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RESEARCH ARTICLE

Memory, stress, and the hippocampal hypothesis: Firefighters' recollections of the fireground

Janet Metcalfe[1] | Jason C. Brezler[2] | James McNamara[2] | Gabriel Maletta[1] | Matti Vuorre[1]

[1]Department of Psychology, Columbia University, New York, New York
[2]FDNY Mental Performance Initiative, New York, New York

Correspondence
Janet Metcalfe, Department of Psychology, Columbia University, New York, New York, 10027.
Email: jm348@columbia.edu

Abstract
Nadel, Jacobs, and colleagues have postulated that human memory under conditions of extremely high stress is "special." In particular, episodic memories are thought to be susceptible to impairment, and possibly fragmentation, attributable to hormonally based dysfunction occurring selectively in the hippocampal system. While memory for highly salient and self-relevant events should be better than the memory for less central events, an overall nonmonotonic decrease in spatio/temporal episodic memory as stress approaches traumatic levels is posited. Testing human memory at extremely high levels of stress, however, is difficult and reports are rare. Firefighting is the most stressful civilian occupation in our society. In the present study, we asked New York City firefighters to recall everything that they could upon returning from fires they had just fought. Communications during all fires were recorded, allowing verification of actual events. Our results confirmed that recall was, indeed, impaired with increasing stress. A nonmonotonic relation was observed consistent with the posited inverted u-shaped memory-stress function. Central details about emergency situations were better recalled than were more schematic events, but both kinds of events showed the memory decrement with high stress. There was no evidence of fragmentation. Self-relevant events were recalled nearly five times better than events that were not self-relevant. These results provide confirmation that memories encoded under conditions of extremely high stress are, indeed, special and are impaired in a manner that is consistent with the Nadel/Jacobs hippocampal hypothesis.

KEYWORDS
extreme stress, FDNY, human memory

1 | INTRODUCTION

Despite intense interest in understanding how extremely high stress impacts human memory, scientific investigation of this issue remains problematic. Indeed, there is scarcely any area of psychological research that is more fraught with difficulties. The problem at issue is understanding what happens and why: Are special mental processes engaged under conditions of traumatic stress? Is the impact of stress selective to particular kinds of memories—perhaps those involving conscious recollection—or are all memories affected equally? Is encoding different for salient, threatening, or emotional events? Is memory altered by personal involvement? Is there anything in the memory systems of humans that could account for the disturbing and fragmented phenomenology reported by people who have undergone traumatic stress? There have been a number of conjectures on these issues, of course. Nadel and Jacobs (1998) laid out their position in an article entitled: "Traumatic memory is special." As will be outlined below, they and their colleagues have proposed what we will here call the "hippocampal hypothesis" (Jacobs & Nadel, 1985; Nadel & Jacobs, 1996; Payne et al., 2006; Payne, Nadel, Allen, Thomas, & Jacobs, 2002), some predictions of which are investigated here. We will begin by contrasting this hypothesis with the default concerning the effects of traumatic stress on memory—the Freudian "repression" construct.

1.1 | Historical overview

On the assumption that traumatic memory is, in fact, special, the best-known specialized mechanism is repression. Repression is thought to be a defense mechanism that is recruited when an individual experiences stress at the level of trauma. Under these circumstances, the mind is conjectured to defensively push the memory down to a deep and inaccessible level (consciously and intentionally, in early writings by Freud, see Brueur & Freud, 1957, but unconsciously according to later accounts). Such a memory cannot be consciously accessed, but it can wreak havoc on the person's mental and emotional life, causing neuroses. Repression is not mere forgetting. Nor is it a lack of encoding. The trace, instead, is thought to be encoded in a detailed manner but actively pushed out of mind by a special process that may be engaged if the situation is sufficiently traumatic. The memory—which is susceptible to later recovery—is like an in-focus, high contrast photograph that is buried and protected. It is inaccessible so long as the defense mechanism pushing it down is working, but even though it is consciously inaccessible it is nevertheless thought to be perfectly intact, preserved in a tightly sealed container awaiting recovery. Only under special circumstances, such as therapy, can repressed memories be recovered.

