from *cold reasoning* (rationally driven, underpinned by DLPFC) to *hot reasoning* (emotion-driven, subserved by OFC) under financial incentive. This suggests that pilot erroneous trend to land could be explained by a perturbation of the decision-making process due to negative emotional consequences associated with the go-around. According to these studies, our results show that decision-making under reward influence (either primary or secondary) crucially relied on OFC integrity, while negatively correlated with damage in DLPFC.

In conclusion, the neuro-economics approach herein adopted coupled with the neuropsychology lesion method suggests a neural distinction between reward types, thus emphasizing the importance of investigating in future ad-hoc designed studies, how reinforces can affect flight activity in accounting for pilot impulsive behavior. Further investigations in this direction would greatly contribute to the study of human factors in aviation, ultimately improving flight safety.

Acknowledgements

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