Visualizing Risky Behaviors Induces a Stronger Neural Response in Brain Areas Responsible for Mental Imagery and Emotions Than Visualizing Neutral Behaviors

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Abstract

In the present study, we used a neuroimaging technique (fMRI) to test the prediction that visualizing risky behaviors induces a stronger neural response in brain areas responsible for emotions and mental imagery than visualizing neutral behaviors. We identified several brain regions that were activated when participants produced mental images of risky versus neutral behaviors and these regions overlap with brain areas engaged in visual mental imagery, speech imagery and movement imagery. We also found that producing mental images of risky behaviors, in contrast to neutral behaviors, increased neural activation in the insula – a region engaged in emotional processing. This finding is in line with previous results demonstrating that the insula is recruited by tasks involving induction of emotional recall/imagery. Finally, we observed an increased BOLD signal in the cingulate gyrus (mid-cingulate area), which is associated with reward-based decision making and monitoring of decision outcomes. In summary, we demonstrated that mental images of risky behaviors, compared to risk-free behaviors, increased neural activation in brain areas engaged in mental imagery processes, emotional processing and decision making. These findings imply that the evaluation of everyday risky situations may originate in visualizing the potential consequences of risk taking and may be driven by emotional responses that result from mental imagery.

Introduction

Risk assessment is an important aspect of both professional and everyday decision making. Although different expert contexts (e.g., engineering or finance) require risk to be defined in a numerical format (e.g., the size and the probability of potential outcomes), people often form their personal risk evaluations independently of quantitative parameters. Ample evidence indicates that subjective risk perception can be driven by negative emotions such as fear and anxiety. However, less is known about specific psychological factors providing input to risk-related emotions, and our present research aimed to fill this gap. In particular, we proposed that mental imagery involved in the consideration of future events evokes emotions shaping the perception of risk. We attempted to investigate the interplay between mental imagery and emotions in risk perception on both self-report and neural levels.

Mental imagery and emotions

According to a widely cited definition, “Mental imagery occurs when perceptual information is accessed from memory, giving rise to the experience of ‘seeing with the mind’s eye,’ ‘hearing with the mind’s ear’ and so on...” In this sense, mental imagery refers to representations and the accompanying experience of sensory information without a direct external stimulus. When people consider the future, they can use mental images to “try out” various versions of what might happen, depending on which course of action is chosen. For example, they can use their imagery to visually simulate both the form and the size of a danger, which allows the subjective severity of risk to be estimated. In such a case, risk perception may be an indirect effect of both the richness (i.e., the personally meaningful affective load) and the vividness
Generating mental visualizations has the capacity to evoke emotions\textsuperscript{15–17} that in turn have an impact on risk perception\textsuperscript{18}. This means that risk perception may also depend on the valence of mental imagery. For example, an individual who considers their enrollment in an exciting but risky behavior may generate an affect-laden image of a severe accident, which will result in both an intense emotional experience and a rise in the perception of danger, possibly motivating this individual to withdraw.

**Risk perception as a product of mental imagery and emotions**

Different models of risk suggest that emotions play an important role in decision making\textsuperscript{7,11,19}, but such models do not always investigate the origins of feelings. Prior research has provided initial evidence supporting a theoretical claim that affective evaluation of risk originates in imagery-based processes. For example, it has been shown that the way in which people perceived the risk associated with a nuclear waste repository was strongly related to both affective responses and their imagery of this risk\textsuperscript{20}. Peters and Slovic\textsuperscript{21} found a significant and positive correlation between affect associated with mental images related to nuclear power and the nuclear support index. More recent research investigated affect and emotions as mediators of the relationship between mental imagery and risk perception. Sobkow et al.\textsuperscript{22} documented that generating mental images of negative outcomes of risk taking, compared to generating images of positive consequences or a neutral condition, boosted negative emotionality and increased risk perception. In the same vein, Zaleskiewicz et al.\textsuperscript{23} revealed that entrepreneurs, compared to controls, produced more vivid and positive mental images of risky business projects and consequently declared a greater preference for risk taking. This suggests that the positive mental images they generated decreased their risk perception.

