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A multimodal approach to understand and improve cognitive decision-making during firefighting

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Abstract

Day-to-day we have to make choices. When it comes to critical decisions which may lead to impactful and irreversible consequences, the understanding of the decision-making process is highly relevant but scarcely explored. In the present project, we aim to understand decision-making in the context of firefighting and to study how neurocognitive control and stress management strategies affect decision-making, while also addressing coping responses.

We present here the preliminary results from a cohort of 13 firefighters. We used a functional magnetic resonance brain imaging coupled with biosensors while firefighters played a dilemmatic decision-making task of structural firefighting.

We found brain regions, including the ventromedial and dorsolateral prefrontal cortices and angular gyrus, showing a parametric pattern of activation during the decision phase, i.e. the lower the risk of house collapsing, the higher the neural activity in these areas. This suggests that these regions are processing that risk information and signalling the chances of being successful in the rescue phase. We also found that the power in high frequencies of the pulse rate variability was higher when they decided to enter for the rescue. It is suggestive that deciding not to enter for rescue causes an increase in arousal, which may be related to the expectation about the victims' survival. Concerning coping strategies, we found that active coping used in personal context was significantly correlated with the age and the years of experience of firefighters.

We aim to understand if this pattern of brain activity reflects the coping strategies and if, in turn, it is reflected in the physiological signals we measure. Our results provide here preliminary evidence for a role of specific brain regions in decision-making under critical conditions, with concurrent physiological responses. In the future, we will investigate whether the decision processes in firefighters are different from non-firefighters, and we will address if post-traumatic stress disorder impairs decision-making in this context. Biosignals will also be used in a second phase of the project to inform virtual reality training systems. This may help developing optimal neurocognitive control and better coping strategies to deal with stress.

1. Background

Decision-making implicates making choices based on the balance between associated risks and possible rewards(Shad et al.,2011). This higher order cognition skill involves a complex set of processes that includes different steps of building preferences, choosing behaviours, performing actions and evaluating the outcomes(Ernst&Paulus,2005).

Previous research from our group has pointed out the importance of optimising decision-making and controlling emotions effectively during intensely stressful experiences(Almeida et al.,2015;Banca et al.,2015). This holds particular pertinence in the context of firefighting, wherein poor decisions can bring devastating consequences.

Studies on decision-making during firefighting are scarce despite their potential relevance, mainly in which concerns optimal neurocognitive control and stress management. While some manage to properly deal with these experiences, others adopt maladaptive responses and are at a high risk of developing stress-related disorders and other complications(Sindhu et al.,2020). Dysfunctional coping patterns of response are associated with higher levels of stress and trauma(Fonseca et al.,2020;Skeffington et al.,2017).

Stressful events that are perceived as potential threats can trigger not only emotional but also physiological responses that can be measured by biosensors and functional magnetic resonance imaging (fMRI, an approach that measures in an indirect way the neural activity)(Lee et al.,2022).

It is our goal to study decision-making and stress responses under extreme scenarios of uncertainty in firefighting. We developed a dilemmatic task in the context of strategic decisions considering fire management/victim rescue and self-protection, involving decisions that encompass rational reasoning, risk perception and emotional control. We therefore used fMRI to investigate the neural correlates underlying the decision process and error monitoring in firefighting. Further, we coupled biosensors to measure physiological stress aiming at understanding how different variables influence physiological responses and how they relate with the emotional perception of the firefighter.

We hypothesize that the process of decision in firefighters is associated with specific brain activation patterns and with changes in biophysiological responses to stress, including in pulse rate variability. A further question of our interest is the firefighters' use of coping responses to better understand their resource availability, the level of risk and protection, and the main strategies adopted by these professionals in unpredicted critical scenarios in which immediate decisions and prompt actions are needed.

Here, we provide some preliminary data of our ongoing Project.

2. Methods

This study was approved by the Ethics Committees of the Faculty of Medicine of the University of Coimbra, of the Coimbra Hospital and University Center (CHUC) and of the Regional Health Administration (ARS Centro), and was conducted according with the Declaration of Helsinki. All subjects gave written informed consent.