The notion of repression, as well as the purported recovery of repressed memories has come under fire. First, insofar as there is forgetting over time (Murdock, 1974) which can apply even to important events, a person's inability to retrieve a memory does not mean that some special mechanism is pushing it out of consciousness. Second, hypermnesia is characteristic of normal memory: sometimes memories that are not retrievable at time t can be retrieved later at time t + x (Roediger & Wheeler, 1993). Thus, recovery of the so-called repressed memories is not the only pathway to bring a hitherto forgotten memory into consciousness. Third, people's judgments about the truth of their memories are fallible. They can believe that they are remembering events that never occurred. Examples of such false memories range from remembering that one was lost in a shopping mall as a child (Loftus, 1999), to remembering visitations from space aliens (McNally, 2012). Thus, good faith "recollections" of atypical events (as might occur for traumatic situations) does not guarantee that a traumatic event actually happened and was repressed. Fourth, people routinely smooth and rationalize fragmentary inconsistencies into a narratively coherent whole (Johnson, Foley, Suengas, & Raye, 1989). Thus, detailed narrative "recall" is no assurance of veridicality. In addition, in court cases in which recovered repressed memories have been evoked, secondary financial gain has sometimes been associated with the alleged recovered memories. These arguments undermine the notion of a special mechanism of repression. Indeed, the validity of the construct has risen to the level of a legal debate, and a number of courts have ruled that there is insufficient scientific evidence to support the construct for use in trials (see, Howe & Knott, 2015).

Outside of the courtroom, several investigators have studied whether there might be a psychological mechanism that is even remotely akin to repression. Bjork and colleagues have shown that people are sometimes able to selectively forget (e.g., Geiselman, Bjork, & Fishman, 1983), and they postulate an active process. Anderson and colleagues have shown that it is possible to selectively "not think" about particular items, and that this voluntary inhibition can make later recall less likely (Anderson & Green, 2001; c.f. Bulovitch, Roediger, Balota & Butler, 2006). While the idea of inhibitory processes in memory is gaining traction, it is not clear exactly how these postulated mechanisms relate to Freudian repression which specifically implicates stress as causal. Neither the selective forgetting mechanism nor the inhibition/repression mechanism has been proposed to be stress dependent. Indeed, some studies suggest that selective inhibition may be adaptive, and the failure to inhibit a marker of dysfunction (Eich, Razlighi, & Stern, 2017). Thus, the laboratory studies on selective forgetting and inhibition leave unresolved the question of whether there is a special memorial process associated with stress.

1.2 | Ethical problems with testing memory under extreme stress in humans

Although there is considerable interest in understanding the effects of extremely high stress on memory, stressing human subjects experimentally in the laboratory is problematic due to ethical considerations. Accordingly, the stressors that have been used are benign enough to pass the scrutiny of ethics panels. At the most extreme, people might have done the Trier task, in which they are told they have to give a public presentation that will be evaluated and which is touted as indicating their intelligence. Alternatively, they might have had the unpleasant, painful (but not life threatening) experience of submerging a hand in icy cold water for 3 min. More usually, they read or hear a story, read words (some of which may be taboo), watch a movie, or see slides that are thought to be emotional, disturbing, or stressful. The results from such studies are mixed (Mather, 2007). Some show enhanced memory (MacKay & Ahmetzanov, 2005; Mather & Nesmith, 2008); a few show impaired memory (Kuhlmann, Piel, & Wolf, 2005; Sharot & Phelps, 2004). But it could be debated whether any of these experiments provide insight into the question of what happens to memory under extremely high stress because in none of them were the levels of stress extremely high.

1.3 | The hippocampal hypothesis

Understanding of hippocampal function, which is at the center of an emerging story about the effects of extremely high stress on human memory, was spearheaded by O'Keefe and Nadel's (1978) breakthrough investigations and discoveries on the hippocampus as a spatial map—a system that they dubbed the "locale" system. The postulated interaction with stress was soon delineated in a seminal paper by Jacobs and Nadel

(1985). This article set the stage for a number of subsequent elaborations (Jacobs & Nadel, 1998; Metcalfe & Jacobs, 1996; 1998; 2000; Metcalfe & Mischel, 1999; Nadel & Jacobs, 1996, 1998; Payne et al., 2006). Basically, Jacobs and Nadel (1985) puzzled over clinical findings indicating that many adult patients described symptoms of childhood phobias re-emerging when they underwent extreme stressors in later life that typically had nothing to do with the distressing childhood event. These observations seemed nothing like uncovered repressed memories. They were often fragmentary and piecemeal. And, because of the lack of relation between the stressor and the original event, the re-emergent phobias could also not be attributed to spontaneous recovery of conditioned responses. Jacobs and Nadel (1985) presciently proposed an alternative possibility. They postulated that under extreme stress, the hippocampal (locale) system shuts down, leaving exposed conditioned learning from childhood (in a different, taxon, system) that had been suppressed when the hippocampal system was fully functioning. These two systems (taxon and locale) morphed into the "hot" and "cool" systems of Metcalfe and Jacobs (1996), (1998), (2000) and of Metcalfe and Mischel (1998). Over the ensuing decades, the notion that extremely high stress can have a selective impairing effect on the hippocampus and frontal lobes has gained currency, and considerable research has been directed at the purportedly inverted u-shaped function relating stress to memory and the hippocampal system. The argument, which is based almost exclusively on animal research, is that the complex, contextual, spatial, and temporal memory system does not behave in a "business-as-usual" manner when the stress level is extremely high.