To summarize, existing research demonstrates that mental imagery may be an important psychological factor involved in risk evaluation. However, all the above-reviewed studies used self-report measures of mental imagery, which entails potential limitations and suggests that the presented effects should be interpreted with caution. To address this limitation, in our present study we used neuroimaging techniques to provide evidence that visualizing risky behavior induces a stronger neural response in brain areas responsible for mental imagery and emotions than visualizing neutral, risk-free behaviors, because when people are faced with risk they generate richer and more vigorous or alive visual mental images than when they consider risk-free activities.

Different arguments seem to support the thesis that when people are faced with risk, they use their mental imagery more intensely than when they perceive neutral situations. First of all, using mental images of future risk-taking outcomes seems highly adaptive: the capacity that allows humans to mentally project themselves forward is considered a crucial evolutionary advantage\textsuperscript{24–30}. Importantly, generating visual mental images goes beyond logically analyzing future outcomes and their likelihoods, which is not only time consuming but also requires high risk literacy\textsuperscript{31,32}. Visual processing that is
typically engaged in mental imagery is faster than verbal thought (Blackwell, 2020) and thus can evoke emotional reactions more effectively. When people are faced with the dilemma of how much risk to accept (e.g., whether to continue a risky climb when weather conditions are worsening), it is important that the choice is made relatively quickly and that the limits of acceptable or controlled risk are not exceeded. In such a situation, using mental imagery may be not only useful but also effective, representing gist-based intuition instead of processing based on verbatim memory representations. On that basis, we hypothesized that depicting risky stimuli, in comparison to neutral stimuli, will evoke a stronger neural response in brain regions that are responsible for mental imagery and emotions.

**Neural basis of mental imagery and its relationship with vividness, emotion and risk perception**

Evidence demonstrates that mental imagery engages similar brain areas to perception in the same modality. For example, auditory mental imagery engages the superior temporal gyrus, olfactory imagery is associated with activations in the primary olfactory (piriform) cortex and visual mental imagery activates the occipital lobe, including the early visual cortex. In a recent review on visual mental imagery, Pearson proposes a top-down general model of voluntary mental imagery based on the sensory representation of information retrieved from memory – a reverse visual hierarchy. This model suggests a large neural network encompassing, among others, frontal areas involved in organizational and executive tasks, medial temporal areas associated with memory retrieval and spatial information, and primary sensory areas such as V1, implied in visual representation.

Interestingly, the levels of activation in several brain areas associated with mental imagery have been related to subjective measures of vividness, both at inter-individual and intra-individual levels. For example, Cui et al. (2007) investigated individual differences in visual imagery vividness assessed by the Vividness of Visual Imagery Questionnaire (VVIQ) and observed that people reporting higher levels of vivid imagery showed higher activation in the early visual cortex when performing an imagery task. Likewise, Dijkstra et al. (2017), through a retro-cue imagery task where participants were asked to imagine a set of stimuli as vividly as possible (faces, letters and fruits), observed that the levels of neural activity in a network of areas including the early visual cortex, precuneus, medial frontal cortex and right parietal cortex were positively correlated with the experienced vividness in each of these mental images.

In line with the assumption that mental imagery has the power to elicit emotions, mental images may evoke neural responses in brain areas that are responsible for emotional processing. For example, Hoppe et al. demonstrated that mental images of fearful stimuli, compared with neutral stimuli, were related to increased activation in such regions as the amygdala, insula, mid-cingulate cortex, thalamus and cerebellum. Greening et al., in a study using mental imagery to generate differential fear conditioning, observed significantly greater activation in the right anterior insula, right dorsolateral prefrontal cortex and bilateral inferior parietal lobe when imagining fear-conditioned stimuli compared with safe-conditioned stimuli.
Finally, following the purpose of the present study, it is important to note that research investigating the neural substrates underlying risky behavior has identified a brain network that comprises numerous areas associated with emotional processing, such as the anterior insula, anterior cingulate cortex, amygdala, thalamus or ventromedial prefrontal cortex\textsuperscript{48–51}. Particularly relevant for risk perception would be the role of the anterior insula, a brain region commonly related to the processing of aversive emotions (e.g., fear, sadness, or anxiety) and that appears to be implied in estimation of the potential negative consequences associated with risk stimuli\textsuperscript{48,50}. Nevertheless, to our knowledge, no previous studies have explored the neural basis of risk perception in the context of mental imagery.

