Abstract

The pulvinar nucleus represents a key neural structure involved in signalling emotional content in the domain of visual perception, whereas its role in the processing of *simulated* emotional events is less clear. fMRI research has hinted at a role for the pulvinar in imagined emotional scenarios, but the evidence is mixed and this proposal has yet to be tested using the lesion study method. In this study, 3 patients with unilateral lesions to the pulvinar, and 10 matched control participants, completed a set of well-established tasks that required them to think about emotional past and future events. This procedure allowed for a comprehensive evaluation of emotional past and future thinking, using both subjective and objective measures. The results indicate that, relative to controls, processing of emotional past and future events is *not* impaired in patients with unilateral pulvinar nucleus lesions. However, outcomes of this study should be interpreted in the context of the volume, lateralisation and location of pulvinar lesions in these cases. These data have implications for understanding of the processing of emotionally-salient stimuli in the context of pulvinar damage.

Emotional past and future events after pulvinar damage: A neuropsychological case series

The pulvinar is the largest distinct structure within the human thalamus. It is a key subcortical area, found in human and nonhuman primates, and well positioned as a ‘nexus’ because dense white matter tracts connect it with important subcortical (e.g., amygdala) and cortical (e.g., orbito-frontal cortex) structures (Rafal et al., 2015). These neuroanatomical connections, along with neuroscientific and behavioural evidence, have led to the consensus position that the human pulvinar has an important role in attention and emotional processing (Tamietto and deGelder, 2010; Rafal et al., 2015). Neuroscientific research on the pulvinar has mostly centred around its role as a secondary subcortical pathway of visual processing, which rapidly detects emotionally-salient visual information without the need for conscious attention (Tamietto and deGelder, 2010).

Nevertheless, recent functional magnetic resonance imaging (fMRI) research has suggested that the human pulvinar may also be involved in the construction of *internally-generated* emotional events (Szpunar et al., 2015). Specifically, Szpunar et al. (2015) used a repetition suppression paradigm (see Barron et al., 2016) with personalized cues (i.e., participant-generated person-location-object pairings) to examine the neural correlates of emotional future thoughts. They reported that regions of a core network including medial frontal, posterior cingulate and medial temporal areas (Schacter et al., 2012) -a network whose functions putatively encompass remembering the past and imagining the future- were involved in simulating future events irrespective of their emotional tone, and that the pulvinar was specifically sensitive to processing negative future events (based on reduced activity over repeated negative simulations, as opposed to increased activity as it is typically used in fMRI studies). However, in a more recent study that used a similar repetition suppression paradigm but with non-personal simulation cues (i.e., nouns), Devitt et al. (2020) found that similar regions of the core network were involved in simulating future events irrespective of emotional tone but did not find that pulvinar was specifically involved in the simulation of negative events.

If the pulvinar is involved in the processing of internally-generated negative events, one might assume that damage to this region might disrupt negative future thinking or negative mental time travel in general (depending on lesion location and size). Here, *mental time travel* is defined as the ability to mentally represent spatiotemporally-specific events from one's personal past and possible future and is derived from the episodic memory system (Tulving, 2002). Mental time travel is not only characterised by specific information content (Tulving, 2002), but also by the associated subjective experience; hence the terms *re-experiencing* (for remembering a past event) and *pre-experiencing* (a future event) have been used in the literature (e.g., D'Argembeau & van der Linden, 2004; Addis et al., 2007). No study to our knowledge has examined non-visual emotional processing in patients with focal pulvinar damage.

A Role for the Pulvinar in Mental Time Travel?

Recent years have seen a rapid accumulation of neuroimaging studies concerning simulation of future and other hypothetical events, as reflected in a meta-analysis establishing the core network including medial (hippocampus, parahippocampus) and lateral temporal lobe structures, frontal areas (ventromedial and dorsomedial prefrontal cortex) and posterior cingulate (including retrosplenial cortex) (Benoit & Schacter, 2015). But what role for the pulvinar?

Although the role of the pulvinar in visual processing of emotional stimuli is clear from converging evidence, its connections with modality-general subcortical and cortical regions (e.g., anterior cingulate, orbitofrontal cortex, amygdala, Tamietto & deGelder, 2010) raises the question of whether the pulvinar has a more general role in emotional processing. Suggestive support, in addition to the mixed findings that we noted from the fMRI literature

(Devitt et al., 2020; Szpunar et al., 2015), comes from the fact that depressed individuals show changes in the function and structure of the pulvinar nucleus (Young et al., 2008) and patients with posterior thalamic lesions following stroke (implicating the pulvinar) exhibit domain-general emotional disturbances, compared with individuals with non-posterior thalamic stroke (Lieberman et al., 2013). It is particularly relevant here that regions with dense pulvinar connections (e.g., medial prefrontal cortices, amygdala) have also been shown to be involved in remembering the past and imagining the future (Barron et al., 2015; Schacter et al, 2012). It is worth highlighting that the pulvinar is a heterogenous region with circumscribed sub-regions (Burton & Jones, 1976). A recent connectivity analysis demonstrated that ventromedial and dorsomedial clusters have a particular role in emotional processing, compared with anterior inferior and lateral areas (Guedj, & Vuilleumier, 2020), so the role of the pulvinar in different functions is based on regions within this thalamic structure.

Given the structural connections that exist between the pulvinar and regions of the core network, we believed that it would be important to further explore the role of pulvinar in event simulation, especially in relation to negative aspects of simulated events. Although the recent fMRI work on emotional aspects of event simulation, and the possible role of pulvinar (e.g., Szpunar et al., 2015), has focused on future thinking, we aimed to assess whether the pulvinar plays a role in emotional processing of memories *and* future events. The fact that emotions can be, *and often are*, represented in remembered and imagined scenes is now well-established (Barsics, et al., 2016; D’Argembeau & Van der Linden, 2004). Hence, investigating emotional past and future thinking offers a unique inroad to understand the role of the pulvinar.

For several decades, the guidance in neuropsychology has been to adopt a multiple methods approach (Nickels et al, 2011; Shallice, 2015; Turnbull, 2001; Vaidya, 2019): most notably to supplement methods such as fMRI and ERP with the classic lesion study approach, especially where this can be delivered by case series (Nickels et al, 2011). This approach helps to avoid the biases that are inherent in any single approach, and notably to helps to determine whether a brain region is essential for a psychological function, rather than simply correlated with it (see Bub, 2000 for more on this). This approach, then, constitutes a methodological need for the topic of emotional imagination. fMRI research has hinted at a role for the pulvinar in imagined emotional scenarios, but the evidence is mixed and this proposal has yet to be tested using the classic lesion study method – hence the focus of the present study.

The Current Study

The experimental measures employed herein incorporated a range of tasks that putatively tap key objective and subjective (phenomenological) characteristics associated with emotional past and future thinking, as well as estimating their frequency in daily life. These were as follows:

1) An *Autobiographical Cue Word Task* that examines event generation and construction processes (see Addis et al., 2007, 2008) by examining the amount of details associated with self-generated past and future thinking. This measure of episodic detail generation has been integral in episodic memory research (Schacter et al., 2012), and has reliably differentiated brain injury (Rasmussen & Berntsen, 2014) from associated controls.
2) An *Autobiographical Fluency Task* that measures the ease of generating positive and negative past and future events. Fluency tasks have been used to assess autobiographical memory accessibility (see Dritschel, Williams, Baddeley & Nimmo-

Smith, 1992) and may reflect accessibility of stored categories of events (e.g., negative events) over others (i.e., positive events).

3) We devised a questionnaire in which participants estimated the frequency of emotional and non-emotional future events voluntarily generated in everyday life in the previous week. Retrospective estimations are frequently and reliably used in memory research (e.g., Berntsen, 1996) as well as in standardised clinical measures (e.g., Hospital Anxiety and Depression Score, Zigmond & Snaith, 1983).

