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Tracking Deceased-Related Thinking with Neural Pattern Decoding of a Cortical-Basal Ganglia Circuit

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Abstract

Background—Deceased-related thinking is central to grieving and potentially critical to processing of the loss. Self-report measurements might fail to capture important elements of deceased-related thinking and processing. Here, we used a machine learning approach applied to fMRI - known as neural decoding - to develop a measure of ongoing deceased-related processing.

Methods—23 subjects grieving the loss of a first-degree relative, spouse or partner within 14 months underwent two fMRI tasks. They first viewed pictures and stories related to the deceased, a living control and a demographic control figure while providing ongoing valence and arousal ratings. Second, they performed a 10-minute Sustained Attention to Response Task (SART) with thought probes every 25–35 seconds to identify deceased, living and self-related thoughts.

Results—A conjunction analysis, controlling for valence/arousal, identified neural clusters in basal ganglia, orbital prefrontal cortex and insula associated with both types of deceased-related stimuli *vs.* the two control conditions in the first task. This pattern was applied to fMRI data collected during the SART, and discriminated deceased-related but not living or self-related

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thoughts, independently of grief-severity and time since loss. Deceased-related thoughts on the SART correlated with self-reported avoidance. The neural model predicted avoidance over and above deceased-related thoughts.

Conclusions—A neural pattern trained to identify mental representations of the deceased tracked deceased-related thinking during a sustained attention task and also predicted subject-level avoidance. This approach provides a new imaging tool to be used as an index of processing the deceased for future studies of complicated grief.

Keywords

Grieving; MVPA; Neural-Decoding; Rumination; Thought-Prediction; Insula

Introduction

Recurrent thoughts of a deceased loved one are common following a loss (1, 2). These thoughts are considered a part of normal grief (1). The evolution of one's feelings towards the deceased is described as “grief-work” or processing of the loss (3, 4). Existing theories of grieving emphasize the importance of “grief-work”, requiring thinking about the deceased (1, 4, 5). Excessive thinking about the deceased is associated with poorer grief outcomes in some studies (6) but not others (7, 8). Furthermore, reductions in avoidance (i.e. more thinking about loss) correlate with positive outcomes (9). In part, these mixed findings likely stem from the different aspects of deceased-related thinking in each study (i.e. worry, rumination, contemplation, avoidance). However, another reason for disagreeing results may be the way these thoughts are measured.

Current methods for assessing deceased-related thinking depend on self-report. Self-report is vulnerable to biases that might influence accuracy (10–12). Furthermore, self-report is limited to thoughts that are consciously experienced and remembered later. However, processing of loss that does not occur consciously or is later forgotten may be especially relevant to psychiatric outcomes (13, 14). We therefore sought to identify a neural signal that could predict ongoing self-generated thoughts of the deceased. This might serve as a better proxy for actual “grief-work” and processing of the loss than self-reported deceased related thoughts.

To do this, we used a two-step technique known as neural decoding where machine-learning methods are used on a first set of fMRI data to detect a pattern of brain activity associated with a target mental process. This pattern is then applied to a second set of data to track the occurrence of that mental process. Neural decoding has been used to track ongoing perceptions (15), memory (16) and emotional processes (17, 18). To our knowledge it has not been used to track the occurrence of a specific type of thought.

To accomplish these goals, we first used machine learning applied to fMRI to identify a neural pattern associated with mental representations of the deceased in subjects grieving a loss. This voxel-pattern was then applied to a second set of fMRI data obtained from a 10-minute sustained attention task where subjects reported the occurrence of deceased-related thoughts during this task. The neural model was used to discriminate instances when subjects reported thinking about the loss.

Deceased-related thinking may be experienced in multiple ways, including as an image (19), an autobiographical memory (20) or a sense of being with the person (21). We therefore sought to identify a neural network responsive to representations of the loss across these three visual, memory and relational modalities, which we term a *transmodal mental representation of the deceased*. Prior studies have identified basal ganglia activity in response to pictures of the deceased (22). Nevertheless, it remains unclear if this pattern is specific to representing a deceased figure or applies to any close attachment. We therefore aimed to determine the neural circuitry of mental representations of the deceased across multiple perceptual modalities while also controlling for demographic and attachment-related representations. To do that, we used memories and images of a living relative and of a fictional but demographically comparable avatar.

We recruited subjects, bereaved of a first-degree family member in the past 14 months, who underwent two fMRI tasks. 1) A multi-modal representations of the deceased task that controlled for attachment and demographic factors. 2) A Sustained Attention to Response Task (SART(23)) interspersed with thought probes about deceased-related thinking. We hypothesized that we would identify a model of transmodal neural representations of the deceased and that neural decoding implemented with this model during the SART would detect deceased-related thinking.

Methods

Participants

23 subjects bereaved of a first-degree relative 3–14 months ago (mean = 7.7 (SD = 4.1) months) participated in this study. This study was part of larger study comparing suicide and non-suicide bereaved. As a result, we recruited subjects across a relatively wide range of times since loss and still capture a moderate to severe degree of grieving severity. Subjects were 18 to 65 years old (mean = 46, SD = 13.6 years), and four subjects were male. All participants had normal color vision and spoke English as a first language. Recruitment was done through social media websites and reaching out to people listed as relatives in obituaries. All subjects were medically healthy as determined by medical history, examination and standard blood and urine tests. Exclusion criteria were recent bipolar disorder (manic episode within the past year), recent substance use disorder (met criteria within past six months), current obsessive-compulsive disorder, lifetime schizophrenia or schizoaffective disorder assessed with the Structured Clinical Interview for DSM-IV Axis I (SCID I). Subjects who were taking psychiatric medications were required to be on a stable dose for two weeks prior to scanning. The New York State Psychiatric Institute IRB approved this study and all subjects gave written informed consent.

Procedure

Subjects underwent a diagnostic interview, pre-scan interview, an MRI scan and then a post-scan interview. During the MRI scan subjects performed the representations of deceased task followed by the SART. Grief severity was measured by the Inventory of Complicated Grief (ICG) (24) and avoidance of reminders of the loss was measured using the Impact of Event avoidance subscale (IES-A) (25), both scales were administered during the post-scan interview.