The characterization of the hippocampal system was elaborated by the discovery of hippocampal time cells and the relational integration or binding postulate of Eichenbaum (2014, 2017). Taken together, these spatial/temporal/binding characteristics of the hippocampal system in animals seem to provide the scaffolding needed for an episodic memory system such as that which underpins human mental time travel, a mental capability that Tulving (2005) has referred to as autonoetic consciousness. Autonoetic consciousness is a type of awareness that involves recollection of personal contextually bound episodic memories, and mental time travel into both the past and future. The status of this kind of memory has been bolstered by extensive studies of patients with hippocampal damage who appear to lack such an ability while retaining other kinds of learning and memory abilities. The hippocampal hypothesis, then, proposes that under conditions of extremely high stress hippocampal functioning is impaired, and this results in a kind of acute amnesia specific to the episodic/autonoetic system. High- and low-affinity glucocorticoid receptors that give rise to a u-shaped stress response curve in hippocampus (Reul & DeKloet, 1985) substantiate this view. Such stress sensitive receptors, and their relation to hippocampal functioning, were pinned down in animal research. And, because of the ethical considerations in humans, most of the behavioral work concerning extreme stress that provides the basis for the hippocampal hypothesis, has been most rigorously and systematically investigated in animals.

The idea that under conditions of extremely high stress something special happens to memories is common to both the Freudian perspective and to the "hippocampal" hypothesis. But *what* happens is different. As noted earlier, by the Freudian view, the traumatic memory is pristine and replete but buried—awaiting recovery. By the hippocampal view, when the hippocampus becomes dysfunctional because of the influx of glucocorticoids associated with extremely high stress, episodic memories are likely to become fragmented (because of a binding failure) or may fail entirely to be recorded. If a spatially and temporally coherent representation is not encoded, then, by the encoding specificity principle (Tulving & Thomson, 1973), even the best retrieval cue will not provide access to it. Thus, there is no possibility of uncovering of a true coherent narrative episodic memory trace. The trace laid down under conditions of extreme stress is something like a photograph taken by an extremely jittery hand and projected onto overexposed film—blurry, fragmentary, and incomprehensible at the outset and subject to forgetting, overwriting, interference, and distortion induced by subsequent events.

Such loss of memory and fragmentation of what little memory persists is sometimes reflected in the recollections of traumatic events, of people experiencing PTSD. It is also reported by firefighters: "When we respond to a call, we always have to suppress our emotions and use our logic and our past experiences to perform our job. If they're very strong emotions, sometimes we never get to process them. So we wind up with fragments of an incident left over," Captain Jacques Roy, Firefighter of 25 years (Ushery, Stulberger, Wagner, Bott, & Manney, 2018).

If there is a direct mapping between the kind of locale (hippocampal/spatial/temporal/relational binding) system that has been extensively explored in rats and the human episodic memory system, then we may be justified in using the extensive animal literature to compensate for the non-existent human experimental literature on memory and trauma and to draw conclusions about the effect of stress on humans.

1.4 | A cautionary note concerning overreliance on animal research

Despite the appeal of generalizing to humans from the findings in the animal literature, such a generalization is particularly precarious in the present case because the kind of memory (explicit/episodic memory, which is associated with mental time travel and autonoetic consciousness) that is of central interest in understanding the effects of extreme stress in humans, may not even exist in animals. Indeed, the literature on true episodic memory in animals provides scant assurance that any animals other than humans have this capability (Templer & Hampton, 2013). There are some examples of behavior resembling episodic-like memory, but they are few and far between. Menzel (1999) showed that a lexigram-trained chimpanzee could point to the lexigram of a food hidden several hours ago and direct a human caretaker to its location. Schwartz (2009) showed that King, a circus gorilla, was able, after extensive training, to select a token representing a food that he had eaten several hours ago along with a token representing the keeper who had given him this food, but at only slightly above chance levels. Scrub jays (Clayton & Dickinson, 1998) have been able to discriminate different foods, their locations, and how long ago they were cached. These are the only examples of episodic-like memory in animals, and they are very minimal at best. Whether they are “real” episodic memory, as exhibited by people, is debatable. No such capabilities have been demonstrated in rodents—the animals on which most memory and stress-related experiments have been conducted. Furthermore, no studies have yet indicated that these episodic-like capabilities, in the animals that have them, break down under conditions of stress. It may be that stress impacts a delicate human system that is, at best, nascent in other animals, at worst, nonexistent. Thus, while taking the animal literature as a source of inspiration, it is essential that it be augmented by findings in human beings.