In short, we examined whether the lesions to areas within the human pulvinar affected self-generating, accessing and p/re-experiencing negative past and future events by investigating a case series of rare individuals with focal unilateral (two right, one left lateralised) pulvinar damage (all caused by stroke).

Laterality of damage may be important due to the right hemisphere hypothesis that identified this hemisphere as having a prioritised role in emotion (Borod et al., 1998). Relatedly, the valence hypothesis states that right-sided brain damage can disproportionately affect processing of *negative* emotions. We were open to laterality effects, but did not make direct hypotheses regarding these due to the novelty of these tasks with these specific patients.

We predicted that a selective deficit of emotional processing of self-generated negative events across cases of right, left (or both) lateralised pulvinar damage would offer suggestive evidence in favour of a role for the pulvinar in emotional processing involved in mental time travel. We hypothesised a dissociation between non-emotional and emotionally negative mental time travel in pulvinar-damaged individuals compared to a group of non-brain damaged controls.

Methods

Individuals with Pulvinar Damage

Based on prior work, and links with pulvinar-lesioned patients at Bangor University (e.g., Danziger, et al., 2004; Ward et al., 2007), several individuals were contacted who had (1) focal damage to the pulvinar region and (2) who previously agreed to be contacted for research participation. Four individuals were tested initially, but after one was excluded due to showing signs of dementia (severe memory impairments on some tasks), three individuals with unilateral pulvinar lesions were included in this study. Brain scans and clinical histories are from this prior work (see below), whereas all other data are from the present investigations.

Case SC

SC is a male who was 53 years old at the time of testing (with 10 years education). He incurred an intracerebral haemorrhage in the right thalamus affecting his pulvinar. He was employed as a mechanic before his stroke in 2007. He is a smoker and has hypertension. Previous neurological examination (by RR) demonstrated that he experienced some pins and needles down his left side, has dystonic posturing of the left arm and deficits in left finger dexterity. He also experienced a reduction of sensory perception on the left side of his body (including his face) and perceives some ordinary stimuli as being painful (allodynia). He functions independently in daily life. Neuropsychological assessment indicated high levels of anxiety and depression, but no impairments in memory or executive function (see Table 1).

A precise analysis of the location and amount of damage to the pulvinar beyond the horizontal sections provided in Figure 1 was unfeasible for SC, as many years had passed since his MRI scan and we were not able original files for reanalysis.

Case TN

TN is a right-handed female who was 70 years of age at testing (with 12 years education). She suffered a right thalamic haemorrhage (3.6 cm^2) eighteen years prior to testing including the latero-anterior portion of the pulvinar. TN experiences residual weakness and sensory loss in left upper and lower limbs, with some 'pins and needles', and requires a wheelchair for mobility. TN has been described previously (Danziger et al., 2004; Ward et al., 2007) in relation to visual perception and the precise lesion location has been fully described previously (Ward and colleagues, 2002; Arend et al., 2008). Standardised neuropsychological assessment showed no evidence of psychological or neuropsychological impairment (see Table 1).

In Arend et al (2008), lesion reconstruction was performed using the Atlas of the Human Thalamus (Morel et al., 1997) with saggital sections. The thalamus was scaled to the dimensions in the saggital atlas sections. As can be observed in the reconstruction in Figure 2 (Arend et al., 2008), the lesion principally affected the anterior pulvinar. The lesion extends ventrally below the anterior commissure (AC) - posterior commissure (PC) line, close to the lateral retinotopic area. The MRI scan also indicated a probable lesion in the 14 mm slice that extends to the ventral pulvinar. It was unfeasible to estimate the percentage of pulvinar damage from this anatomical reconstruction.

Case NB

NB is a male who was 70 years old at testing (with 12 years education). He suffered an ischemic stroke nine years before testing leading to a left pulvinar lesion, confirmed by MRI. Initially, within the acute phase of recovery, NB experienced slurred speech and right-sided neglect. However, these deficits reduced leaving no residual neurological symptoms. NB performed within the normal range on measures of neuropsychological functioning and depression with borderline levels of anxiety (see Table 1).

The anatomical T1-weighted MRI of patient NB was accessible and subject to reanalysis by CB, a neuropsychologist with expertise in lesion analysis and reconstruction. The MRI was spatially normalized with SPM12 (Wellcome Trust Centre for Neuroimaging, London, UK) to the MNI space, preserving its original resolution of .667 x .667 x .7 mm. The lesions were visually detected as hypointense voxels in the left thalamus. To localise the lesions, the normalised MRI of the patient was resized to the dimension of an atlas of the thalamic nuclei in MNI space (Najdenovska et al., 2018) and overlayed on the atlas (see Figure 2) using the software ITK-SNAP version 4.2 (Yushkevich et al., 2016). The overlay showed that the lesions affected 13.58% of the left medio-dorsal nucleus (273 mm3, Supplementary Information, Figure 2A) and 30.96% of the left Central-Lateral/Lateral-Posterior-Medial Pulvinar (Supplementary Information, 453 mm3, Figure 2B).