Stimulus Acquisition and Preparation

Stimuli for the representations of the deceased task were acquired during the pre-scan interview. Subjects were asked to think of a living person who became the living-control. This person could be a brother, sister, friend or anyone that the subject deemed to have a similar relationship as they did with the deceased. Subjects provided two front-facing pictures of the deceased and living control taken within the past five years as well as three stories about the deceased and the living control. Participants were instructed to tell stories that "make you think of that person." Stories were then reduced to three lines each ranging from 30–50 characters including spaces.

A demographic control was then created to match the demographic features (age, ethnicity, gender) of the deceased. Pictures for the demographic control were obtained from the Facial Recognition Technology (FERET) database (http://www.itl.nist.gov/iad/humanid/feret/feret_master.html) and were selected to match the pictures of the deceased in terms of age, ethnicity, gender and facial expression. A parallel set of stories was composed corresponding to the demographic control. These stories always described the same relational dyads as the one described in the deceased stories (father-son, mother-daughter), with the demographic control occupying the same part of dyad as the deceased. Stimuli were preprocessed to equalize visual features (pictures) and valence and arousal (demographic control stories). Details of stimulus preprocessing are included in (Supplemental Information, Preprocessing of Stories and Pictures).

Representations of deceased task

Four runs of the representations of deceased task were administered. Each run consisted of two blocks each of the three persons: deceased, living-control and demographic-control (Figure 1, A). Each person block lasted for 46.5 seconds and comprised three modalities: *picture*, *story*, and *think*. In the *picture modality* two pictures corresponding to the person-condition were displayed for 7.5 seconds each. In the *story modality* one of the three stories was presented in successive phrases of three lines with each line being presented for 5 seconds. The stories were alternated across blocks. In the *think modality* subjects were instructed to imagine being with the person for 15 seconds. Each modality was separated by a 500ms fixation and each person-condition block was followed by valence (1=Very Sad, 2=Sad, 3=Neutral, 4=Happy, 5=Very Happy) and arousal (1=Very Relaxed, 2=Relaxed, 3=Neutral, 4=Aroused, 5=Very Aroused) probes. Presentation order of person blocks was permuted across the four runs. Presentation of modalities within blocks was randomized. Before the first presentation of the demographic control a slide was presented introducing the subject to the demographic control.

Sustained Attention to Response Task

The SART was always performed following the representations of deceased task (Figure 1, B). In the SART, subjects were instructed to press a button every time a number came on screen except for the number “3”. Numbers were presented on screen for 1.5 seconds with an inter-trial jitter averaging 2 seconds. The number 3 was presented 11% of the time to ensure subjects remained engaged in the task. To limit predictability of thought probes, the length of each block of this task was randomly selected from a range of 25–35 seconds. Subjects completed 16 blocks. Following each block, thought probes were presented as follows: A) Did you think about *name of deceased* over the past block (Yes/No)? B) Did you think about *name of living control* over the past block (Yes/No)? C) Did you think about yourself over the past block (Yes/No)? This is similar to the usage of the SART to detect mind wandering in a number of prior studies (26, 27).

Image parameters and preprocessing are provided in (Supplemental Information, Imaging).

Feature Selection

Univariate Analysis of Representations of Deceased Task—The full workflow for this study is presented in Supplemental Figure S1. We sought to identify a mask of voxels involved in transmodal mental representations of the deceased (Figure S1, 1). Multiple mental processes are likely to occur during presentation of the person related stimuli, such as person representation as well as self-related thoughts. We were interested in the representation of the person, which likely occurs first. Therefore, the first 5 seconds of each trial were modeled, with the remaining 10 seconds modeled via a nuisance regressor. Nevertheless, a 15 second block was used to display the stimuli to create the expectation for extended exposure to each stimulus and allow subjects to immerse themselves. Standard six-degree motion regressors were included as covariates in all analyses.

A least squares deconvolution method (Least Squares – Separate; LS-S) and registration were applied and described in (Supplemental Information, Least Squares Deconvolution).

To conduct univariate analyses, we compared parameter estimates of the deceased (D) and control living and demographic (CLD) conditions across the three modalities of picture, story and think (PIC, STO, THI) thus producing the following groups: (D_PIC, D_STO, D_THI, CLD_PIC, CLD_STO, CLD_THI). T-tests were calculated as follows: Picture (D_PIC > CLD_PIC), Story (D_STO > CLD_STO), Think (D_THI > CLD_THI). This analysis was conducted while controlling for valence and arousal ratings. A voxel-wise threshold of $p<0.001$ and a cluster size threshold of $p<0.05$ was applied with the cluster command in FSL. The rationale for using t-tests on standardized data rather than mixed effect models is also provided in (Supplemental Information, Rationale).

Conjunction Analysis—Conjunction analysis was used (28) to identify a transmodal mask for mental representations of the deceased (Figure S1, 2). The conjunction analysis tests the degree to which there is an effect for both Task A and Task B. The non-cluster-corrected results for the contrast between deceased-related stories *vs.* control stories and the contrast between deceased-related pictures and control pictures were input to the conjunction analysis ((D_PIC>CLD_PIC) AND (D_STO>CLD_STO)). Only the picture and story modalities were input into the conjunction analysis because the think condition did not produce significant results.

We applied a voxelwise threshold of p<0.001. We did not apply a cluster correction to this mask because we sought to identify a large set of clusters thereby increasing signal to noise ratio for subsequent MVPA analyses. This is similar to the approach employed in prior conjunction studies (29, 30). To identify a more stringent conjunction mask we employed a cluster threshold of p<0.05.