1.5 | Studies with glucocorticoids

The responsiveness of the hippocampus to the stress hormone cortisol has been implicated in memory effects, both positive and negative, in both humans and animals (De Quervain, Aerni, Schelling, & Roozendaal, 2009). At low levels of glucocorticoids, memory is enhanced, whereas inhibition appears to occur at very high levels. This result that has been ascribed to the consequences of high- and low-affinity glucocorticoid receptors in the hippocampus as has been illustrated in animal studies (Reul & DeKloet, 1985). The effects also appear to obtain in humans. Andreano and Cahill (2006), in a study using the cold-pressor stress task in which the hand is submerged in ice water, were the first to have shown a quadratic relation between memory performance and endogenous glucocorticoid release in response to the stressor in humans. A number of other studies have revealed a relation between cortisol and memory when glucocorticoids have been administered exogenously. Frequently, high doses result in impaired memory, while low doses have a facilitative effect or no effect (Het, Ramlow, & Wolf, 2005).

Furthermore, chronic corticosteroid therapy to control inflammation such as in the treatment of arthritis or autoimmune conditions is associated with decreased hippocampal volume and poor memory (Sapolsky, 1996). Similarly, high levels of glucocorticoids resultant because of chronic stress, such as occurs with jet lag, depression, and PTSD, are also associated with decreased hippocampal volume and memory (Brown et al., 2004; McEwen, 1999). It is interesting that feelings of stress are not consistently reported with the administration of drugs such as prednisone or hydrocortisone (although psychiatric symptoms are sometimes observed, Henns, Poon, de los Angeles, & Koran, 2011). The phenomenology of stress and the memorial effects of corticosteroids—while unquestionably related—appears to be complex.

1.6 | Quasi experimental studies of high stress in humans

The final approach that provides a window, albeit not a perfect window, on the effects of severe stress on human memory has involved tapping into extremely high stress experiences that people voluntarily engage in. For instance, Eich and Metcalfe (2009) contrasted explicit and implicit memory under stressful and unstressful conditions by testing participants either at the “bib parties” where runners obtained their numbers for the New York City or Boston marathons (the unstressful condition), or immediately after the runners had completed the 26.2 mile course (the stressful condition). They used the same tasks that—with amnesic hippocampal patients—had illustrated a selective impairment of the episodic/explicit memory system due to hippocampal lesions. The marathon study revealed a similar impairment for the runners in the stress condition, providing support for the hippocampal hypothesis of stress.

Yonelinas, Parks, Koen, Jorgenson, and Mendoza (2011) investigated the effect of the extremely high stress that occurred post encoding—during the retention interval—by interposing a parachute jump between encoding and retrieval. In this particular situation, stress *improved* the memory (of males but not females). At first blush, this finding might seem to go against the hippocampal hypothesis. However, the stressor did not occur during encoding or the retrieval of the to-be-remembered events. If high stress impairs the memory for events that occur while the stress is being experienced, then the events that had occurred during the jump may have been impacted (but were not tested) but those events that occurred prior to the jump may have been spared or might even have been subjected to less interference from the jump events—accounting for the pattern observed. Thompson, Williams, L'Esperance, and Cornelius (2001) had participants listen to word lists either while they were on the ground or while they were in the air, skydiving, and then recall, 8 min later, either while on the ground or in the air. They found impaired recall for encoding, retrieval, or both, in the air, and an interaction such that people who encoded, unstressed, on the ground and recalled, unstressed, on the ground revealed the best memory. Notably, these studies did not ask people to remember things that were relevant to the stressful event itself.

Several studies, conducted in a military context by Morgan and his colleagues, have done so, although. They investigated memory for events experienced during a mock prisoner of war training situation. Glucocorticoid levels during this training indicated that the participants were experiencing extreme, even traumatic, stress (Morgan et al., 2000). Many also experienced dissociative symptomology (Morgan et al., 2001). In one such study, Morgan et al. (2004) compared participants' recognition memory for a non-threatening interrogator as compared to a highly threatening interrogator. Interestingly, the high stress, threatening, interrogator was consistently remembered less well, suggesting a decrease in memory with increasing stress in real-life traumatic situations.