2.1 Sample characterization

We included a total of 13 right-handed(Espírito-Santo et al.,2017) firefighters (10 males, 3 females), with a mean age of 35.92±9.16 years. Inclusion criteria comprised (1) age between 18 and 75 years and (2) active participation in firefighting. We excluded participants with (1) diagnosed neurological or psychiatric disease, (2) visual or auditory impairments that compromised tasks performance, (3) substance (drugs or alcohol) dependence and (4) contraindications to magnetic resonance imaging. None of the participants reached the cut-off in the Portuguese version of PTSD Checklist for DSM-5 [PCL-5;(Ferreira et al.,2016a)], based on events (identified using Ferreira et al.,2016b;Maia et al.,2016) which ruled out the presence of post-traumatic stress disorder (PTSD). Nine firefighters were volunteer workers and four were professionals, ranging in years of experience from two to 34 years as a firefighter. Our sample worked a mean of 25.15 weekly hours in firefighting activity (ranged from six to 52 hours).

2.2 Coping strategies

The Portuguese version of Brief Coping Orientations to Problems Experienced Inventory [Brief-COPE;(Pais Ribeiro&Rodrigues,2004)] was applied to address dispositional coping strategies to stressful events and problems that occurred, separately, in personal life and during firefighting activity. Scores were obtained with a 4-point Likert scale, ranging from 0 to 3 points in each item, corresponding to lower or higher frequency of actions. In this work, we sought to analyze three distinct coping strategies (subscales Active, Planning and Behavioral disengagement) and three patterns of coping styles [Problem-focused, Emotion-focused and Dysfunctional (Cooper et al.,2008)].

2.3 Functional imaging and biosignals

Magnetic resonance imaging was performed on a 3T Siemens MAGNETOM Prisma Fit scanner (Siemens, Erlangen), equipped with a 64-channel birdcage head coil. Structural images of the brain were obtained with the Magnetization-Prepared two Rapid Gradient Echo (MP2RAGE) sequence [voxel size=1×1×1mm3; FOV (field-of-view)=256×256mm2; 192 slices]. We acquired three fMRI runs using a multi-band accelerated echo planar imaging (MB-EPI) sequence [multi-band acceleration factor 6; phase encoding: anterior-posterior; TR=1000ms; TE=37ms; FA=68°; voxel size=2×2×2mm3; FOV=200×200mm2; 72 axial slices].

During fMRI, participants were performing a decision-making task following an experimental paradigm with mixed block event-related design [as in Banca et al.(2015)]. An initial scenario (Fig.1) was presented with a burning house, indicating the number of people that were inside the house [1 adult or 1 family], the risk (%) of the house to collapse and the probability (%) of victims saving themselves without external help. Firefighters had to decide, based on these data, if they would enter to try saving the victims, knowing that if unsuccessful, they could also "die". After each decision, the outcome was presented showing what happened to the victims, the firefighter and the house. The stimuli were presented on an LCD monitor and participants selected responses with a Hybridmojo MR-compatible joystick. This was repeated for 20 trials in each of the 3 runs.

Figure 1- Initial scenario of the fMRI trials.

Pulse Rate Variability (PRV) was computed from the blood volume photoplethysmography (PPG) recordings acquired through the Physiological Measurement Unit (PMU) of the MRI scanner with a sampling rate of 400Hz. To reduce noise contamination, the PPG signal was bandpass filtered using a 6th order Butterworth filter with a lower and higher cut-off frequencies of 0.5Hz and 20Hz. The clean PPG signal was then used to compute the PRV by first identifying the PPG pulse peaks, computing the interbeat intervals (IBI), and using a cubic spline interpolation to obtain a uniformly sampled time series with a new sampling frequency of 4Hz. The PRV from each run was then divided into 8s segments, comprising the entry/no entry decision block of the task, and the relative power in the High Frequency (HF) band (0.15–0.4Hz) of the PRV was extracted as a marker for each of the segments using the Fast Fourier Transform algorithm.

2.4 Data analysis

A significance level of 0.05 was adopted in all statistical tests. We did not correct for multiple comparisons due to the preliminary and exploratory nature of these analyses.

Statistical analyses were performed using the IBM SPSS statistics software (v.27). The sociodemographic variables were explored through descriptive analyses. We used Wilcoxon test to investigate within-group differences in coping strategies in life versus firefighting contexts. The correlations between age, years of firefighter activities and workload (hours per week) and coping strategies (used in both personal and firefighting activity contexts) were analysed with Kendall rank correlation coefficient.

FMRI data analyses were fully conducted in the BrainVoyager 22.0 software (Brain Innovation, Maastricht, the Netherlands). We applied pre-processing steps (slices-scan time correction, 3D head-motion correction, temporal high-pass filtering and geometrical distortions correction) and normalized the data to Montreal Neurological Institute (MNI) space. We performed General Linear Model (GLM) analysis for obtaining whole-brain statistical maps at the group level (cluster threshold=20 voxels).