Model Training—To identify a pattern for representations of the deceased in the conjunction results we calculated a logistic regression MVPA model discriminating deceased related and control picture and story blocks within these voxels controlling for valence/arousal (Figure S1, 3). We used Fast Simultaneous Training of Generalized Linear Models (FaSTGLZ) (31) to obtain an optimal penalization constant to predict the condition type of hold-out data across 100 out-of-sample cross-validation runs. Full details of the classification approach are provided in (Supplemental Information, Model Training). Additional control analyses were conducted on two null regions to highlight the specificity of conjunction based model training. Full details of these analyses are provided in (Supplemental Information, Null MVPA Analyses).

Model Application: Neural decoding of the SART data—In addition to standard preprocessing, 4D time-series of SART data were registered to standard space and motion effects were regressed out using standard FSL 6-degree motion regressors. Each SART time series was also standardized by its own mean and standard deviation.

Neural decoding was implemented by applying the model developed in the representations of deceased task to the SART data (Figure S1, 4). Model application entails voxel-wise multiplication of regression weights in the conjunction mask with the values for the new BOLD data from the SART, followed by a linear summation across voxels. This produces a one-dimensional TR-by-TR neural prediction of the pattern similarity between the new data and the pattern that optimally corresponds to mental representations of the deceased. To account for the hemodynamic response delay we applied the model starting at the 4^{th} TR following each probes period and into the second TR into the next probes period. Block-wise model output was given as the mean for model output over all the TRs in each block (Figure S1, 5).

Thought Prediction: Prediction of Deceased-Related Thinking—A linear mixed effects logistic regression was implemented in R 2.15.13 (32) to predict deceased-related thinking from average block-wise model output (Figure S1, 6). Subject identity was modeled as a random intercept. The average model output for a block was entered into the model as a continuous predictor of responses to the binary deceased thoughts probe.

Blocks of SART trials with errors (i.e. commissions or omissions) were excluded from this analysis, because the neural processes occurring during non-error blocks are likely to be more homogenous as compared to those that occur during blocks with errors. As a result, comparing across a set of more homogenous blocks is likely to yield a better discrimination between blocks with and without deceased-related thinking on the basis of neural data.

Results

Reliability was acceptable for both the ICG scale (α=0.96) and the IES-A (α=0.76). Subjects were experiencing a considerable amount of grief with average ICG score of 26.5(13.4). ICG score correlated with avoidance, arousal during the mental representations of deceased task, frequency of thinking about the deceased on the SART and average motion during the SART (Table 1).

Representations of the Deceased Task

Figure 2 describes characteristics of responses to the representations of deceased task. Deceased-related blocks evoked more valence and arousal than both types of control blocks. The *story modality* displayed a widely distributed set of clusters associated with the deceased *vs.* control conditions (D_STO>CLD_STO): including anterior and posterior cingulate, insula, orbital frontal cortex (OFC) and basal ganglia (Figure 3A, Supplemental Table S1). In the *picture modality*, activity in a single contiguous cluster extending across right putamen, caudate, insula and OFC was associated with viewing pictures of the deceased as compared to controls (D_PIC>CLD_PIC) (Figure 3B, Supplemental Table S2). The *think modality* showed no significant clusters associated with thinking about the deceased. Neural analyses controlled for self-reported valence and arousal. To demonstrate the effect of this control we highlight the voxels that were excluded by accounting for valence/arousal (Supplemental Figure S3). There were no clusters whose activity was greater for the control conditions as compared to deceased condition.

Conjunction analysis

The conjunction analysis identified voxels in bilateral putamen, caudate, insula and orbital prefrontal cortex (OFC) and left posterior cingulate whose activity was conjointly associated with viewing pictures and stories of the deceased as compared to controls at a threshold of voxel p<0.001 ((D_PIC>CLD_PIC) AND (D_STO>CLD_STO)) ((Figure 3C, Table 2). There were a number of very small clusters ranging in size from 1–12 voxels. We therefore applied a lenient cluster correction of cluster p<0.1 to remove very small clusters whose activity was unlikely to be biologically significant. This threshold removed the small clusters. When applying a more stringent cluster correction (p<0.05) the cluster in the right putamen, insula and OFC remains significant (Figure 3C, Green) (Cluster Center(X,Y,Z) = 58,69,32, #Voxels=147, average z-score=3.33).

Classification results

On the representations of deceased task data, the multivariate logistic regression model achieved significant cross-validated average out-of-sample classification accuracy (p<0.01) across a large range of regularization constants. The maximum accuracy achieved was AUC=0.63.

SART—21/23 subjects completed the SART task. One subject completed only 14 SART blocks due to timing limitations. Out of a total of 334 SART blocks there were 209 that did not include an error. The average number of error-free blocks was 9.9 (SD: 2.8, Range: 3–14). An additional 3 blocks had insufficient neural data and were excluded from subsequent neural analyses. A chi square test showed no association between a block having errors and deceased-related thinking (x^2=0.003, p=0.96). Errors were associated with arousal as measured on the mental representations task but no other clinical variables like grief severity or valence (Table 1).

Deceased-related thinking occurred on 68 (32%) out of 209 blocks. There were 49(23%) living-control and 93 (44%) self-related reports of thinking. Blocks with deceased-related thinking were also more likely to contain living-control (x^2=0.48, p<0.001) and self-related thinking (x^2=0.13, p=0.045) (Figure 4). To identify subject-level correlates of thinking about the deceased we calculated the percentage of reported thoughts of loss out of total non-error SART blocks (M(SD)=.33, Range: 0–1). Percentage of thinking about the deceased correlated with grief severity and avoidance but not valence/arousal, motion or errors (Table 1).

Greater block-wise output of the neural model predicted higher odds of thinking about the deceased on that block (B_{203}=2.92, SE=1.39, p=0.035) (Figure 5). These findings persisted after controlling for ICG score and time since loss (B_{201}=2.89, SE=1.37, p=0.033) as well as valence/arousal and average motion (B_{200}=3.01, SE=1.38, p=0.02). The output of a model trained in the voxels defined by the more stringent conjunction results also predicted deceased-related thinking although only at a trend level (B_{203}=2.96, SE=1.59, p=0.063). The effect of model output was not significant for thinking about the living control (B_{203}=−0.04, SE=1.36, p=0.97) or predicting self-related thoughts (B_{203}=1.01, SE=0.99, p=0.31).