The present study

We propose that when people are confronted with a risky option and must evaluate the level of threat, they can build a mental visualization of the potential consequences to better understand how they feel about it\textsuperscript{18}. One reason behind the expected relationship between mental imagery and risk perception is that generating alive, rich and personally meaningful mental images typically leads to experiencing intense emotions in the same way that negative mental images evoke negative affect and positive mental images evoke positive affect\textsuperscript{15–17,44,52}. Knowing that mental imagery may induce emotions on the one hand and that emotions have an impact on risk appraisal on the other, we postulate that: (1) mental imagery can be involved in risk perception; and (2) when people are faced with risk, they generate more intense and affect-laden mental images compared to facing neutral stimuli. Additionally, we explored whether mental images of the risky scenarios would be reported by participants as more vivid (in terms of the perceptual clarity of details) than neutral scenarios.

In the current experiment, we used functional magnetic resonance imaging (fMRI) to register the brain activity of participants who were asked to imagine the consequences of various risky and neutral behaviors. Each participant rated the vividness of these mental images and the fear and perceived risk associated with each behavior. We also controlled individual differences in temperamental emotional reactivity and ability to produce vivid mental images. We hypothesized that exposure to risky behaviors would trigger risk-related mental imagery and emotions to a greater extent than exposure to neutral behaviors. On the neural level, we predicted that emotional mental imagery (Blackwell, 2020) in response to risky behaviors (in contrast to neutral behaviors) would be observed as enhanced activation in brain regions engaged in mental imagery and emotional processing.

Method

Participants

A total of 31 healthy right-handed volunteers (20 females; $M_{\text{age}} = 26.5$, $SD_{\text{age}} = 6.2$) from the general population were recruited for this study, selected from a pool of participants taking part in an unrelated online study that employed various psychological measures, including measures of the vividness of mental imagery\textsuperscript{VVIQ,43} and emotional reactivity\textsuperscript{ER,53}. All participants reported no neurological or
psychiatric disorders and gave informed consent before the study. They were informed about the general design of the task and that they could withdraw at any time without any consequences. Every participant received financial compensation of PLN100 (approximately $25). Two participants were excluded from further analyses because of scanner failure and one participant decided to withdraw from the study. The procedure was approved by the ethical committee at SWPS University.

**Materials and procedure**

We used 40 brief descriptions of 20 risky situations (e.g., “you are investing a large amount of money in stocks”) and 20 neutral situations (e.g., “you are reading a book”; a full list of situations is given in the Supplementary Materials; situations were tested in a pilot study). All situations were displayed to participants in the MRI scanner in black font on a grey background (Figure 1). Each trial started with an oval fixation point (presented for a randomly chosen period of time ranging from 5000 to 7000 ms), which was immediately followed by a description of the situation displayed for 5000 ms. Next, participants were instructed to imagine all consequences of the presented situation for 15000 ms when a fixation cross was presented on the screen. Finally, participants used three 5-point scales to rate vividness, fear and perceived risk that were associated with each situation (with higher values indicating that a more vivid, fearful and risky situation). These questions were presented in a fixed order whereas the situations were arranged in a pseudorandom order. We did not control for the valence of mental images generated by participants.

All materials were presented to participants in the Polish language because the experiment was conducted in Poland.

**fMRI data acquisition**

Structural and functional magnetic resonance images were acquired using a Siemens 3-Tesla Trio MRI scanner with a 32-channel head coil at the Laboratory of Brain Imaging, Nencki Institute of Experimental Biology (Warsaw, Poland). Before the main fMRI experiment, participants completed a training session in a mock scanner where they were familiarized with the equipment, study conditions and modes of responses. Participants were instructed to remain relaxed and motionless during the scan. In addition, foam pads were used to limit head motions and reduce scanning noise. Participants were only allowed to move the right index finger to make their responses during the task by pressing a response-box button.