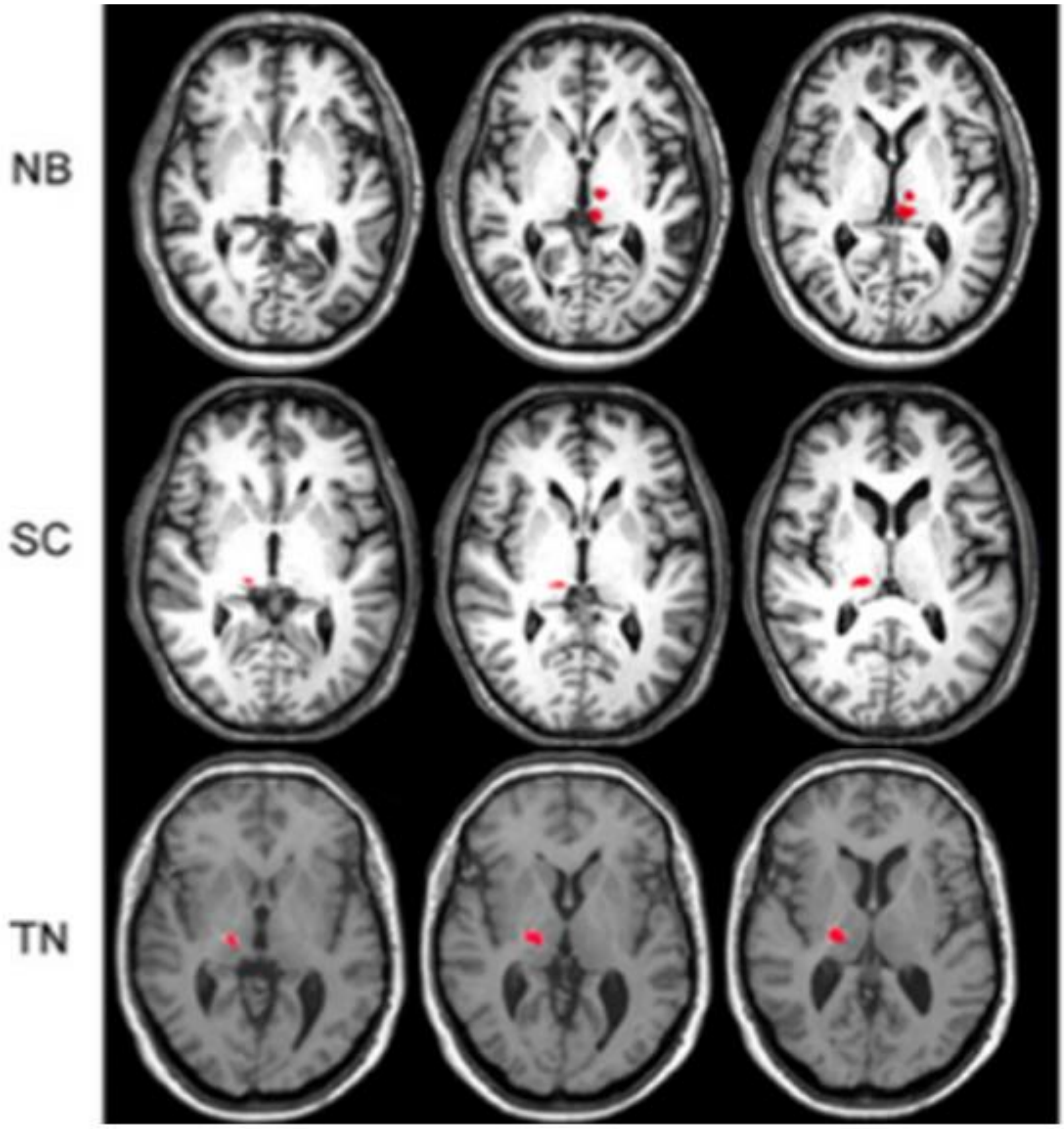

Figure 1: T1-weighted Structural Magnetic Resonance Imaging scans of three pulvinar-lesioned individuals (horizontal sections). Red dots for illustration purposes to pinpoint pulvinar damage. Scans are reverse lateralised: Right side of each image = left side of brain.

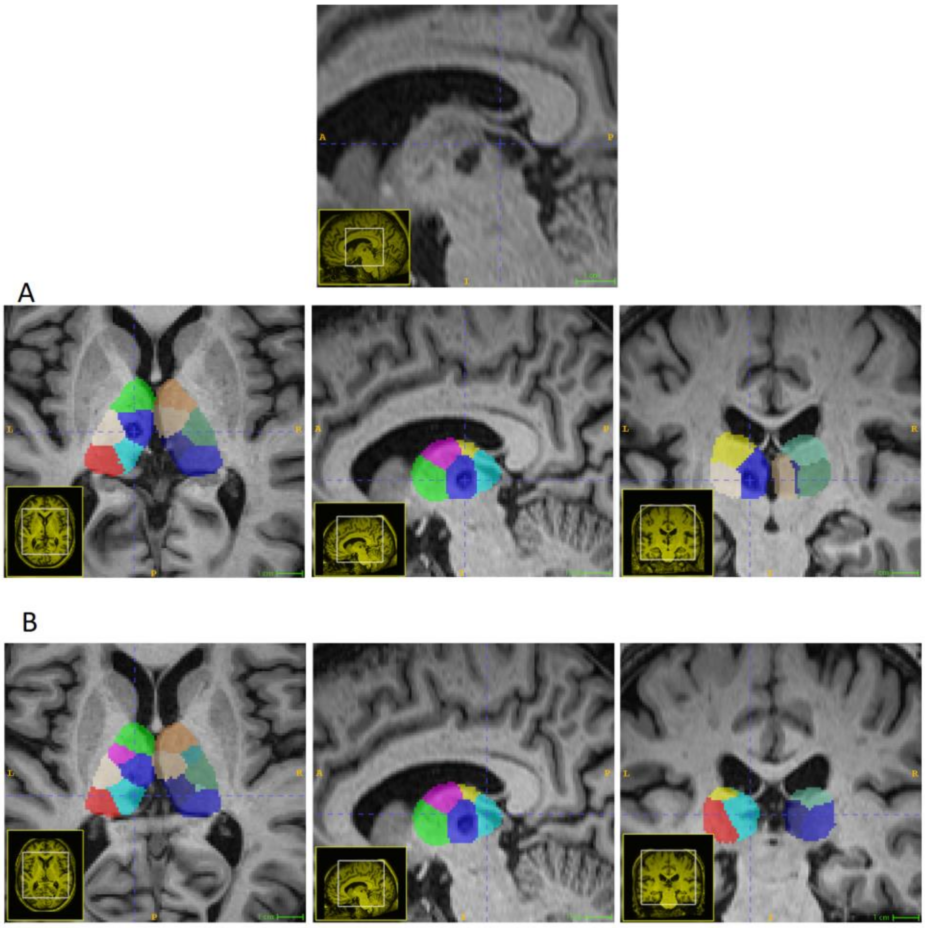

Figure 2: Anatomical mapping of Patient NB's lesion. Patient's anatomical MRI is overlayed on the digital atlas of thalamic nuclei by Najdenovska et al. (2018) in MNI space. **A.** One lesion affects the left medio-dorsal nucleus. **B.** The largest lesion affects the left Central-Lateral/Lateral-Posterior-Medial Pulvinar.

Table 1. Neuropsychological Assessment of Individuals with Pulvinar Damage

Test	**SC**	**TN**	**NB**
Hospital Anxiety and Depression Scale (HADS)			
Anxiety (HADS) [a]	17*	4	8
Depression (HADS) [a]	16*	3	6
Weschler Memory Scale (WMS)			
Logical Memory 1	10	16	12
Logical Memory 2	8	15	13
Delis-Kaplan Executive Function Scale (D-KEFS)			
Letter Fluency	7	17	9
Category Fluency	12	15	10
Category Switching (Total correct responses)	6	18	11
Category Switching (Total switching accuracy)	7	17	11
Trails (visual scanning)	8	8	11
Trails (number sequencing)	12	14	13
Trails (letter sequencing)	11	13	14
Trails (Number-Letter sequencing)	8	13	15
Trails (motor speed)	12	12	13
Colour-Word Interference Task (colour naming)	5	9	12
Colour-Word Interference Task (word reading)	6	13	11
Colour-Word Interference Task (inhibition)	7	12	10
Colour-Word Interference Task (Inhibition/Switching)	9	9	11

Note: Except where indicated ([a]), all scores are age-corrected standard scores based on norms in the appropriate test manual; D-KEFS tests, Mean = 10, *SD* =3; WMS tests, Mean =10, *SD*=3. HADS; Normal = 0-7; Borderline = 8-10; Clinical levels > 11. * indicates pathological levels of depression/anxiety.

Control Group Control participants were recruited from the local community in York and from the database of healthy controls at Bangor University (Department of Psychology). We targeted recruitment around participants aged 55-75 years of age (*M* = 65.10) to reflect the ages of the three cases. This resulted in ten well-matched individuals (Range = 11-21 years in formal education, 6 females), with none reporting any history of neurological disturbance (e.g., epilepsy, stroke).

General Procedure

All experimental measures were administered to pulvinar-lesioned individuals and controls. There were three measures presented in the following order; *Autobiographical Cue Word Task*; *Autobiographical Future Fluency Task*; and a *Future Thinking Frequency Questionnaire*. Pulvinar-lesioned individuals were given the option of being tested at home, of which one (NB) accepted this offer. All other participants were tested in a quiet room within a University. All measures lasted two sessions of approximately two hours. Neuropsychological measures were only administered to pulvinar-lesioned individuals to assess general functioning. All testing was conducted by the first author. All participants gave written informed consent, and the study was approved by an NHS Ethics Committee (16/EM/0218) and locally at Bangor University and York St. John University. No part of the study design, analysis or procedures were pre-registered prior to commencement of the research.

Task 1: Autobiographical Cue Word Task

To assess emotional and non-emotional event construction, a task designed by Williams and colleagues (1996) was administered using cue phrases to elicit negative, neutral and positive events. For each trial, cue words were embedded within sentences (e.g., “try to remember an occasion in the past when you felt [proud]” or “try to picture a situation in the future where you will feel [fear]”) and presented verbally. Participants were instructed to generate a *specific* event associated with each cue word, and based on ethical considerations, could opt-out if they felt describing an event would generate unpleasant emotional reactions (such as describing the death of a relative). Participants were provided with a maximum of one general prompt per cue (i.e., ‘can you imagine any specific details about that event’) if their description was over-general (e.g., ‘I will be afraid in the future”).