Avoidance is a cognitive strategy that provides respite from frequent painful thoughts of loss (1). Consistent with prior work (33, 34), subject-level avoidance correlated with more frequent thoughts of the deceased on the SART (Table 1) and higher model output (Figure 6, r_{21}=0.54, p=0.01). Deceased-related thinking also correlated with intrusion (r_{21}=0.44, p=0.04) while model output did not (r_{21}=0.05, p=0.82). In a simultaneous regression analysis, model output was a predictor of avoidance (B_{21}=0.43, t=2.25, p=0.03) while deceased-related thinking on the SART was not statistically significant (B_{21}=0.34, t=1.77, p=0.09). The prediction of avoidance from neural model output remained significant while controlling for ICG (t_{18}=3.11, p<0.01). Because motion during the SART and arousal, were both associated with ICG we calculated the prediction of avoidance from model output while controlling for these (t_{17}=2.64, p=0.01).

Discussion

This study identified a neural pattern in insula, basal ganglia and OFC involved in the transmodal mental representation of a deceased loved one independently of valence/arousal. Neural decoding of this pattern during a sustained attention task tracked ongoing deceased-related thinking.

A generic grief effect was seen in the correlation of grief severity with experiential avoidance, arousal and motion. Nevertheless, the neural pattern of mental representations of the deceased predicted thinking about the loss and experiential avoidance independently of these generic grief factors (i.e. ICG, motion, arousal). These findings point to a specific relationship between mental representations of the deceased, deceased-related thinking and experiential avoidance that is distinct from generic grief severity. The independence of these relationships from generic grief severity suggests a potential subtype of grieving. This subtype would be characterized by greater experiential avoidance and a stronger relationship between mental representations of the deceased and experienced thoughts of loss. This neural probe can be used to further understand the relationship between mental representations of the deceased, thoughts of loss and experiential avoidance.

While we interpret our findings as a measure of mental representations of the deceased it remains possible that the neural pattern detected valence/arousal occurring during the SART. The neural tracker was developed controlling for valence/arousal as reported during the first task. The fact that deceased-related blocks evoked more valence/arousal suggests that these probes were successful and subsequently controlling for them would exclude voxels associated with valence/arousal (Supplemental Figure S3). Nevertheless, probes were presented at the end of each block rather than after each stimulus. Certain stimuli (i.e. stories, pictures) may have evoked more valence/arousal than was measured in the probes and these processes may then have been included in the subsequent neural marker. Future studies should measure valence/arousal occurring at each stimulus and during the SART to ensure that the process being tracked is truly specific to grief rather than a generic valence/arousal process.

The regions activated by the representations of deceased task provide insight into the type of the deceased-related processing potentially identified by the neural pattern. The involvement of both approach-related regions (i.e. basal ganglia) as seen in prior work (22) and regulation-related regions (i.e. insula and OFC) may indicate the simultaneous yearning towards the deceased as well as distancing from the deceased that is unique to grieving (35). By controlling for a living attachment and an anonymous demographic avatar this task specifically targeted the unique combination of attachment (i.e. deceased-attachment vs. anonymous) as well as loss (i.e. deceased-attachment vs. living-attachment) that is present in grieving.

We build on prior neural decoding studies in two ways. 1) Neural decoding predicted a specific thought rather than a general cognitive or emotional process (15–18). 2) Neural decoding was applied during a cognitively active task rather than a rest period. Neural tracking of thoughts during an active cognitive state rather than a rest state may provide a better analogue for the types of irrelevant thoughts or mind wandering that occurs outside of the laboratory which often happens during states of activity and not just rest (36).

The specificity of our model training as well as decoding is underscored by the tracking of thoughts of the deceased but not the living-control or self. Task irrelevant thoughts occurred as a general process by which self and living related thoughts were more likely to occur during blocks with deceased-related thoughts. Despite these relationships between self-related, living-related and deceased-related thinking, our model only predicted deceased-related thinking.

Limitations

To maximize recruitment, we recruited from month 3 to 14 post loss. However, this time period spans acute and integrated grief stages. Controlling for time since loss and complicated grief inventory scores gave more confidence in the results but it would be ideal to begin recruitment at 6-months post loss to avoid blurring across these stages. Furthermore, the sample size is small and these findings should be replicated in a larger sample. The instruction of “imagine being with [person]” that was used in the think condition may have elicited more variable responses across subjects (i.e. visual imagination, memory elicitation) and therefore failed to yield a consistent neural circuit. Future studies should use a more concrete stimulus like the person’s name or an instruction to think about an aspect of their personality. As mentioned above, valence/arousal probes could be included in the SART and after each stimulus presentation in the mental representations task to ensure that the neural pattern is specific to grief rather than tracking more generic processes. An additional alternative would be a physiological measure of arousal.