T1-weighted images were obtained using a magnetization-prepared rapid gradient-echo sequence (MPRAGE) with a repetition time (TR) of 2530 ms, an echo time (TE) of 3.32 ms and a flip angle of 7°. For each volume, 176 axial slices of 1 mm thickness were acquired, which allowed the whole brain to be covered with the following parameters: voxel size = 1 × 1 × 1 mm³, matrix size = 256 × 256 voxels and FOV = 256 mm. Functional images were obtained using a T2*-weighted echo-planar sequence with a TR of 2000 ms, TE of 25 ms, and a flip angle of 90°. Each volume, covering the whole brain, consisted of 39 axial slices parallel to AC-PC plane with 3.5 mm thickness each: voxel size = 3.5 × 3.5 × 3.5 mm³, matrix size = 64 × 64 voxels and field of view (FOV) = 224 mm.
fMRI pre-processing and data analysis

Image pre-processing and statistical analyses were conducted in SPM12 (Wellcome Trust Centre for Neuroimaging, University College London, UK; http://www.fil.ion.ucl.ac.uk/spm/). First, all anatomical and functional images were reoriented to the anterior commissure. For each participant, functional volumes were spatially realigned to their mean image and co-registered with the individual structural T1-weighted image. Next, these images were spatially normalized to the standard Montreal Neurological Institute (MNI) space and resampled to a resolution of 3’3’3 mm. Finally, they were smoothed by Gaussian kernel (8 mm full width at half-maximum).

Statistical analyses of fMRI data were conducted using a two-level general linear model approach. In the subject-specific first-level model, experimental conditions (risky situations and neutral situations) were convolved with the canonical hemodynamic response function. fMRI data for each condition were time-locked to the onset of the reading phase with a duration of 20 s (until the end of the imagery phase). Serial autocorrelations were corrected using an autoregressive (AR) 1 model, with a high-pass filter (128 s) to reduce low-frequency noise. We computed two whole-brain contrasts in order to determine brain areas showing differences between conditions: risky situations > neutral situations and risky situations < neutral situations.

The resulting contrast images from each participant's first-level analysis were entered into the second-level (group) analysis. A one-sample $t$-test was performed to determine significant activation at the group level. We conducted a non-parametric cluster-based permutation approach using the SnPM13 toolbox integrated within the SPM toolbox (Statistical nonParametric Mapping; http://warwick.ac.uk/snpm;54). Cluster-based permutation tests were used to control for multiple comparisons due to its better fit to the spatially correlated nature of the fMRI signal and its higher sensitivity to weak and diffuse changes in the BOLD signal, particularly with moderate sample sizes $^{55,56}$. The number of permutations was set to 5000 and the level of significance was $p < .05$; this value was family-wise error (FWE)-corrected (cluster-wise $p$ value) using a cluster-forming threshold of $p < .0001$ (voxel-wise $p$-value). Gender and age were included as covariates.

In addition, as a secondary aim, we were interested in studying how the possible differences in brain activation found in the previous risky versus neutral contrast (at the whole trial level) can vary throughout processing of the task (a time-course analysis). To this end, the temporal sequence of the trial was divided into four 5-s bins during the first-level (subject-specific) analysis. fMRI data for the first bin were time-locked to the onset of the reading phase and data for the second, third and fourth bins were time-locked to 5, 10 and 15 s, respectively, after onset of the reading phase (i.e., onset of the imagery phase). Analysis was restricted to a set of regions of interest defined from the significant clusters found in the whole trial (using an implicit mask). In this case, given that the analysis was not carried out across the whole brain, we decided to adopt a non-parametric voxel-based permutation approach to conduct the second-level (group) analysis (SnPM13 toolbox; 5000 permutations; $p < .05$, FWE corrected; Nichols & Holmes, 2002). Gender and age were included as covariates.
We declare that all methods were carried out in accordance with relevant guidelines and regulations.

Results

Behavioral results

The descriptive statistics and correlations among self-report measures are presented in Table 1. We found that higher risk perception was related to higher ratings of fear ($r = .816, p < .001$) and higher scores on the ER scale ($r = .388, p = .041$). Ratings of the vividness of presented scenarios were positively related to the ability to create vivid images as measured by the VVIQ ($r = .457, p = .015$). Additionally, the correlation between fear ratings and temperamental ER was significant ($r = .583, p < .001$), suggesting that the measures used in the fMRI procedure were valid.