The research that will be detailed below is in the same tradition as those naturalistic studies outlined previously. We did not manipulate stress, experimentally. Instead, we asked our participants—New York City firefighters—for their memories of events they had recently experienced while voluntarily being exposed to what were sometimes extremely high levels of stress. We evaluated the degree of stress both by asking our subjects and an experienced firefighter not involved in the particular fire for stressfulness ratings, allowing us to begin to systematically relate the amount of stress experienced to memory.

1.7 | Stress on the fireground

Firefighting is widely acknowledged to be the single most stressful, non-military, occupation in our society. Firefighters are frequently exposed to risks such as structural collapse, structure fires, electrocutions, asphyxiation, burns, heat stress, physical injuries, noise exposure, hazardous materials, contaminants, and medical emergencies, such as are unknown in other occupations (Hard et al., 2018). Firefighters take on, and train for, such risks in the service of the community. Compounding factors include the fact that firefighters routinely work 10 or 11, 24 hr shifts per month and take on extra 24 hr shifts as needed. Sleep while on shift is frequently interrupted by emergencies. A firefighter may be sedentary or even sleeping and, within 2 min, has to be fully geared up (with gear weighing well in excess of 50 pounds), on the truck, and ready for a dire emergency with almost no information about what will be encountered next. As might be expected, there is a high rate of hypertension (Choi, Schnall & Dobson, 2016) and of PTSD (Kristin, Klimley, Van Hassel, & Stripling, 2018) among firefighters. Such reactions are buffered by protective factors that include a strong sense of belongingness and social support from co-workers and family. Adverse reactions are also modulated by intense training, high levels of resilience, and a light hearted, supportive sense of humor among fire fighters. Following September 11, there have been several programs designed to address the human factors involved in firefighting, including the FDNY Mental Performance Initiative. The present study was conducted under the auspices of this initiative. To the best of our knowledge, it is the first study to investigate episodic memory for fires, among firefighters who were actively engaged in the incidents.

2 | METHOD

2.1 | Participants

The participants were 54 New York City firefighters. Eighteen participants provided reports from more than one incident (there were 21 incidents in total), for a total of 92 incident-person reports. The mean age was 36 years, and all participants were male. This research was approved by the Uniformed Firefighters Association, the Uniformed Fire Officers Association, and the Columbia University IRB under protocol AAAR7542. Participation was entirely voluntary.

2.2 | Procedure

In this study, we investigated the recall of incidents in which firefighters had very recently participated. Although firefighters often respond to calls that are not emergencies, because we were interested in memory under conditions of stress, only incidents that were fires were included in our study. The stress level at all fires is high. Upon returning to the firehouse, fire fighters provided their written free recall of the fire that they had recently fought. Because of the voluntary nature of the study, the exact amount of time between the end of the fire and recall was provided could vary. Typically, although, the recall was written down within 5 hr of returning to the firehouse.

One difficulty that occurs in nearly all cases of people's recall of naturalistic incidents is that it is impossible to know ground truth—there is usually no objective recording of what happened. This poses an obvious problem for evaluating the accuracy of recall. We did not have this problem in the present study. Firefighters co-ordinate their actions at a fire by communicating with each other using Handy Talkies. All transmissions made on the Handy Talkies are recorded and were available to our team after each of the fires. These provided a detailed recording of all communications during the fire and hence of what happened. Scoring of the protocols was conducted by two officers at the FDNY (with consent of the participants and of the Firefighters' Union). The Columbia University team members were blind to the identity of the participants as well as to the location and public characteristics of the fires. They were provided only with de-identified numerical data spreadsheets. Participants were simply asked to recall everything that they could about the fire from which they had just returned. They were given as much time as they needed to do so.

After recalling, the participants answered several standard questions. Most importantly, they were asked for their rating of the stressfulness of the fire, on a scale of 1–5, where 1 was "little to no stress" and 5 was "severe amount of stress." They were asked how many years they had been a firefighter. They were asked to record the time and date of the recall session, to allow calculation of the retention interval. Forty-three participants also provided a time estimation of how long the fire had lasted. The coders who scored the recall and who listened to the Handy Talkie recordings (and who were both experienced firefighters) independently rated the severity of each fire.

2.3 | Scoring

The Handy Talkie protocols were categorized into two kinds of items: Schematic and Emergency. Concerning the former, just as in other events that recur (such as going to a restaurant) in which there are a set of events that are standard for that event (the hostess seats the person at a table; the diner looks at a menu; the diner orders; the waiter brings the food, etc.) so, too, are there standard events that occur in every fire. These **Schematic items** occurred in nearly all fires and were:

1. *Start a Line*: This is the first major communication that the action has started. According to firefighters' reports it feels like going to a fight—the heart rate is through the roof, and adrenaline is very high.