PRV data were analyzed in Matlab (R2021a, MathWorks, USA). Observations were split into enter or not enter, and the balance of the sample sizes was obtained through random elimination of samples belonging to the bigger group. The two conditions were tested against each other using the Wilcoxon signed-rank test.

3. Results and Discussion

We started by evaluating whether the coping style was different comparing firefighters' strategies used in personal contexts and during the activity as a firefighter and found no significant differences ($p>0.05$, $n=12$). Active coping strategies used in personal context were significantly correlated with age ($\tau=0.568$; $p=0.016$, $n=12$) and years of experience as firefighters ($\tau=0.493$; $p=0.034$, $n=12$) (Fig.2). Active coping involves the ability to take active actions to suppress the stressor or to minimize or remediate these effects(Carver et al.,1989). We suggest that older individuals accumulated learning to improve mechanisms of adaptive coping to deal with stress, using active coping as a dispositional tendency in their lives. Concerning coping strategies related to firefighting activity, we did not find any correlation with age or years of firefighting ($p>0.05$). Firefighters are trained to take immediate actions and decisions early in their activities. We hypothesize this growth ability may be transposed to personal events later in life. Also, existing literature suggests the protective effect of resilience in firefighters and experience of personal growth following stress-related events(Sattler et al.,2014).

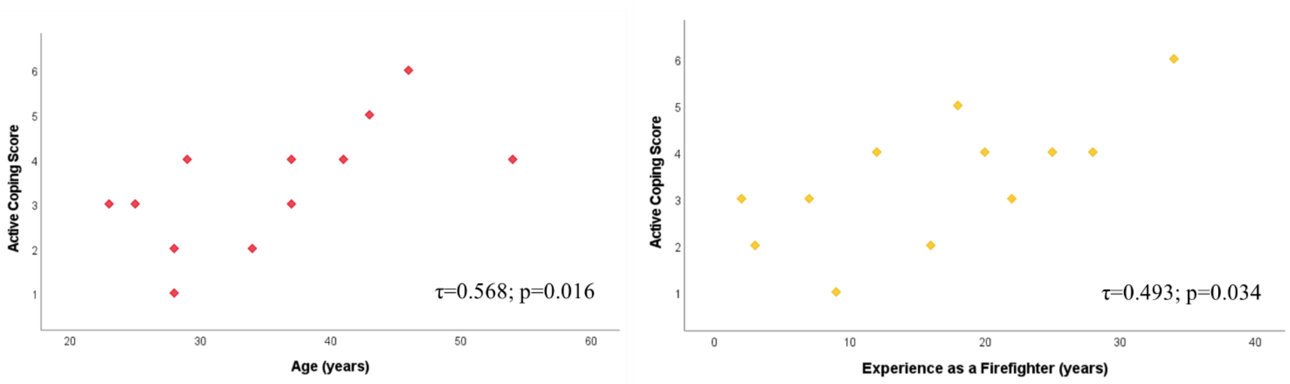

Figure 2- Correlations between active coping score and age (left) and years of experience in firefighting (right).

We studied, with an fMRI task, which brain regions are involved in the decision-making process under the context of firefighting. In Fig. 3 we present brain activity patterns during the decision phase. A parametric analysis showed that the lower the probability of the house collapsing, the higher the activity in the ventromedial prefrontal cortex (vmPFC) ($p<0.05$). We suggest that the activation of vmPFC was related to risk perception, given its association with valuation and risk assessment(Spaniol et al.,2019). The right dorsolateral prefrontal cortex (dlPFC) also showed a significantly greater activation for more favorable probabilities ($p<0.05$), which might possibly be explained by greater risk-taking behavior that was found in the literature to be associated with an increase in the activity of dlPFC(Leota et al.,2021). A role of angular gyrus (AG) in both decision-making, visuospatial attention(Studer et al.,2014) and number processing(Seghier,2013) has been recognized. In this work, the right AG was significantly more active when the risk was smaller ($p<0.05$). We hypothesize that when firefighters have more chances of being successful, they spend more efforts in deciding if they will take the risk.