Two lists of cue words (each consisting of six negative, six positive and six neutral cues) were devised based upon the 36 cue phrases used by Williams and colleagues. The exception was that a subset of basic emotions (fear, sadness, joy, anger, taken from the Affective Story Recall task (Turnbull et al., 2005) were substituted for four other cues in each list., on the basis that they have been used to successfully elicit well-established basic emotions in neurological patients. Each list was used to either elicit past or future events (18 past, 18 future, list assignment counterbalanced), and the temporal direction condition (past, future) was blocked with the order counterbalanced (half completed past condition first). All cue phrases (positive, negative and neutral) were administered in a random order within each block.

After each audio-recorded event description, participants were asked to complete a series of 5-point rating scales measuring their subjective experience (in the following fixed order) assessing a variety of appraisals, cognitive feelings and somatic reactions to remembering and imagining the events (see Table 2). The scales measuring difficulty, p/reliving and physical reactions were adapted from the Pretraumatic Stress Reactions Checklist (e.g., Berntsen & Rubin, 2015) to assess cognitive and somatic aspects of emotional thoughts. The emotional valence and intensity of past/future events varied in terms of when the event was brought to mind *and* the time of the event itself, thus distinguishing mental simulation (p/reliving) and event-based emotions (see Barsics, Van der Linden & D’Argembeau, 2016).

This entire task (and its components) was unspeeded with one limitation that participants were allowed three minutes per event description. Finally, to verify understanding of the cue words participants were asked to provide a short definition or synonym of each cue word used in the task. This task was administered after all other experimental measures were administered (Tasks 1, 2 and 3), to confirm understanding of words used in the Autobiographical cue word task (as the meaning of cue words was important to convey the condition, i.e., negative valence). The results of this procedure showed that all participants understood the meanings of all cue words used.

Table 2

Rating scales used in the Autobiographical Cue Word Task

Measure	**Item**	**Scale**
Difficulty	It was difficult to imagine that event	*Do not agree* 1 2 3 4 5 *Completely agree*
Emotional P/reliving	Feeling as if a possible emotional experience in the future already were happening (as if you were pre-living it)	*Do not agree* 1 2 3 4 5 *Completely agree*
Physical reactions	Having physical reactions (e.g., heart pounding, trouble breathing, sweating) when you imagined the possible stressful experience in the future?	*Do not agree* 1 2 3 4 5 *Completely agree*
Event-related Emotional valence	The emotions I will have in the episode in the future will be…?	*negative 1 2 3 4 5 positive*
P/reliving-related Emotional valence	The emotions I have when I imagine the episode are…?	*negative 1 2 3 4 5 positive*
Event-related Emotional Intensity	The emotions I will have when I experience the event in the future will be…?	*negative 1 2 3 4 5 positive*
P/reliving-related Emotional Intensity	The emotions I have when I imagine the episode are…?	*negative 1 2 3 4 5 positive*

Note: Only the future versions of the Items are presented. Wording was changed for past-related questions to indicate past temporality. *Difficulty, Emotional P/reliving and Physical reactions* were taken from the Pretraumatic Stress Reactions Checklist (e.g., Berntsen & Rubin, 2015), and the emotional scales were adapted from D'Argembeau and colleagues (see Barsics, Van der Linden & D'Argembeau, 2016).

Event Coding for Episodic Details. To assess the ability of participants to generate episodically detailed past and future emotional events, we applied the Internal Detail / External Detail coding scheme from the Autobiographical Interview (Levine et al., 2002) that has been effectively used in mental time travel research to distinguish specific groups (e.g., traumatic brain injury, older adults) and controls (Addis et a., 2008; Cole et al., 2013; Rasmussen & Berntsen, 2014). It allows researchers to measure the level of episodic detail in event narratives, based on a manualised coding scheme (see Levine et al., 2002 for details). In line with this scheme, each event was decomposed into details. Each detail was then coded as either *internal* (i.e., concerning episodic details of the main event described) or *external* (i.e., semantic information and any other type of non-episodic detail). For analyses provided here, only internal and external details were extracted for analysis (rather than sub-categories, e.g., perceptual details), to create averages across each condition per participant (positive, neutral and negative; past and future).

Internal and external details were then used to calculate an internal-to-total proportion (internal / [internal + external details]), which is a measure of how episodic participants' responses were across all six conditions. This measure is often used as it controls for verbal output, whilst providing a measure of "episodicity" (Cole et al., 2013). The first author coded all events except for those from 5 controls which were coded by postgraduate assistants trained on the coding scheme; the inter-rater reliability between SNC and other coders, based on Intraclass correlation, was 0.96 (indicating excellent consistency, Koo & Li, 2006). Additionally, a trained coder blind to the hypotheses of the study (and whether the participant was brain damaged or not) coded a random subset of (35) events, resulting in an intra-class correlation of .80 showing good inter-rater consistency of coding (Koo & Li, 2006).

Task 2: Autobiographical Future Fluency Task

In this task, devised by MacLeod, Rose and Williams (1993), participants are asked to list as many things that they *are/are not* looking forward to in the next week/six month's time/twelve month's time. At the start of the task, participants were made aware that they will be given one minute for each of the six items (3 positive, 3 negative), presented randomly. They were also informed that events could be important or trivial, and asked to avoid repeating events across time period conditions. This task measures the accessibility of positive and negative future events. Answers were audio recorded and tallied after testing. A score for each emotion condition was calculated by averaging the tally across the three time periods.

Task 3: Future Thinking Frequency Questionnaire

To assess the frequency with which participants experience negative, neutral and positive future events, a questionnaire was devised with one item for each (e.g., "In the past week, I have wilfully imagined an emotionally positive future event"). Participants were asked to estimate how often they voluntarily imagined these different types of events on a 1-5 scale (1=never, 5=often). Items were presented in a random order for each participant.

Data Analysis Plan

Findings from all three tasks are presented, in a case series analysis, in which each pulvinar-damaged case is compared to the mean scores of the control group, independently. In general, scores from pulvinar-damaged individuals were converted to z-scores to provide a measure of standardised difference from the control mean (zero indicating no difference and negative values indicating lower performance). To determine whether pulvinar-lesioned individuals significantly differed from controls on each task we used Crawford and colleagues' (2010) single case t-test ("singlism" analysis program[1]) which compares single

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[1] Relevant computer programs for analysing case-control designs from Crawford and colleagues can be accessed free from this website: https://homepages.abdn.ac.uk/j.crawford/pages/dept/SingleCaseMethodsComputerPrograms.HTM

scores to those of a small control group. The possible effect of age was checked using the Bayesian single case test controlling for covariates (Crawford et al., 2011). We opted to use these specific programs because Z scores are known to overestimate deficits, resulting in Type 1 Errors (Crawford et al., 2010). *Z* Scores are presented for descriptive purposes.

Results

The central idea to the following analyses is that if the pulvinar plays a role in constructing mental representations of negative events, past or future, then individuals with pulvinar damage should have a deficit in producing, accessing and subjectively ‘p/re-experiencing’ emotionally-negative past and future scenes.

Autobiographical Cue Word Task

This task resulted in two types of data that were analysed here: Verbal descriptions of past and future events (which were analysed via averaged coded event detail) and ratings of subjective experience (analysed via averaged rating scales). Individuals with pulvinar damage were able to produce, on average, 5.0 past and 5.6 future events (controls produced, on average, 5.4 past and 5.0 future events) showing that all participants successfully followed instructions and produced sufficient data for analysis.