2. *Start Water:* This has a similar salience to [1], with high adrenaline and heart rate.

3. *All visible fire is knocked down*: This communication indicates significant progress, and is accompanied by an increasing level of relief and reduced stress.

4. *Primary Searches are positive or negative*: This communication conveys the results of the initial quick sweep of the structure.

5. *Secondary searches on the floor(s) above and/or below the fire are positive or negative*: This communication conveys the results of slower

methodical searches, once the fire has been knocked down. If all is well then this is very reassuring.

The second kind of events that were isolated in the Handy Talkie protocols were **Emergency items**. These were extremely stressful events pointing to a dire situation. These communications did not occur in all fires. If they did occur in the Handy Talkies, although, they were noted, and the participants' recall protocols were scored for whether they had remembered each of these. They were

1. *A "10–45" transmission*: This transmission indicates that a firefighter has found a body. The person could be either alive or dead. This is a tremendously stressful event.

2. *Lost water/back-out:* This communication means that there is enormous trouble with the fire hose. It is a huge, potentially catastrophic issue.

3. *A "10–70" transmission*: This code indicates that there is a problem with the water pumper. It is of similar urgency to 2, above.

4. "*May-Day*": This indicates that collapse may be about to happen, or that a firefighter is down. This is the single most severe radio transmission. It is as bad as it gets.

5. "Urgent": This communication is used to clear the radio line for a must hear message. It gets everyone else to cease talking over the Handy Talkies immediately. It is only used in extreme circumstances.

The recall protocols were scored both in terms of whether the event had been recalled or not (0 or 1), and if it had been recalled, in how much detail (on a scale from 1 to 3). They were also scored for whether the communication was either personally relevant (made by the participant or directed at the participant) or not.

3 | RESULTS

The mean time between the end of the fire and recall was 13.25 hr; the median time was about 5 hr. There was no effect of either the retention interval or of whether the subjects had slept before recalling, on recall or on ratings of the stressfulness of the fire. Time estimations of the duration of the fire were examined, but none of the effects relating time estimation and the stressfulness of the fire were significant (perhaps because of too few observations). Therefore, we did not further consider these variables in the analyses that follow.

Recall scores were lower for the Schematic (mean proportion recalled = 0.19, SE = 0.02) than for the Emergency items (0.69, SE = 0.08). The relation between stress and memory for these two categories of items was analyzed using a multilevel logistic regression model. The predictors of the binary recall scores were (a) item category (Schematic and Emergency) and, (b) stressfulness of the incident, as given by each firefighter for each incident. To allow for variation across participants and items, random intercepts were allowed for participants and items. Both standardized linear and quadratic predictors were used to allow for detection of the theoretical possibility of an inverted U-shape relation between stress and memory.[1]

The results are shown in Figure 1, and the parameters of the model are provided in Table 1. There was a negative linear relation between recall and stress: recall was worse with increasing stress. The inverted U-shaped relation between stress and memory that is postulated by the hippocampal hypothesis was also significant in the model outcomes; there was a quadratic relation between stress and memory. As another test of the importance of the inverted U-shaped relation, we compared the model with the quadratic term against a model without the quadratic term using the model comparison metric WAIC (Watanabe, 2010): The former model (WAIC = 340.2) outperformed the latter (WAIC = 343.7). Thus, both the significance of the parameter and a model comparison approach supported the idea of an inverted U-shaped relation between stress and memory. The model also showed that Emergency items were recalled better than were Schematic items.

The literature on chronic medicinal administration of glucocorticoids suggests that exposure to glucocorticoids/stress over long periods of time might adversely impact the individual's reaction to stress and their memory. It was therefore hypothesized that those firefighters who had been on the job for longer might be both more