Table 1. Descriptive statistics and Pearson’s $r$ correlation coefficient

<table>
<thead>
<tr>
<th>Variable</th>
<th>$M$</th>
<th>$SD$</th>
<th>Risk</th>
<th>Fear</th>
<th>Vividness</th>
<th>VVIQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Risk</td>
<td>2.38</td>
<td>0.36</td>
<td>–</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Fear</td>
<td>2.25</td>
<td>0.38</td>
<td>.816</td>
<td>***</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>3. Vividness</td>
<td>4.06</td>
<td>0.49</td>
<td>-.095</td>
<td>.019</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>4. VVIQ</td>
<td>63.04</td>
<td>8.29</td>
<td>-.175</td>
<td>-.283</td>
<td>.457</td>
<td>*</td>
</tr>
<tr>
<td>5. ER</td>
<td>39.29</td>
<td>8.35</td>
<td>.388</td>
<td>.583</td>
<td>***</td>
<td>-187</td>
</tr>
</tbody>
</table>

Note: ER, emotional reactivity; VVIQ, Vividness of Visual Imagery Questionnaire; Risk, Fear and Vividness refer to ratings of scenarios provided by participants in the scanner.

* $p < .05$, ** $p < .01$, *** $p < .001$.

Next, we performed a paired-samples $t$-test to investigate differences in mean ratings of risk perception, fear and vividness between risky and neutral conditions. We found that ratings of risk perception were higher in the risky condition ($M = 3.59$, $SD = 0.58$) compared to the neutral condition ($M = 1.18$, $SD = 0.58$): $t(27) = -24.84, p < .001$ and Cohen’s $d = -4.69$. Fear rating were also higher in the risky condition ($M = 3.31$, $SD = 0.64$) than in the neutral condition ($M = 1.19$, $SD = 0.22$): $t(27) = -19.61, p < .001$ and Cohen’s $d = -3.71$. Interestingly, participants rated their mental images of neutral scenarios as more vivid ($M = 4.39$, $SD = 0.54$) than mental images of risky scenarios ($M = 3.73$, $SD = 0.56$): $t(27) = 6.71, p < .001$ and Cohen’s $d = 1.27$.

Finally, we fitted a hierarchical linear regression model with varying intercepts for participants and scenarios and varying slopes for the effects of the condition, fear and vividness on risk perception (the outcome variable). Additionally, we included the VVIQ and ER scores as predictors. All predictors were
mean-centered. The neutral condition was coded as -.5 and the risky condition as .5. The model was estimated in the lme4 package and implemented in the R statistical environment.

Our experimental manipulation was effective. We found that the ratings of risk were higher in the risky condition than in the neutral condition ($b = 1.38, p < .001$). Moreover, higher ratings of risk were associated with higher fear ($b = 0.68, p < .001$) and a greater ability to create vivid visual images as measured by the VVIQ ($b = 0.09, p = .024$). We did not find a significant relationship between the ratings of vividness and risk perception ($b = -0.05, p = .075$) or ER and risk perception ($b = 0.05, p = .144$). The fixed and random effects explained $R^2 = .81$ of the variance.

To summarize, we demonstrated that our behavioral task was valid: scenarios in the risky condition were indeed rated as riskier in comparison to the control condition. The higher ratings of risk were associated with higher reported fear, showing that risky scenarios have a greater capacity to evoke strong emotional responses than risk-free scenarios. We did not find a relationship between risk ratings and vividness, and, surprisingly, the ratings of vividness were higher for neutral compared to risky scenarios. Nevertheless, we think that this result might be simply driven by the lack of control over the valence of mental images in our experimental design - participants were asked to produce mental images and report on their vividness but not to rate the degree to which these images were either positive or negative. For example, the positive and vivid mental images that people could also generate in response to risk may lead to lower risk perception in comparison to a situation in which mental images are vivid but highly negative.