Coded event detail. Scores and Control Means for Specificity across all conditions are presented in Table 3. Due to multiple comparisons across six conditions (negative, neutral and positive past, same for future), the cut-off value for significance was corrected to $p <$ 0.008 (0.05 / 6 conditions). According to this criterion, no deficits were found across all conditions and pulvinar-lesioned individuals[2]. All t and p values for the single case analysis can be found in the Supplementary Information, including for Internal (episodic) and External (non-episodic) detail, which also resulted in no significant differences. Visual examination of Z Scores (see Table 3) confirmed the similarity of pulvinar-lesioned individuals with controls across all conditions; case TN had no Z scores below zero, NB had 2/6 scores below zero (but within 2 SDs of the mean) and case SC similarly had only 2/6 scores below zero. In sum, there was no evidence indicating that pulvinar-lesioned patients

[2] Only one condition – past positive – for case SC met the less conservative standard [p <.05] criterion for significance, but the direction of the effect showed that SC produced *more* specific events, rather than demonstrating a deficit.

were impaired in the production of episodic details when remembering or imagining negative events, or otherwise. There were also no differences in the extent to which pulvinar-lesioned and control participants generated external (non-episodic) details (see Supplementary Information).

Further, age did not correlate with the average specificity of past and future thinking in controls (r = .36, p = .31), thus it is unlikely that age was diminishing any genuine single case deficits. Nevertheless, considering strong theoretical links between age and episodic memory (Addis et al., 2008), we carried out analyses comparing each patient to the control group on event specificity controlling for age (Crawford et al., 2011). This did not lead to any significant deficits (all ps > .008).

Table 3 Average Episodic Specificity of Individuals with Pulvinar Damage and Controls as a Function of Condition

	Past			Future		
	Negative	Neutral	Positive	Negative	Neutral	Positive
SC	.80 (1.41)	.48 (-0.09)	.89 (2.53)	.26 (-0.06)	.52 (0.95)	.49 (1.43)
TN	.59 (0.39)	.61 (0.50)	.68 (1.42)	.32 (0.31)	.42 (0.48)	.46 (1.21)
NB	.71 (0.97)	.44 (-0.27)	.45 (0.21)	.25 (-0.13)	.61 (1.38)	.40 (0.79)
HC (SD)	.51 [.21]	.50 [.22]	.41 [.19]	.27 [.16]	.32 [.21]	.29 [.14]

Note: Scores are presented for pulvinar-lesioned individuals, and means for the Controls. For pulvinar-lesioned individuals, Z-scores are presented in parentheses, whereas for Healthy Controls (HC), standard deviations are presented in squared parentheses.

Subjective ratings. Initially, we examined several variables to assess the participants' ability to carry out the tasks and to serve as a manipulation check. Ratings of difficulty (to remember and imagine events) indicated that, on average, cases and controls found it relatively easy to generate events (all mean ratings across conditions <3, on a 1-5 scale of difficulty, no case significantly differed from controls, see Supplementary Information). Emotional valence ratings indicated that all cases and controls generated appropriate events for each condition (i.e., negative condition = negative subjective ratings): For *P/reliving-related Emotional valence,* events in the negative condition were remembered and imagined negatively (mean ratings < 3); and positive ratings (mean ratings > 3) in the positive condition. Neutral words led to somewhat positive events, in line with the positivity bias phenomenon (Cole et al., 2016; Marsh et al., 2019). A similar pattern was found for *Event-related Emotional valence* (see Figure 2). Single case statistics (see Supplementary Information) demonstrated that no case significantly differed from controls and all participants understood the instructions and produced appropriate events. Controlling for age did not affect any of these results (*p*s > .008).

Next, we compared cases and controls on sense of *P/reliving-related Emotional Intensity and Event-related Emotional Intensity* (Figure 3) *as well as Emotional P/reliving* and *physical reactions* (Figure 4) (see Supplementary Information for Means, Z Scores and Single-case t-tests). Single-case t-tests demonstrated that no case differed from controls in any condition (*p*s > .008,. SC experienced lower levels across several measures in the positive memory condition (*Zs* = [-2, -3] on *Emotional P/reliving*, *Event-related Emotional valence, P/reliving-related Emotional Intensity* and *Event-related Emotional Intensity*), representing the largest deviation from the controls amongst the pulvinar-lesioned individuals, but none were significantly different to controls using the single-case t-test. These low scores likely reflect SC's low mood (see Table 1). As above, age was not correlated with performance on any of the subjective measures for the control group (*r*s = 0.00 – 0.42, *p*s = 0.25 - 1.00), and analyses controlling for age did not uncover any significant deficits in subjective measures (*p*s > .02).

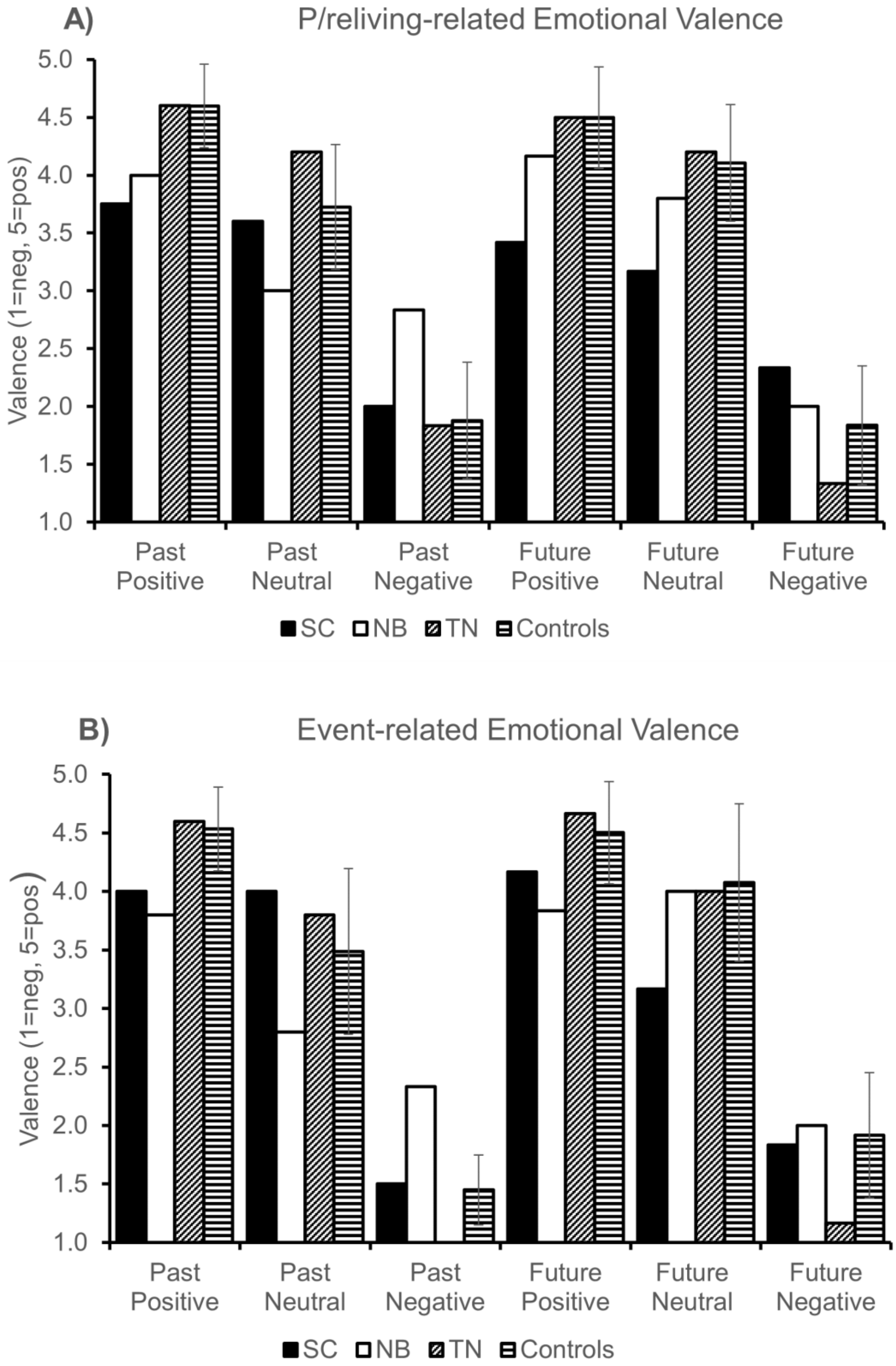
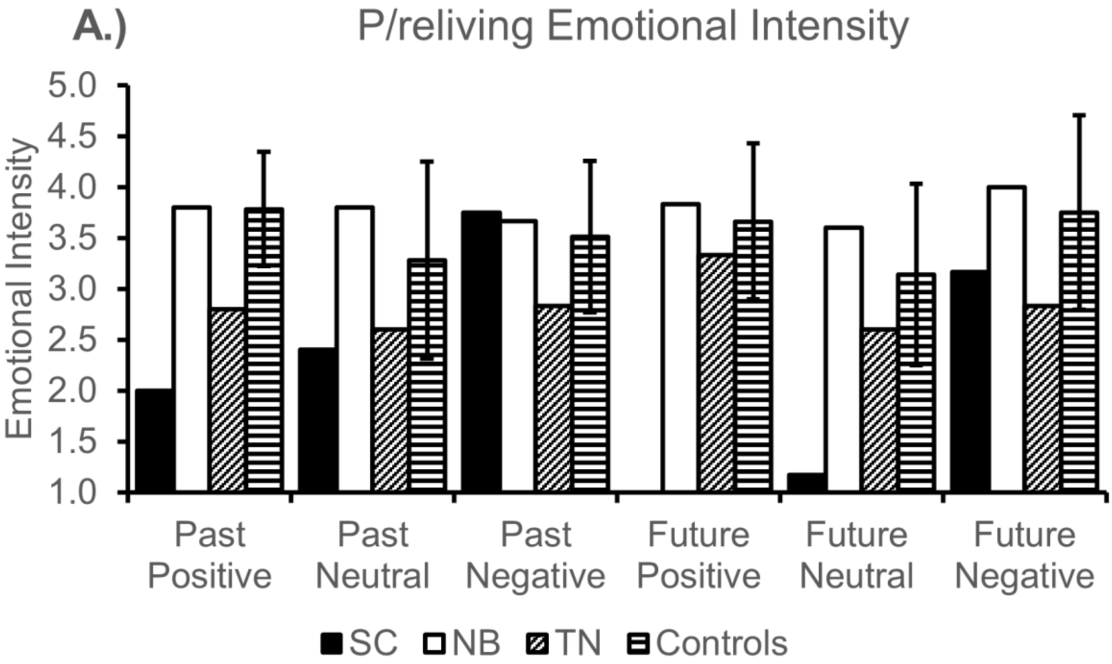