Conclusions

We identified clusters of neural activity in the insula, OFC and basal ganglia associated with transmodal representation of the deceased *vs.* living attachment and demographic control figures in grieving subjects. These findings were independent of general emotional and arousal reactivity. A model trained in these clusters was used to decode neural data produced during a sustained attention task. Neural decoding predicted the occurrence of deceased-related thinking occurring during this task. The neural marker of deceased related thinking predicted subject level avoidance over and above the prediction by deceased-related thinking on the SART. These findings present a new measure of mental representations of the deceased that can be used for predicting the risk of complicated grief and further developed into a tracker of deceased-related thinking.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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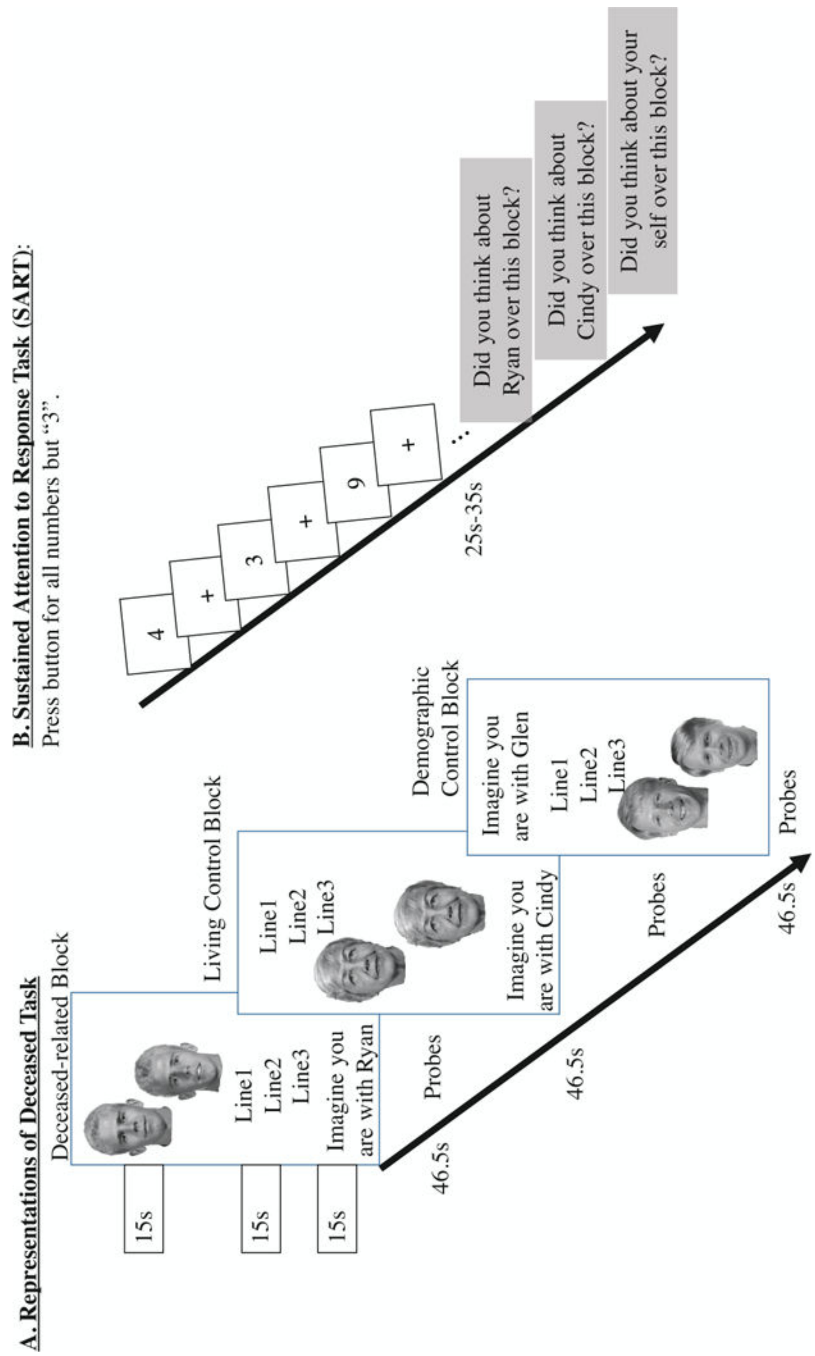

Figure 1.

A. Representations of Deceased Task: In this task three person blocks (deceased, living-control, demographic-control) were presented in a permuted order twice per run across four runs. Each block comprised three modalities (picture, story, think). For the picture modality two pictures were presented for 7.5 seconds each. For the story modality one story was presented in three lines with each line being presented for 5 seconds each. Stories alternated across blocks. In the think modality subjects were instructed to think about the deceased for 15 seconds. 500 millisecond fixations were presented in between each modality. Hence, each person block lasted 46.5 seconds. Within each block the ordering of modalities was randomized. Valence and arousal probes were presented following each block. To protect confidentiality, sample images for this figure are all taken from the FERET database of facial images collected under the FERET program, sponsored by the DOD Counterdrug Technology Development Program Office (37). **B. Sustained Attention to Response Task (SART):** The SART was presented following the representations of deceased task. During SART trials subjects were instructed to press a button every time a number aside from “3” was presented. Numbers were presented for 1.5 seconds with a fixation jitter of around 2 seconds. Blocks lasted for 25–35 seconds. Following each block subjects were probed regarding deceased and living-control related thinking. 16 SART blocks were performed per subject.