**Neuroimaging results**

Cluster-based permutation analysis of the risky versus neutral contrasts for the whole period of the trial revealed six significant clusters showing increased BOLD signal activation in the risky situations compared to the neutral situations (see Table 2; $T > 4.35$, minimum cluster size [k] > 20 voxels). There were no significant differences for the risky < neutral contrast. The six significant clusters for the risky > neutral contrast encompassed part of the precentral gyrus, cingulate gyrus (mid-cingulate area), insula, superior temporal gyrus and medial frontal gyrus for the right hemisphere, and the cerebellum anterior lobe, cerebellum posterior lobe and occipital lobe (cuneus) for the left hemisphere. Table 2 and Figure 2 provide details of the significant clusters and their anatomical localization.

**Table 2.** Statistically significant clusters showing greater activation for the risky condition than for the neutral condition
To study the processing of risk in more detail, we decided to explore the brain activation time-course in the significant clusters observed in the risky > neutral contrast, dividing each trial into four bins of 5 s (see Method). Results for Bin 1 revealed three clusters ($T > 3.17$) involving postcentral gyrus, precentral gyrus, insula, superior temporal gyrus and the cerebellum anterior lobe. Bin 2 showed differences in three clusters involving precentral gyrus, postcentral gyrus, the occipital lobe (culmen) and the cerebellum posterior lobe ($T > 3.48$). Bin 3 showed one cluster in the cingulate gyrus (mid-cingulate area) ($T > 3.58$). Finally, Bin 4 showed four clusters involving medial frontal gyrus, cingulate gyrus (mid-cingulate area), precentral gyrus and the occipital lobe ($T > 3.39$). Table 3 provides details of the significant clusters for each bin. Figure 3 presents the anatomical localization of the cluster found in each bin through a series of sagittal glass-brain projections.

**Table 3.** Statistically significant clusters showing greater activation for the risky condition than for the neutral condition for each of the four bins in which the trials were divided.
| Cluster (size) | Region                      | L/R | MNI coordinates |  
|---------------|-----------------------------|-----|-----------------|---
|               |                             |     | x    y    z   T |   |
| **Bin 1 - reading (5 s)** |                             |     |     |     |   |
| Cluster 1 (k = 543) | Postcentral gyrus | R   | 40   -20   48  7.19 |   |
|                 | Precentral gyrus           | R   | 32   -18   70  6.25 |   |
| Cluster 2 (k = 83)   | Insula                     | R   | 52   -22   16  4.25 |   |
|                 | Superior temporal gyrus    | R   | 60   -2    8   4.93 |   |
| Cluster 3 (k = 14)   | Cerebellum anterior lobe   | L   | -26  -52  -20  3.45 |   |
| **Bin 2 - imagery (first 5 s)** |                             |     |     |     |   |
| Cluster 1 (k = 546) | Precentral gyrus           | R   | 38   -14   66  7.26 |   |
| Cluster 2 (k = 153)  | Cerebellum posterior lobe  | L   | -22  -54  -20  5.81 |   |
| Cluster 3 (k = 24)   | Occipital lobe (cuneus)    | L   | -12  -78   4  4.18 |   |
| **Bin 3 - imagery (from 5 s to 10 s)** |                             |     |     |     |   |
| Cluster 1 (k = 12)   | Cingulate gyrus (mid-cingulate area) | R | 8    -22   42  4.29 |   |
| **Bin 4 - imagery (last 5 s)** |                             |     |     |     |   |
| Cluster 1 (k = 68)   | Medial frontal gyrus       | R   | 2    42   32  6.28 |   |
| Cluster 2 (k = 45)   | Cingulate gyrus (mid-cingulate area) | R | 2    -22   38  5.11 |   |
| Cluster 3 (k = 12)   | Precentral gyrus           | L   | 36   -14   68  3.92 |   |
| Cluster 4 (k = 8)    | Occipital lobe             | L   | -10  -72   2  3.83 |   |

Analysis was restricted to regions of interest defined from the significant clusters found in the previous risky > neutral contrast analysis performed for the whole trial.

To summarize, the neuroimaging part of the study supported our initial predictions. In particular, we demonstrated that mental images of risk (as compared to mental images of neutral activities) evoked neural activations in brain areas responsible for mental imagery, emotions and the processing of risk.