Figure 2 Mean Scores (and SDs [error bars]) for Subjective Ratings of (A) *p/reliving-related emotional valence* and (B) *event-related emotional valence* for Individuals with Pulvinar Damage and Controls.



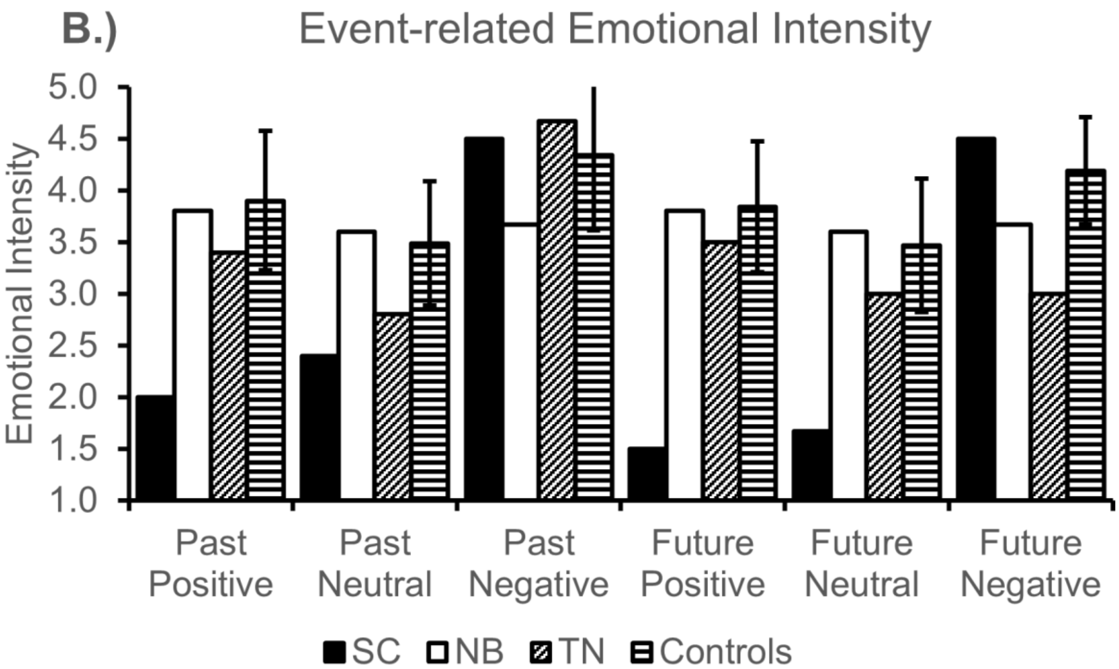


Figure 3 Mean Scores (and SDs [error bars]) for Subjective Ratings of (A) *p/reliving-related emotional intensity* and (B) *event-related emotional intensity* for Individuals with Pulvinar Damage and Controls.