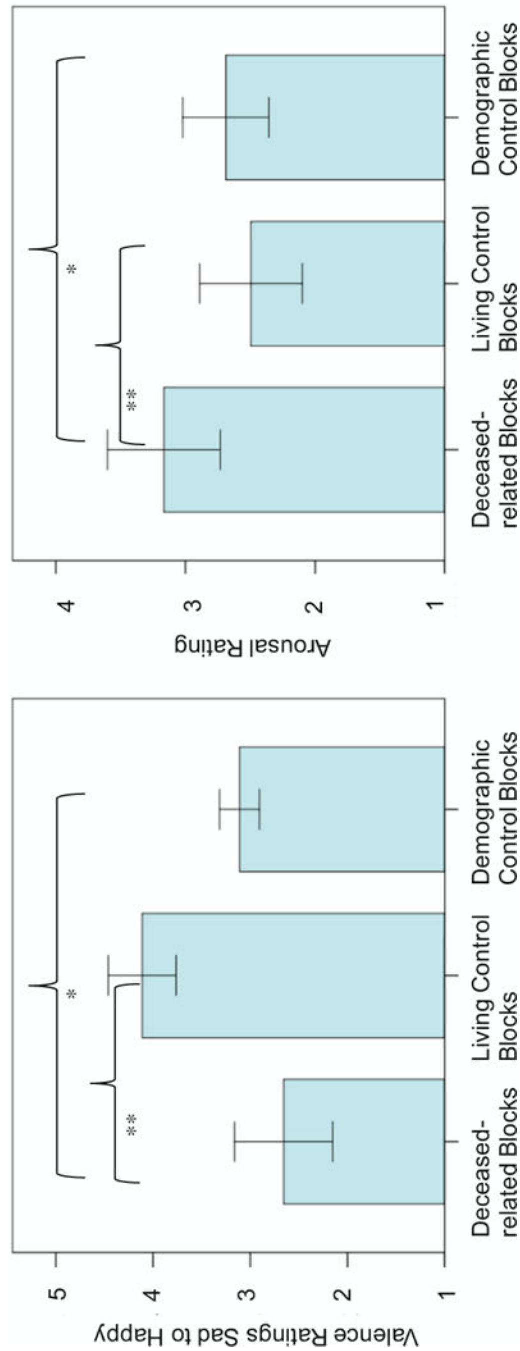

Figure 2. Representations of Deceased Task Valence and Arousal

Average valence and arousal ratings for deceased-related, living control and demographic control blocks. Paired samples t-tests show that deceased-related blocks evoked greater valence as compared to both living (t_{22}=−5.6,p<0.001) and demographic control blocks (t_{22}= −2.2,p=0.031). Deceased-related blocks were more arousing than living (t_{22}=3.15, p=0.005) and demographic control blocks (t_{22}=2.16, p=0.041). Valence ratings were given as: (1=Very Sad, 2=Sad, 3=Neutral, 4=Happy, 5=Very Happy), arousal ratings were given as: (1=Very Relaxed, 2=Relaxed, 3=Neutral, 4=Aroused, 5=Very Aroused). **p<.01. *p<.05.

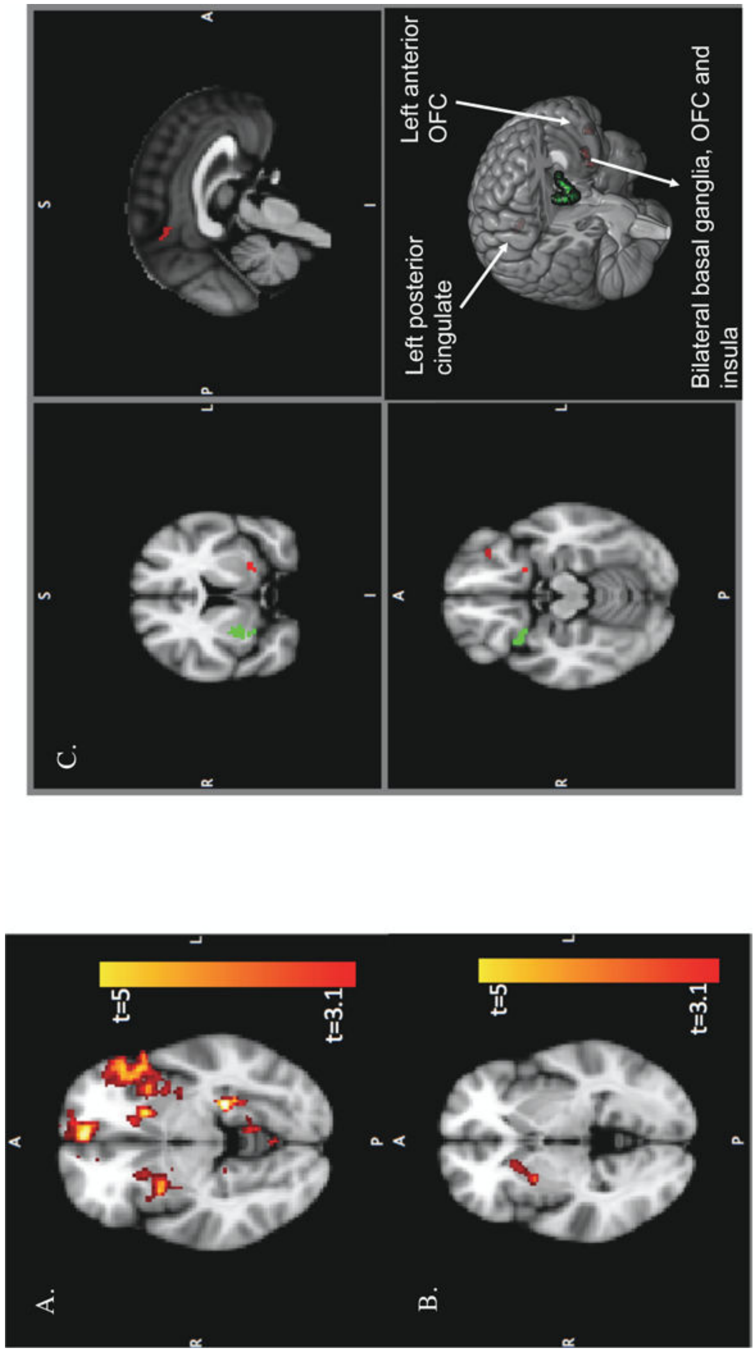

Figure 3. Neural Circuitry of Mental Representations of the Deceased

A. Clusters showing greater response to deceased-related as compared to control stories (D_STO>CLD_STO). Clusters are significant at a voxel-wise threshold of t_{523}=3.1, p<0.001 and cluster corrected with a threshold of p<0.05. A large cluster in right insula as well as a distributed network across anterior and posterior cingulate, orbital prefrontal cortex and bilateral basal ganglia are seen. Image coordinates (X,Y,Z=25,70,33) **B.** Cluster in right putamen, insula, and caudate whose activity is associated with viewing pictures of the deceased as compared to controls (D_PIC>CLD_PIC) of t_{522}=3.1, p<0.001, cluster-p <0.05.