**General Discussion**
The main aim of the present research was to empirically investigate the theoretical idea that when people are confronted with risky stimuli, they tend to generate visual mental images to a greater extent than when they face neutral stimuli. Unlike in previous studies that tested similar predictions but used self-report measures of mental imagery, here we used a neuroimaging technique (fMRI) to verify the hypothesis that visualizing risky behaviors induces a stronger neural response in brain areas responsible for mental imagery and emotions than visualizing neutral behaviors.

We identified several brain regions that were more activated when participants produced mental images of risky compared to neutral behaviors. In particular, we found that these regions largely overlap with the brain areas engaged in visual mental imagery (such as the occipital lobe; \textsuperscript{12,39,59,60}, speech imagery i.e., \textit{superior temporal gyrus}; \textsuperscript{35} and movement imagery (e.g., medial frontal gyrus, precentral gyrus and cerebellum; \textsuperscript{38,61,62}). These findings support our prediction that visualizing risky versus risk-free behavior would be reflected in intensified activation of the brain areas responsible for mental imagery. Additionally, using self-report measures, we observed that the vividness of the generated mental images correlated positively with scores on the VVIQ that measure individual differences in people's ability to produce vivid visual mental imagery. This means that some people may be prone to more intensely visualize the potential consequences of risky behaviors, which may lead to either greater risk acceptance or risk aversion, depending on the valence of mental imagery.

Importantly, we found that producing mental images of risky behavior, in contrast to neutral behavior, increased neural activation in the insula – a region engaged in emotional processing. This finding is in line with previous results demonstrating that the insula is involved in tasks related to emotional recall/imagery \textsuperscript{45-47}. In addition, the insula has been shown to play a central role in estimating the potential negative consequences of risky situations and risk-taking behavior \textsuperscript{48,50}. Regarding this effect, we observed two clear tendencies on the behavioral level. First, and supporting previous research \textsuperscript{18,22}, our study indicated that risk perception was intensified when people experienced stronger fear as a consequence of generating visual mental images of risk taking. Second, this effect was confirmed by the correlation between risk perception and dispositional ER (defined in terms of the tendency to experience frequent and intense emotional arousal): those participants who declared that they are more emotionally reactive estimated the risk as higher.

From the perspective of mental imagery and risk perception, the insula is of special importance because activation in this region can be elicited solely by the mental image of a fear-related stimulus in the absence of an actual percept \textsuperscript{46}. Consequently, this means that emotional response to risk might be evoked by the mental image of risky behavior itself, and a decision maker does not have to face the real risk to generate an adaptive course of action.

Finally, we also observed an increased BOLD signal in the cingulate gyrus (mid-cingulate area), which is usually recruited in reward-based decision making and monitoring of decision outcomes. In particular, this area exhibits increased activity when people process information about a decision, make predictions and monitor possible outcomes and consequences \textsuperscript{63-65}. Mental imagery of risky behavior allows...
different consequences and outcomes of risky behavior to be simulated without experiencing them personally. Such emotionally laden mental images of outcomes are processed and integrated in order to estimate the riskiness of different alternatives preceding selection of the subjectively best one. The time-course analysis in four bins seems to support these temporal dynamics and provide initial support for this prediction: neuroimaging data suggested that at the beginning of a trial (i.e., when participants started processing a risky scenario) there was an enhanced activation in areas associated with mental imagery and emotions. Along with the subsequent processing of the risky scenarios, significant activation in the cingulate gyrus emerged, suggesting the engagement of higher-order cognitive functions related to making predictions, monitoring outcomes and making a decision. In any case, it is important to note the limitations of fMRI and the study of the hemodynamic response in terms of temporal resolution. Thus, further research using different neuroimaging techniques and more suitable designs are needed to confirm the dynamics of mental imagery processes.

Building a theoretical model explaining the interplay between mental imagery, emotions, risk perception and decision making is definitely a challenge for future research. Although several notable theoretical models \(^7,^9\) posit that behavior under risk and uncertainty can be shaped by both anticipated and experienced emotions, none of these frameworks implemented the construct of emotional mental imagery in decision making. In the present study, we provided initial evidence that mental imagery of risky behavior might serve as an input to emotional responses, shaping risk perception and guiding decisions under risk and uncertainty. Nevertheless, there are still some open questions that should be addressed.