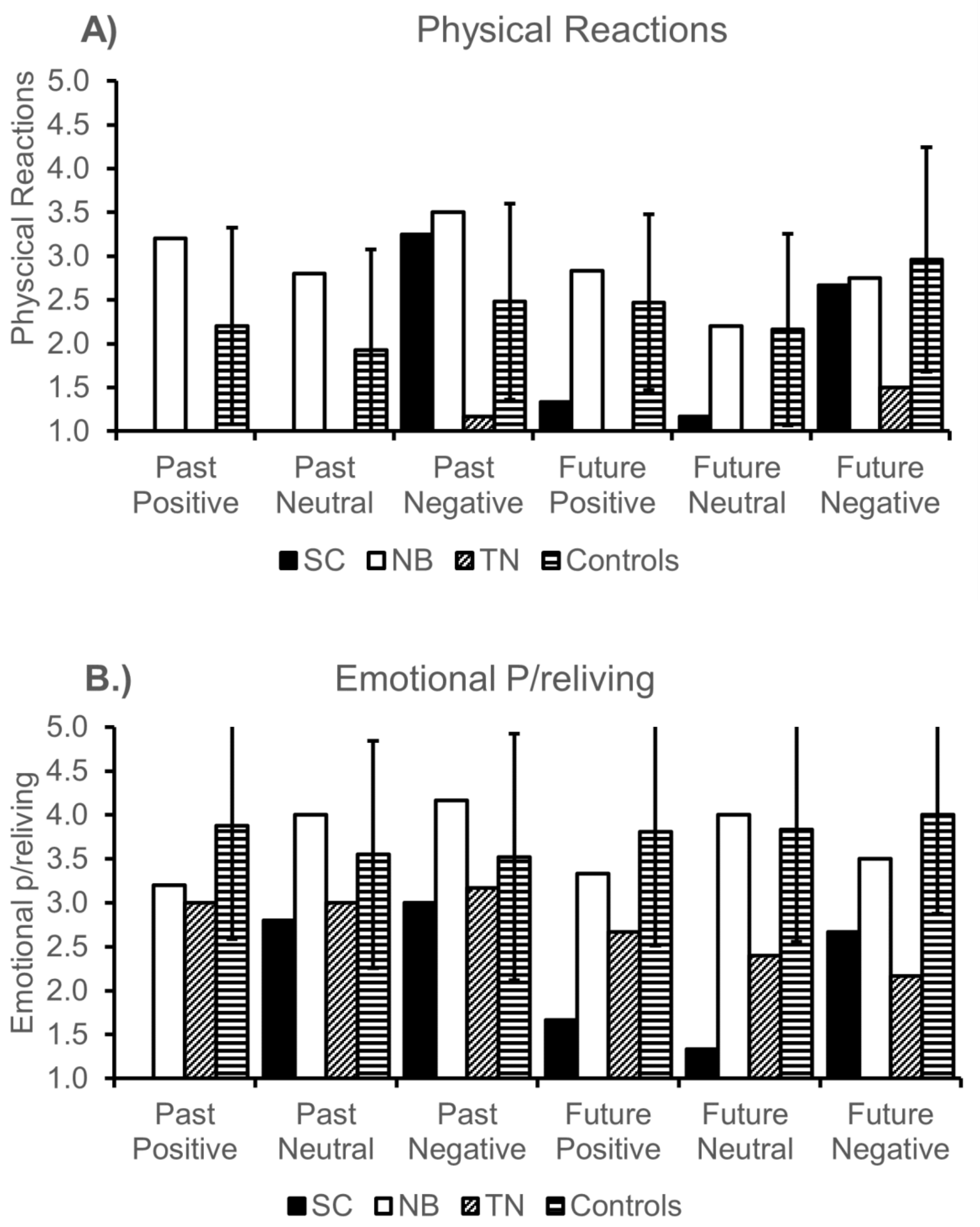


Figure 4 Mean Scores (and SDs [error bars]) for Subjective Ratings of (A) *physical reactions* and (B) *sense of emotional p/reliving* for Individuals with Pulvinar Damage and Controls.

Autobiographical Future Fluency Task

For this task, we recorded how many discrete events participants were able to produce based on six cues. Except for one missing data point due to a technical error (6 months future negative), all participants completed all conditions. In general, cases and controls were able to produce several events they were and were not looking forward to in each condition within one minute. Additionally, all participants were able to produce more positive future happenings than negative ones, replicating a well-documented positivity bias that is typically reported with younger participants (e.g., Cole et al., 2016; Shrikanth et al., 2018). As can be observed in Table 6, pulvinar-lesioned individuals generally produced fewer events than controls (reflected in negative *Z* scores). Nevertheless, single case *t*-test statistics collapsed across temporal distances (due to no a priori hypotheses regarding this variable) revealed that none of the pulvinar-lesioned individuals scored significantly less than controls (*p*s > .006, see Supplementary Information). The significance level was set at .025 to control for multiple comparisons (.05/2[positive, negative]). No deficits were found when controlling for age (*p*s ≥ .37), however, SCs score in the positive condition trended toward significance ($p = .04$).

Table 6: Fluency scores for Pulvinar-Damaged Individuals and Controls by Condition

	Positive	*Negative*
SC	0.33 (-1.85)	0.33 (-0.99)
TN	3.00 (-0.72)	1.00 (-0.71)
NB	2.67 (-0.86)	0.67 (-0.85)
HC (SD)	4.70 [2.36]	2.73 [2.42]

Note: Scores are presented for pulvinar-lesioned individuals, and means for the Controls. For pulvinar-lesioned individuals, Z-scores are presented in parentheses, whereas for Healthy Controls (HC), standard deviations are presented in squared parentheses.

Future Thinking Frequency Questionnaire

On a scale from *never* (1) to *often* (5), participants were asked to estimate how often they wilfully imagined (positive, neutral and negative) future events through the preceding week. As with previous tasks, participants estimated imagining more positive than negative future events. Generally, *Z* Scores indicated lower frequencies for pulvinar-lesioned individuals than controls. However, consistent with other tasks, no cases had scores significantly lower than that of the healthy control group (ps > .02, see Supplementary Information, based on .05 / 3 condition correction for multiple comparisons). No deficits were found when controlling for age (ps ≥ .12).

Table 7: Subjective Estimates of Weekly Frequency of Future Thinking for Individuals with Pulvinar Damage and Controls by Condition

	Future		
	Negative	Neutral	Positive
SC	1 (-1.19)	1 (-1.85)	2 (-1.36)
TN	2 (-0.44)	1 (-1.85)	2 (-1.36)
NB	1 (-1.19)	1 (-1.85)	4 (0.34)
HC (SD)	2.60 [1.35]	3.50 [1.35]	3.60 [1.17]

Note: Scores are presented for pulvinar-lesioned individuals, and means for the Controls. For pulvinar-lesioned individuals, Z-scores are presented in parentheses, whereas for Healthy Controls (HC), standard deviations are presented in squared parentheses.

Discussion

The current case-control study, involving three individuals with unilateral damage to areas within the pulvinar, aimed to examine the role of the pulvinar in emotional mental time travel processing. Based on prior fMRI (Szpunar et al., 2015; but see Devitt et al. 2020), neurobiological (Romanski et al., 1997) and neuropsychological studies (e.g., Rafal et al., 2015;; Ward et al., 2007), it was hypothesised that the types of focal pulvinar damage observed in these patients might impair negative emotional processing in mental time travel. An investigation of emotional past and future thinking was conducted using coded verbal responses, phenomenological experience, information availability, and a measure of everyday cognition, offering a unique test of this hypothesis.

Pulvinar-lesioned adults, with no deficits in other cognitive domains, did not differ significantly from non-brain damaged controls. This initial evidence then is not suggestive of a simulation-related emotional processing deficit, on any measure of emotional mental time travel in patients with unilateral damage to areas of the pulvinar. This within-normal-range functioning was found in generating emotional event detail *and* subjective experience of event-related emotion.

Neuropsychological evidence differs from neuroimaging evidence in its potential to support causal inferences about the role of a specific brain region in a particular cognitive function. Based on this idea of modularity (Caramazza, 1984), it was expected that a component of emotional mental time travel (i.e., the ability to process the emotion associated with a memory or future event) could be mediated by the pulvinar. Although the lesions to the pulvinar in these patients were not complete and bilateral, these lesions (and others like them, e.g., Arend et al., 2008), were able to cause large, significant deficits in emotional processing of visual stimuli (see Danziger et al., 2004; Ward et al., 2007). Thus, although we cannot determine the effect of total bilateral lesions of the pulvinar, we reason that specific lesions that cause emotional processing deficits in the visual system, do not translate to deficits in emotional mental time travel. An interesting extension of this work would be to examine neuropsychological patients for whom emotional mental time travel is impaired in the absence of an emotional deficit in the visual domain, such as patients with damage to the prefrontal cortex leading to confabulation (and unrealistically positive future thoughts) or reward processing deficits (Ciaramelli et al., 2021; Cole et al., 2014).

Such large effects might be expected in these pulvinar-lesioned individuals, as all have damage to this region, albeit unilaterally. In the present study, it is acknowledged that one case (SC) had pathologies extending beyond brain damage which may affect mental time travel (Williams et al., 1996): SC had exhibited high levels anxiety and depression and lower levels of positive MTT was observed across findings from the Autobiographical Past and Future Task and Fluency tasks (see Figures 3, 4 and Table 6). Nevertheless, across all cases, standardised neuropsychological measures indicated that these individuals were moderate-high functioning with no deficits in neuropsychological domains (e.g., memory, executive function). Moreover, pulvinar-lesioned individuals did not struggle to understand or carry out the tasks. However, none of these cases presented with a deficit in emotional processing when engaging in emotional mental time travel or mental time travel in general. Based on this evidence, one possible conclusion is that the pulvinar does not have a necessary role in mental time travel.

However, although we believe this conclusion is plausible, for the following reasons it may be premature. First, unlike studies of visual perception (e.g., Ward et al., 2005, 2007) which focussed on threat (e.g., with images of spiders, angry faces), we elicited past and future negative events associated with a variety of human emotions (sadness, fear, anger). Thus, we cannot test whether the pulvinar has a role in threat-based events that are internally-generated [3]. Second, it is also possible that the contralesional versus ipsilateral space comparison in visual perception studies allows for more sensitive analyses (see Ward et al., 2007). Mismatches between visual perception and memory literatures could be addressed in future.