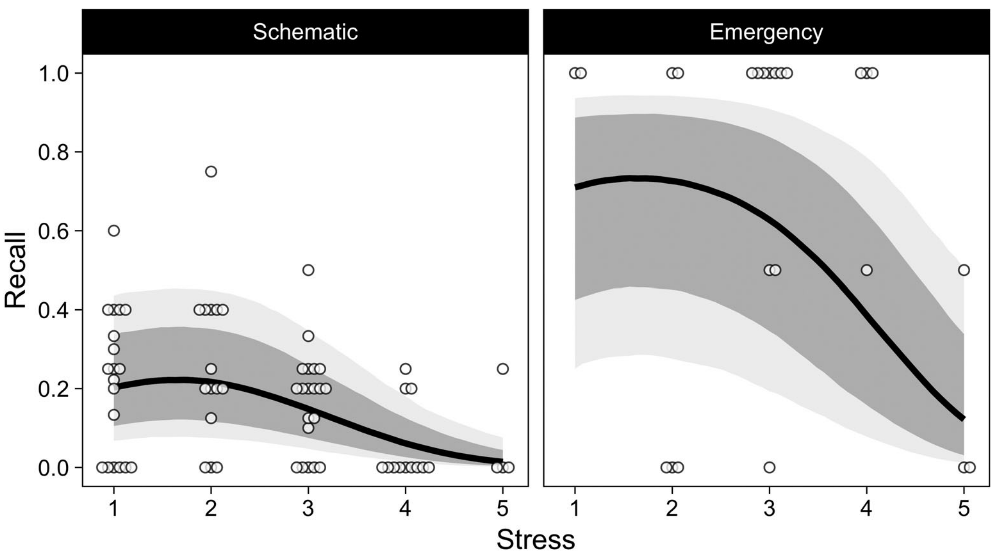

FIGURE 1 The relation between stress and recall for Schematic and Emergency questions. Points are proportions of recalled items for individual subjects at each level of stress (horizontal noise was added to display overlapping subjects). Lines are fitted recall probabilities (with 95% and 80% CIs as grey shades) from multilevel logistic regression model

TABLE 1 Estimated parameters of model of recall scores

Parameter	β estimate	SE	95% CI	Post. Prob
Stress (linear)	−.55	0.18	[−0.91, −0.21]	.999
Stress (quadratic)	−.40	0.17	[−0.75, −0.07]	.992
Emergency vs. Schematic	2.27	1.08	[0.12, 4.30]	.021
Intercept	−1.47	0.59	[−2.67, −0.33]	.992

Note: Estimates are posterior means from multilevel logistic regression model, and as such indicate effects on the log-odds scale (SE indicates the posterior standard deviation). "Post. Prob" is the posterior probability that the parameter was negative.

stress prone and have worse memories that those firefighters with a shorter history of chronic stress. To investigate this possible detrimental effect of chronic stress, the relation among participants' stress ratings, their years on job, and the coder's ratings of incident severity were modeled. To allow for multiple measures on some individuals, intercepts and effects of severity were modeled as random across participants. All predictors were mean centered. As is shown in Figure 2, stress ratings were strongly positively associated with the event severity ratings (β = .54, SE = 0.13, 95% CI = [0.28, 0.78]). People who had been on the job longer, though, had *lower* stress ratings (β = −.36, SE = 0.14, 95% CI = [−0.64, −0.1]). The interaction between severity ratings and years on job was not different from zero (β = −.08, SE = 0.13, 95% CI = [−0.34, 0.17]). Additionally, the model's intercept was not different from zero, indicating that participant's stress ratings were, on average, in accordance with the fire chief's event severity rating (β = −.03, SE = 0.13, 95% CI = [−0.29, 0.23]).

To investigate possible fragmentation of memory as a function of stress, a conditional analysis was conducted to examine how much detail was given to each of the recalled events. Recall of each of the events had been coded as being either a 0 (not recalled), a 1 (indicating that the event was merely mentioned), a 2 (indicating a moderate level of detail) or a 3 (indicating that a considerable amount of detailed information was reported). The analysis shown in Figure 1 was based on binary scores: was the event recalled or not? For the present analysis, we looked only at those events that were recalled to determine how much detail was given for each item. If increasing stress resulted in fragmentary recall, then, we expected to see more detailed recall at lower levels of stress and less detail at higher levels. This prediction was not confirmed by the results, however. In a multilevel regression model of recall detail scores (1, 2, or 3) with random intercepts for participants, neither the linear (β = .10, SE = 0.10, p = .320) nor the quadratic effect (β = −.13, SE = 0.10, p = .201) of stress was statistically significant. However, there were only 85 recalled items, and thus the power to detect these effects was small. Furthermore, very few events, at any level of detail, were recalled at extremely high levels of stress, as can be seen from Figure 1. Finally, the events themselves that were recalled under extremely high stress were often highly salient—a fact that might attenuate fragmentation.