Image coordinates (X,Y,Z=60,67,35) **C.** Red and green maps together display clusters in bilateral basal ganglia, OFC and insula as well as left anterior OFC and posterior cingulate conjointly activated by pictures and stories of the deceased as compared to the control conditions ((D_STO>CLD_STO) AND (D_PIC>CLD_PIC)) (voxel $p<0.001$, cluster-p <0.1). Green mask highlighted by 3D rendering displays the larger cluster on the right that survived a more stringent cluster size threshold of $p<0.05$ and was previously seen in cluster corrected story and picture results. Image coordinates (X,Y,Z=45,67,28)

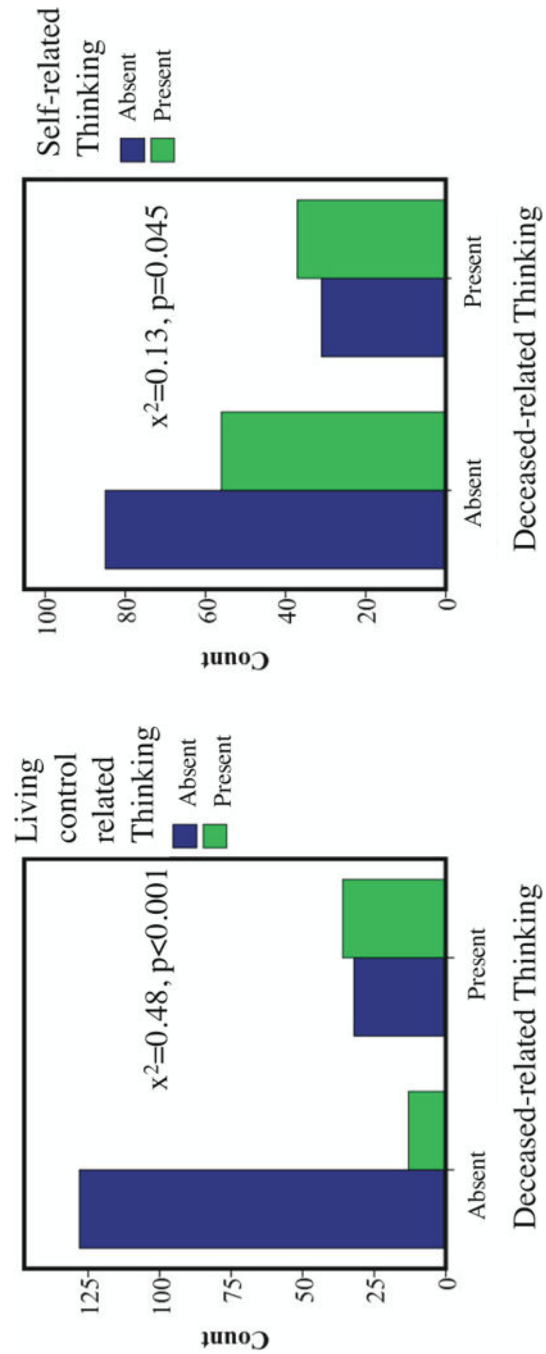

Figure 4. Mind Wandering During Sustained Attention to Response Task

Bar graphs display the co-occurrence of self and living-control related thinking with deceased-related thinking during SART. Chi square tests show that self and living control related thinking were more likely to occur during blocks in which deceased related thinking had also been reported.

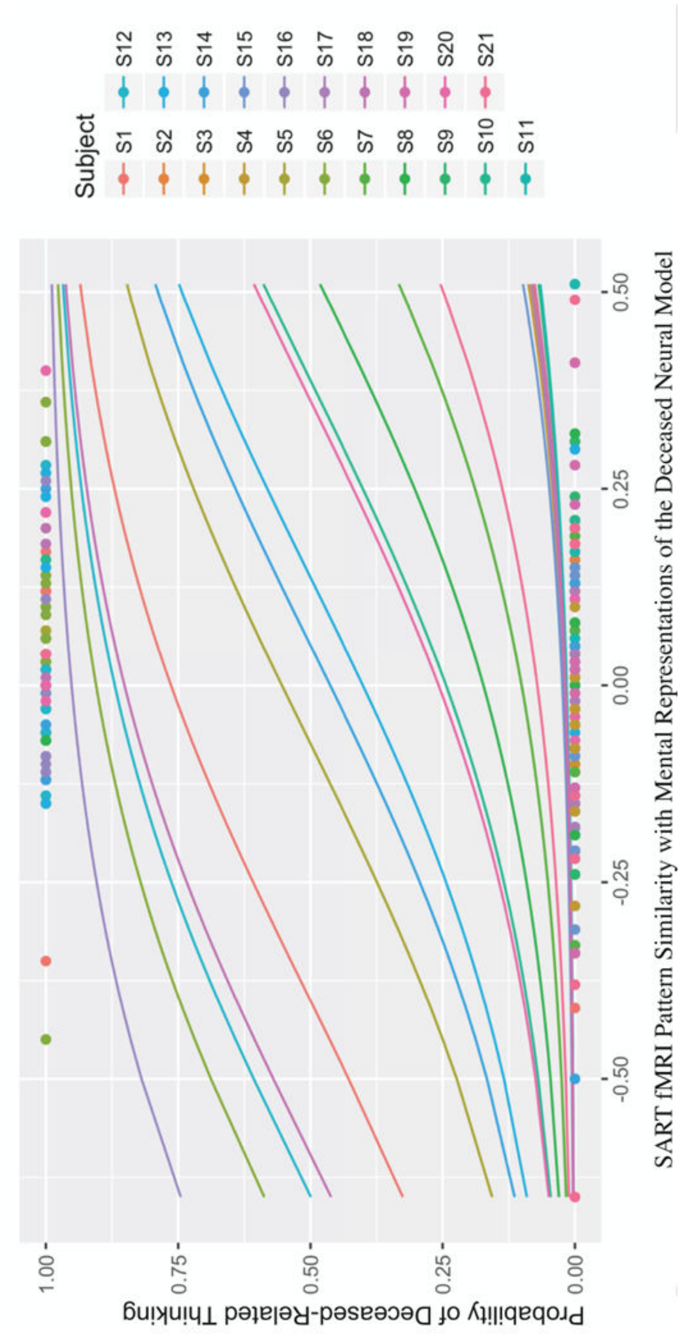

Figure 5. Prediction of Deceased-Related Thinking During SART

Deceased-related thinking during the SART was predicted by neural decoding of SART fMRI. Higher model output in a given SART block indicates that the pattern of neural activity in that block was more similar to the pattern linked to mental representations of the deceased. Higher pattern similarity in a given block predicted a higher chance of subsequent self-reported deceased-related thinking. Individual slopes are displayed for each subject.