Third, location and size of lesions are worthy of greater consideration (see Barron et al., 2015). Connectivity analyses (Guedj, & Vuilleumier, 2020) and a pulvinar lesion location-controlled neuropsychological study led to the finding that the medial pulvinar has a role in emotional processing (Ward et al., 2007). Of our cases, two had damage to lateral pulvinar sub-regions and, perhaps most importantly, none had bilateral lesions (see Figure 1). Only NB had evidence of *medial* pulvinar damage (see Figures 1 and 2). However, corresponding deficits in NB's visual emotional processing had not been previously examined, so it was unclear whether this lesion affected emotional processing. In short, although the strength of the present study is in the focal nature of neurological damage, one possibility is that lesion size and/or location may not have been sufficient to cause deficits. It is also untested whether bilateral pulvinar damage would result in deficits we predicted in this study. Future investigations might examine emotional mental time travel in individuals with greater medial pulvinar damage, or pulvinar infarcts that extend bilaterally.

It should also be that as with other thalamic regions (e.g., mediodorsal nuclei) task deficits may only become apparent under specific task conditions such as multitasking, interference and delay (Pergola et al., 2011). Although the tasks included here were not selected for these task characteristics, the fact that no deficits were shown across different paradigmatic tasks used in mental time travel research gives some reassurance that gross task characteristics (e.g., speeded versus un-speeded tasks) may not cause deficits in people with unilateral pulvinar lesions when remembering or imagining. However, as this study

[3] We thank Ronnie Setton for bringing this point to our attention.

represents only initial work on the pulvinar-mental time travel link, future work will have to consider more deeply the task-specific neurocognitive aspects (e.g., dual tasking, effects of delay).[4]

Linking back to the fMRI findings, Szpunar et al. (2015) reported evidence for pulvinar involvement in negative emotional future simulations using personalised person-place-objects cues. These cues differed from those used in the present study, and might have elicited negative simulations that were more likely to evoke some sense of internally-generated threat and hence engage the pulvinar more than the cues used here. Alternatively, because the findings reported by Szpunar et al. (2015) were not corrected for multiple comparisons, the pulvinar effects they reported might not be reliable. Given that Devitt et al. (2020) did not report evidence of a link between negative emotional simulation and pulvinar activity using word cues more like those employed in the present study, it seems clear that further fMRI studies of emotional future simulations will be needed before any firm conclusions can be drawn.

Limitations

One important limitation is the use of non-validated measures. Specifically, the Future Thinking Frequency Questionnaire included items that had been devised for a relatively quick 'litmus test' of real-world thought frequency. In retrospect, other validated scales, with good reliability, would have been preferable, such as the Involuntary Autobiographical Memory Inventory (IAMI, Berntsen et al., 2015) which contains a frequency scale for involuntary and voluntary mental time travel. A further caveat to our findings from the Autobiographical Cue Word Task was that participants verbalised the events, which can dampen the emotionality of events (Andrade et al., 2023), and the fact that words were selected from William et al's

[4] We thank an anonymous reviewer for raising this issue.

(1998) seminal study, in which concreteness was not controlled across conditions (there were likely more concrete words in the neutral conditions).

Another limitation was broad range of ages in the control group, which were selected to bookend the ages of the pulvinar-damaged individuals. It is possible that age could have affected performance in these tasks (Addis et al., 2008). However, covariate analyses did not reveal a strong influence of age on the findings. Nevertheless, it is unknown whether findings would be different in younger populations, as older adults produce fewer episodic details, for past and future events (Addis et al., 2008) and experience less emotional expressivity in the context of emotional self-regulation (Gross et al., 1997) than do younger adults.

Conclusion

Together, the present findings from three individuals with focal pulvinar damage suggest, with some limitations, that these lesions do *not* lead to deficits in emotional mental time travel. The pulvinar has a recognised role in emotional processing (Guedj, & Vuilleumier, 2020; Ward et al., 2007), especially in relation to medial subregions. Nevertheless, we have shown that pulvinar damage – even when lesions affect medial pulvinar subregions (i.e., in NB) - does not appear to be critical for the processing of emotionally negative memories or negative future events.

This result provides much needed evidence to complement previous fMRI-based studies that had reported mixed evidence around a role for the pulvinar in imagined emotional scenarios. Specifically, our findings suggest that deficits in processing of negative visual stimuli in the perceptual domain due to pulvinar damage do not necessarily extend to the domain of imagined scenarios. While more work will be needed to develop a deeper understanding of the role of pulvinar and its subregions in the processing of emotionally salient stimuli, our findings are especially informative in the light of advice for cognitive neuropsychology to adopt a multiple methods approach, notably through case series (Nickels et al, 2011; Shallice, 2015; Vaidya, 2019). Further research using such an approach should increase our understanding of the neural substrates that support emotional past and future thinking.

Data availability statement

Due to agreements made in the informed consent process, the authors are unable to provide any publicly available data on the controls or patients reported in this study. Nevertheless, in line with Open Science good practice, details regarding methods are available on the open science framework (Cole, 2023, https://osf.io/zkds3/) and information about analyses can be shared upon request to the corresponding author.

Disclosure Statement

The authors confirm that there were no financial or non-financial competing interests in this project.

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Appendix A

Stimuli for Autobiographical Past and Future Cuing Task

Emotion of Cue Word	**List A**	**List B**
Positive	Joy	Joy
	Successful	Laughing
	Smile	Friendly
	Gift	Proud
	Relaxed	Helpful
	Compliment	Enthusiastic
Neutral	Garden	Shop
	Conversation	Library
	Late	Made/make
	Package	Walking
	Advice	Travelling
	look	Listening
Negative	Fear	Fear
	Sadness	Sadness
	Anger	Anger
	Danger	Argument
	Mistake	Failure
	Tears	nervous

Cue Words for positive, neutral and negative conditions (adapted from Williams et al., 1996 and Turnbull et al., 2005)

Appendix B

Representative Examples of Negative Past and Future Thinking from Pulvinar-lesioned Individuals and Controls

Temporality	**Past**		**Future**	
Cue word	tears	fear	fear	sad
Participant	Control 06	NB	Control 07	TN
	"Yes I can imagine a situation where it should of course these are all rather dreadful aren't they? No no well let's just say if somebody close to me, yes if somebody close to me were for example to be hit by a car or seriously injured and then took some days to die. I'd imagine that would be very tense and probably quite a lot of sobbing involved at some stage certainly. "	*"I was in Ireland on the Shannon and with scouts…and we were on boats, not kayaks. They had boats and like that and we pulled in at the base of the loch. And it had a rounded entrance to it and I was fending off one part of the boat and somebody yanked on the rope at the end of the boat and it went up and I went [in]. And I had a big thick jumper on which obviously filled with water and I was thrashing around I knew I had to get the jumper off because it was weighting me down."*	*"I think I'd be afraid if I got, if my cancer came back and I was ill again, I think I would be afraid, yeah. Er but that's been a long time, but yeah. It could come back I suppose, yeah ok [prompt] I'm just trying to think what would make me frightened, that would make me frightened."*	*"Yes I can think of times in the future when I will feel sad, mainly about what I've lost and what I can't do because of my disability now. And I will see something and think oh you know, I used to be able to do that or we can't do that anymore… I've got a lady coming next week to do my garden you know to clear it up. But that'll make me feel very sad because I want to do it. I want to do it because I've always have before and I like gardening."*

Note: Quotes have been shortened for formatting and clarity purposes. However, care was taken to only remove irrelevant details, editorialisations and non-linguistic utterances. In short, they are still in the participants' words, reflecting the intended meaning of each event.