Finally, the hippocampal system in humans is thought to bear a relation to the self. As such, it seemed plausible to conjecture that

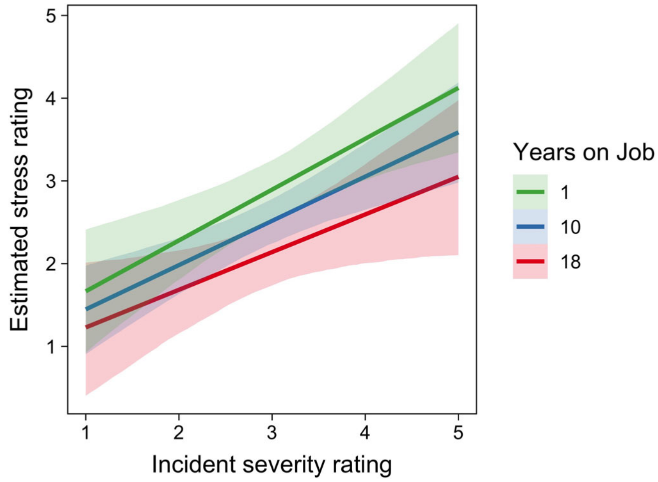

FIGURE 2 The relation between participants' stress ratings (y-axis), the coder's rating of event severity rating (x-axis) and years on job. Lines and shades indicate regression lines and 95% CIs, respectively, from multilevel regression model [Color figure can be viewed at wileyonlinelibrary.com]

events that were self-relevant would be recalled better than events that were not self-relevant. To investigate this possibility, memory for transmissions that were either made by the participant or were directed at the participant (i.e., were self-relevant) were considered self-relevant and were compared to memory for other transmissions. For the non-self-relevant items, overall recall averaged 0.19. Recall was much higher—0.94—for the self-relevant items. However, it should be noted that only 17 of the total 383 (Schematic and Emergency items that had occurred in the Handy Talkie transmissions and were scored as having been recalled or not) were self-relevant. Sixteen of these 17 were recalled. We modeled recall as a function of self-relevance with a multilevel logistic regression model, with random intercepts for participants. The effect of self-relevance was statistically significant (β = 4.25, SE = 1.05, p < .001).

4 | DISCUSSION

Many years ago, Nadel, Jacobs, and colleagues, after careful study of their own experimental research and that of others, and factoring in their clinical observations, generated a hypothesis about the effects of extreme stress on memory. The core notion was that the hippocampal spatial/temporal memory system—that is primarily responsible for episodic memory in humans—can become impaired to the point of shutting down when a person is extremely stressed. They proposed an inverted u-shaped curve relating hippocampal memory and stress. In the intervening years, most of the experiments and the supporting constructs about the characterization of this system have been conducted in non-human animals. Some utilize human participants but typically only at low levels of stress. But although the research that originally generated the hippocampal hypothesis began with single cell recordings in rats and has been followed up most extensively in non-humans, the thrust has always been toward contributing to an explanation of the experiences of people responding to and remembering highly stressful, traumatic, events. The problem comes in testing with humans. Studies with humans are rare. Firefighters, though, experience such events routinely. Because of their participation, we were able to observe their memory for events that they had experienced under conditions of extremely high stress.

The results of the study presented here based on the recall of firefighters in the FDNY for events that occurred while they were fighting fires while sometimes under extreme stress, lend substance to the hippocampal hypothesis. Memory was better for the threatening, emergency events than for more standard, schematic, events. Memory, both for emergency and for schematic events, was impaired by increasing stress. There was a quadratic (inverted u-shaped) memory stress function. These results indicate that memory under stress is, indeed, special, and in a way specified by the hippocampal hypothesis.

The one thing that goes against the hippocampal hypothesis in our data is the lack of fragmentation. However, the data may not have been either powerful enough or specifically directed at the possibility of fragmentation to allow us to examine the hypothesis at this level of detail. One way in which future research might investigate this question—which would have both theoretical and practical implications—would be to specifically examine firefighters' memory for the spatial layout of the fires. Spatial memory is of enormous importance for firefighters. Knowing whether it is unreliable under extremely stressful conditions—as the hipppocampal hypothesis predicts—may, quite literally, be information that will save lives. If it is unreliable, as we posit here, then precautionary measures and training to offset this human fallibility can be implemented. If the hippocampus is indeed, a spatial and temporal map, then finding ways to compensate for a breakdown of those functions that are specific to this system, when the system is itself vulnerable, can be prioritized. Such knowledge and the specific resultant training may be of practical as well a theoretical importance.

These results indicate that memory under extreme stress is, indeed, special. In broad outlines, the patterns that we observed in this study in firefighters remembering events from real-world highly stressful situations in which they were participants, were consistent with the Nadel/Jacobs hippocampal hypothesis.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

ENDNOTE

[1] We used a *t(7, .25, .5)* prior on the standard deviation of the item-specific intercepts, because they could not be identified on the data alone (i.e., there were responses to only three emergency items). We also fitted two additional models, one with an interaction between item category and stress ratings, and one with the firefighter's years on job as a predictor. None of these predictors turned out important, and the models had worse fits then the one presented in the main text.

ORCID

Janet Metcalfe https://orcid.org/0000-0003-3286-9475

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