First, the results of the present study indicated that exposure to risk evokes a neural response related to mental imagery and emotions more intensely than exposure to neutral stimuli, but they do not allow for conclusions about the nature of the relationship between emotions and mental imagery in risk perception. It seems that both causal links (i.e., mental imagery evokes an emotional response) and reciprocal links (i.e., the emotional response produced by mental imagery becomes a basis for new mental images that differ in content, valence or vividness) might be considered and investigated in future research.

Second, the tendency to either accept or reject risk may be moderated by both the valence of mental images and their vividness. When people are faced with the perspective of risky behavior and are free to generate images of its consequences, they may visualize not only negative outcomes (threats) but also positive outcomes (benefits). For example, imagining possible outcomes of risky investments on the stock market may result in either positive visualizations (such as earning money and consequently meeting various needs) or negative visualizations (such as losing money and getting into serious financial trouble). The effect of the negative versus positive mental imagery on risk perception should be intensified by the vividness factor in such a way that more positive and vivid mental images should be related to a decrease in risk perception whereas more negative and vivid mental images should result in a boost in risk perception. In the present study, we did not find correlations between self-report measures of the vividness of mental imagery and risk perception, which may be due to not controlling the valence of mental images that our participants produced in response to the situations they were presented with.
Future research investigating the psychological functions of mental imagery in risk perception should focus not only on the predictive power of vividness but also on the effect of the interaction between vividness and mental image valence on both risk evaluation and risk taking.

Third, it is important to note that the concept of vividness itself can be understood as a combination of clarity and liveliness (Marks, 1972, 1999; McKelvie, 1995), where clarity reflects the detail of the mental image (plus the brightness of its colours and the sharpness of the outline) and liveliness refers to how dynamic, vigorous and alive the image is. Given the relevance of the emotional component in risk perception, the strongest neural response that we have observed in brain areas responsible for mental imagery and emotions could be related to liveliness (i.e., the similarity in intensity between imagery and real performance) rather than to the clarity and detail of the mental images generated by participants. This might also explain why, on the behavioral level, our participants rated the vividness of neutral behaviors higher than the vividness of risky behaviors. It is possible that the neutral behaviors that we presented to participants in the present study were more common and everyday than the risky behaviors, therefore mental images related to them were also clearer and more detailed than those generated in response to risk. In other words, the effect we observed on the neural level potentially concerned the liveliness aspect of mental imagery whereas the effect found on the self-report level was more the clarity type. However, this explanation requires further empirical investigation.

To conclude, we demonstrated that mental images of risky behavior, compared to mental images of neutral behavior, increased neural activation in brain areas engaged in mental imagery processes, emotional processing and decision making. These findings imply that the evaluation of everyday risky situations may originate in visualizing the potential consequences of risk taking and may be driven by emotional responses (e.g., fear) that result from vivid (i.e., dynamic, alive and vigorous) mental imagery.

Open Practices Statement

The data and materials for all experiments will be available upon the acceptance of the paper and Experiment reported in the paper was not preregistered.

Declarations

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Author contributions

T.Z., J.T., K.F. and A.S. designed the study. J.T., K.F. and A.M-R analyzed the data. T.Z., J.T., A.S. and A.M-R wrote the manuscript. All authors reviewed the manuscript.
Competing interests

The authors declare no competing interests.

References


**Figures**
Figure 1

A schematic illustration of the experimental procedure. Participants were presented with brief descriptions of 20 risky and 20 neutral situations. In each trial, they were instructed to imagine all consequences of a situation for 15 s when a fixation cross was displayed on the screen. After this, they rated vividness, fear and perceived risk.
Glass-brain views (top panel) and axial maps (bottom panel) displaying brain areas with a statistically significant increased BOLD signal for the risky > neutral contrast. Note that glass-brain images show projections of the activations across the whole brain volume onto two-dimensional axial, sagittal and coronal views.

**Figure 2**
Glass-brain views (sagittal, coronal and axial) displaying brain areas with a statistically significant increased BOLD signal in the risky > control contrast for each of the four bins. Analysis is restricted to clusters showing significant differences in the "risky > control" contrast on the whole trial.

Figure 3
Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryMaterials.pdf