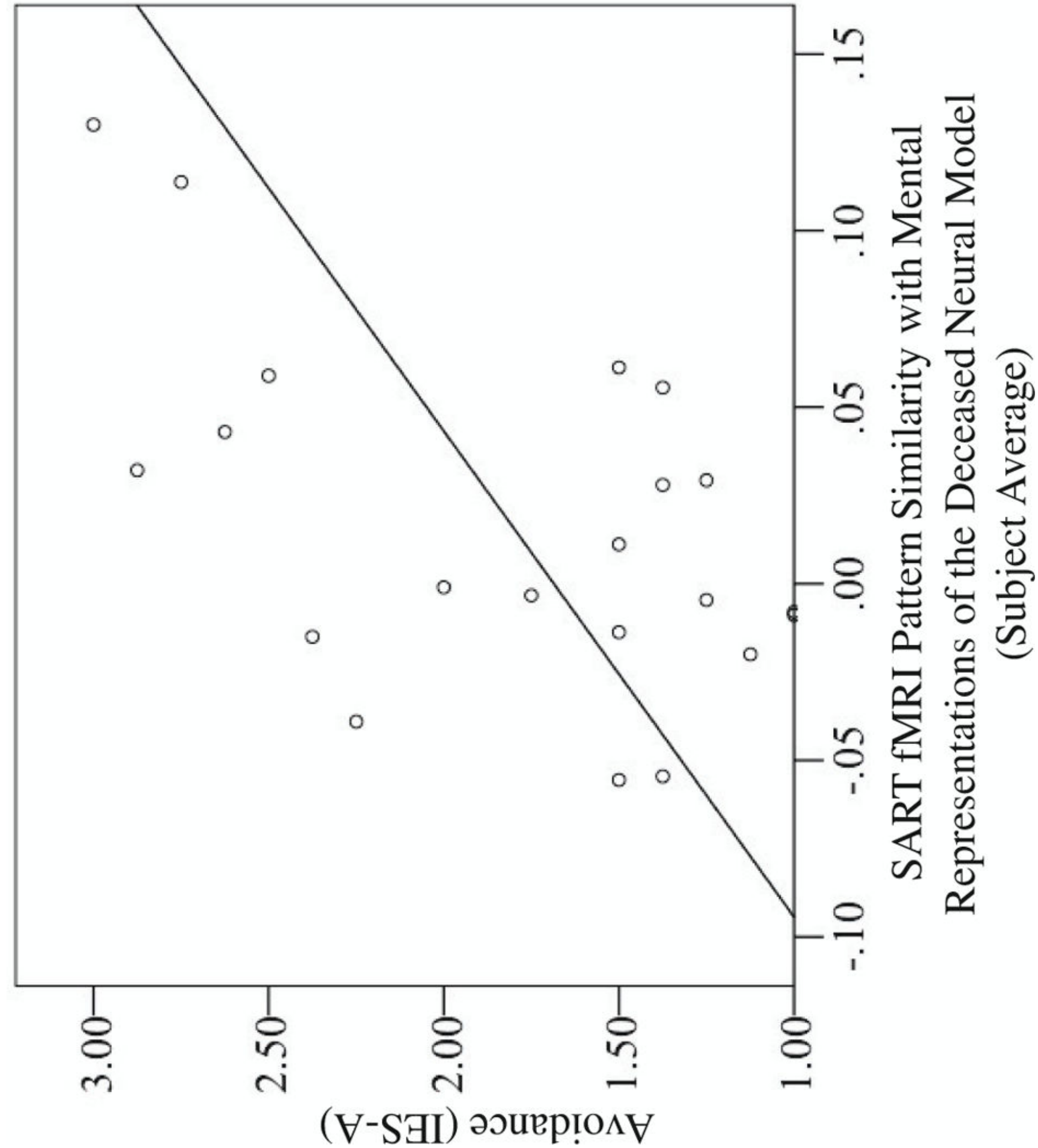

Figure 6. Mental Representations of Deceased During SART and Avoidance

Subjects who showed higher mental representations of the deceased model output during the SART also had higher avoidance scores.

Table 1

Correlation Matrix of Clinical Variables and Performance Characteristics

ICG= Inventory for Complicated Grief, Avoidance= Avoidance as measured on Impact of Event Scale, Valence/Arousal= Subject level average of valence and arousal as measured by the probes in the mental representations of deceased task, Deceased-related thinking= Percentage of non-error blocks on SART in which deceased-related thinking was reported, Total Errors= Total number of errors made on SART, Motion= Average degree of frame to frame displacement for each fMRI task.

		1.	2.	3.	4.	5.	6.	7.
1.	ICG	1						
2.	Avoidance	0.442*	1					
3.	Valence	−0.178	−0.132	1				
4.	Arousal	0.460*	0.11	−0.584**	1			
5.	Deceased-related thinking (SART)	0.586**	0.483*	0.166	0.078	1		
6.	Total Errors (SART)	0.24	0.251	−0.382	0.492*	0.232	1	
7.	Motion (SART)	0.498*	−0.076	−0.121	0.323	0.395	0.245	1
8	Motion (Mental Rep-Task)	0.263	−0.213	0.159	−0.021	0.336	0.105	0.695**

*Correlation is significant at the 0.05 level (2-tailed).

**Correlation is significant at the 0.01 level (2-tailed).

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Table 2

Conjunction of Pictures and Stories of Deceased

Regions in which neural activity was conjointly activated by pictures and stories of the deceased as compared to the control conditions ((D_STO>CLD_STO) AND (D_PIC>CLD_PIC)) (voxel p<0.001, cluster-p <0.1).

Region	#Voxels	X	Y	Z
Left Posterior Cingulate (and Precuneous)	26	44.31	43.24	59.85
Bilateral Frontal Orbital Cortex	76	38.51	72.67	29.35
Bilateral Insula	28	34.50	68.67	30.67
Left Putamen	6	44.24	42.35	60.41
Right Caudate	9	52.89	73.22	35.78
Right Putamen	78	57.18	67.88	33.87