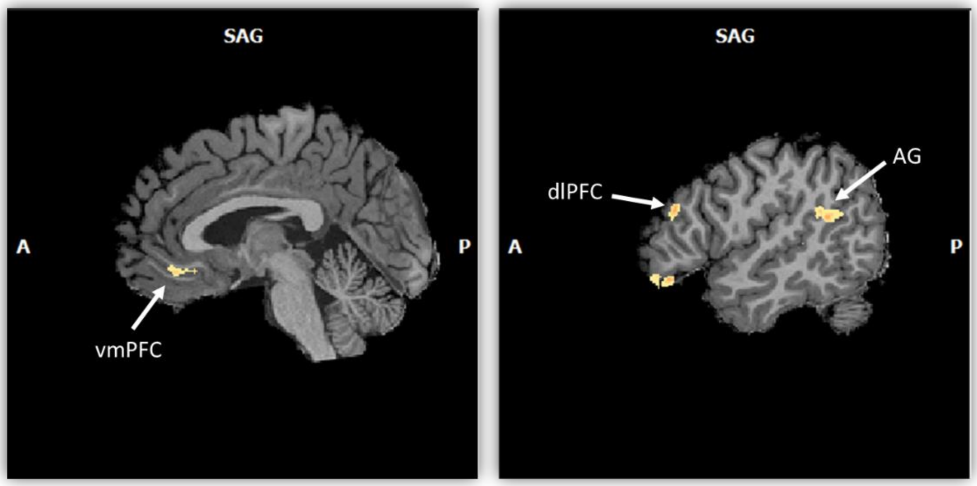

Figure 3- FMRI images showing brain parametric activation associated with lower probability of house collapsing (p<0.05).

The preliminary analysis of the PRV of the participating group of firefighters revealed a significant higher value for the relative power in the HF band of the PRV for the entry decision (median=0.38) compared to the no entry decision (median=0.35), Z=2.59, $p<0.01$. The distribution of values for this marker for both conditions is represented in Fig. 4.

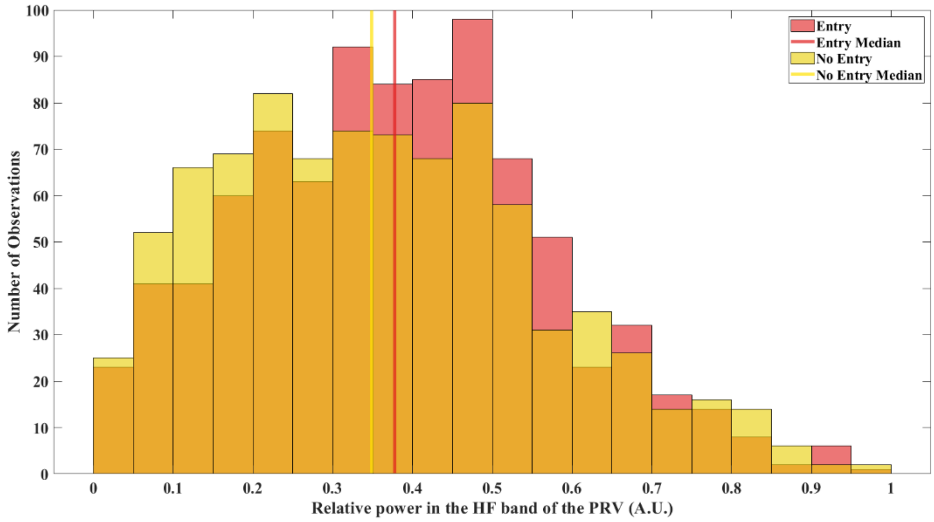

Figure 4- Distribution of values for the relative power in the HF band of the PRV for the entry decision (in red) and no entry decision (in yellow) (p<0.01).

States of stress and anxiety seem to be accompanied by a decrease in HF power(Shaffer&Ginsberg,2017). The lower values found for the HF marker for the no entry decision hint at a decrease in parasympathetic activation and are potentially related to an increase in physiological arousal. A possible interpretation is that choosing not to endanger his/her own life causes a greater expectation in the firefighter to know whether the victims survived or not. Another interpretation, falling in line with Fooken and Schaffner's(2016) suggestion, is that risk aversion in dilemmatic situations is associated with higher arousal, while risk-taking is accompanied by moderate physiological responses. This could suggest that less emotionally involved individuals are prone to taking more risks when confronted with a dilemma.

These results may have potential implications for understanding critical decision processes in firefighters, more directly in structural firefighting contexts. Our findings encourage future works addressing decision-making in different scenarios, such as wildland firefighting.

4. Conclusions

Our results support the relevance of studying decision-making in extreme conditions such as firefighting, from a multimodal approach. These preliminary data suggest an involvement of specific frontal brain regions, that can also be translated into physiological stress and coping strategies. In a future work, we will investigate whether decision processes in firefighters are different from the global community and address if post-traumatic stress disorder impairs effective decision-making. Biosignals will also be used in a second phase of the project to inform virtual reality training systems about the physiological state of the firefighter during firefighting simulation.

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