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Hallucinations in Post-Traumatic Stress Disorder: Insights from predictive coding

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Abstract

Although hallucinations are not one of the DSM-5 criteria for post-traumatic stress disorder (PTSD), they are increasingly documented in PTSD. They are noted in the absence of clear delusions, formal thought disorganization, disorganized speech or behavior, ruling out a co-morbid psychotic disorder like schizophrenia as a better explanation for these hallucinations. Hallucinations in both PTSD and schizophrenia share phenomenological features. We propose that hallucinations in PTSD, like those in schizophrenia, might be explained in terms of aberrant predictive coding, specifically the mis-application of strong prior beliefs which vitiate perceptual inference. This approach highlights the broader relationship between trauma and psychosis. Under predictive coding, the nervous system organizes past sensory data into an internal model of the world. Under stress, the brain prioritizes speed over accurate encoding. However, memories for traumatic experiences are typically strongly consolidated, in order to avoid similar experiences in future. In PTSD, this could lead to a world model comprised of inaccurate but overly precise prior beliefs, that can be triggered by stimuli tangentially related to the index trauma, resulting in hallucinations. Crucially, this evidence accumulation depends upon the relative precision of prior beliefs and sensory evidence (supplied in the form of prediction errors). Our basic argument is that stressful situations induce belief updating, in terms of precise prior beliefs, that are difficult to undo. These unduly precise, trauma-related beliefs then constitute perceptual hypotheses, memories or narratives that bias subsequent experience. This prior bias may be so severe that sensory evidence is effectively ignored; i.e., treated as very imprecise, in relation to prior beliefs. Such an account may lead to cognitive therapies for hallucinations aimed at strong prior beliefs, and the exciting prospect of combining such therapies with drugs that modulate neuroplasticity and enhance the adaptive consolidation of more appropriate priors.

Summary:

We explore the hallucinations that occur in post-traumatic stress disorder through the lens of predictive coding theory. We find that stress might bias towards strong priors which instantiate hallucinations. This analysis underlines the links between perception, cognition, and memory, as well as their aberration in serious mental illness.

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Keywords

Predictive Coding Psychosis Hallucinations PTSD

INTRODUCTION

Although hallucinations are not part of the DSM-5 criteria for post-traumatic stress disorder (PTSD), auditory hallucinations are increasingly noted as a feature of trauma and combat-related PTSD (Steel, 2015). Intrusive memory of a traumatic event, often in the form of a visual image, is a hallmark symptom of PTSD, and occur frequently within individuals who report hallucinatory experiences. Clinically, the presence of auditory hallucinations is often synonymous with a psychotic disorder. However, hallucinations in PTSD often occur in the absence of clear delusions, formal thought disorganization, disorganized speech or behavior, ruling out a co-morbid psychotic disorder like schizophrenia. Predictive processing theories derived from the cognitive neuroscience of perception have been proposed to explain the symptomatology of schizophrenia (Sterzer et al., 2018) (Adams, Stephan, Brown, Frith, & Friston, 2013). In this paper, we propose that a similar framework could be applied to hallucinations in PTSD. Specifically, we explore whether hallucinations in PTSD could be explained by a bias toward errant top-down priors (Powers, Kelley, & Corlett, 2016) which subtends, reinforces, and promotes the persistence of hallucinations. Neither perception nor memory are passive processes. They are both synthetic. The act of remembering changes what is subsequently recalled (Lee, Nader, & Schiller, 2017) (Elsey, Van Ast, & Kindt, 2018) (Haubrich & Nader, 2018). The act of perceiving changes what is subsequently perceived. That PTSD is considered a disorder of memory processing, and hallucinations a mutation of perception, emphasizes the possible interactions between memory and perception, and their dys-interaction in generating psychotic departures from consensual reality. This relationship between memory and perception, invited by, but not necessarily demanded by (Macpherson, 2017), predictive processing accounts of mind and brain, is the focus of the present piece.

THEORIES OF PTSD

PTSD is typically understood, through the lens of cognitive neuropsychiatry, as a problem with memory and learning (Lissek & van Meurs, 2015). It may be underwritten by poor extinction learning about the index trauma (learning that the index trauma no longer pertains to the current context), associative learning deficits and sustained contextual anxiety (impaired ability to learn environmental cues of danger leading to heightened contextual anxiety), overgeneralization of the memory for that trauma (recalling trauma related material in response to weakly associated or partial cues in the current context), and/or excessive reconsolidation of the memories related to the index trauma (excessive rumination on the trauma that causes it to be mnemonically tagged and associated with the current context). Trauma is also theorized to induce autonomic hyperexcitability, and an impaired ability to autonomically habituate to intense environmental stimuli, leading to hyperarousal symptoms.

Notable formal theories of PTSD so far include Mowrer's conditioning model (classic and operant fear conditioning pairing previous neutral stimuli with aversive and threatening stimuli) (Mowrer, 1947), Foa & Kozak's emotional processing theory (stimuli and responses stored in memory form a maladaptive network, identifying non-threatening stimuli as dangerous and generating maladaptive responses and attributions) (Foa & Kozak, 1986), Ehlers & Clark's cognitive model (trauma is processed in a way that creates a sense of serious current threat because of individual differences in the evaluation of trauma or its consequences and individual differences in the nature of memory of the event and its relationship with other autobiographical memories) (Ehlers & Clark, 2000), Rubin's memory-based model (a series of independent systems interact to produce autobiographical memories and each part of this network has a specific and important role in the recall of events) (Rubin, Berntsen, & Bohni, 2008), and Brewin's dual representation theory (two memory systems - verbally accessible memories including context-bound trauma material that can be voluntarily recalled and described, and situationally accessible memories limited to sensory-bound material recalled through involuntary cues; lack of contextual processing compared to sensory information during a traumatic experience results in difficulty narrating the trauma and integrating it with autobiographical memories) (Brewin, Dalgleish, & Joseph, 1996). Brewin's dual representation theory was recently updated (Brewin, Gregory, Lipton, & Burgess, 2010) to propose that the intrusive images and sensory experiences including frank hallucinations and involuntary flashbacks seen in PTSD arise from an imbalance or dissociation between sensory-bound and contextual representations encoded at the time of the trauma. Thus far, these accounts have not utilized predictive coding to offer a unified cognitive and perceptual framework for PTSD, especially to explain the hallucinations. Under predictive coding, we assume that memories can influence perception. In this paper then, we will explore the extent to which aberrant memory processing might engender hallucinations in PTSD.

WHAT IS PREDICTIVE CODING?

Predictive coding is a theory of brain function in which the brain is constantly generating and updating a mental model of the environment, which is then used to generate predictions of sensory input that are compared to actual sensory input, which in turn engenders a continuous refinement of the mental model (Friston & Kiebel, 2009) (Friston, 2009). As Sam Wilkinson et al note in an earlier paper about predictive coding in PTSD (Wilkinson, Dodgson, & Meares, 2017), this is best thought of as a framework to help think about brain function as a whole, rather than of individual neurons, even though the prediction and updating process appear to be happening at various levels in the nervous system. This paper is best conceptualized as an extension and explication of the more general framework put forth in the aforementioned paper, with a special focus on hallucinations. Understanding predictive coding requires understanding of Bayes' theorem, which we will review below.

Bayes' theorem is relevant whenever we have a hypothesis, then observe new evidence, and want to estimate the probability that our hypothesis holds given the evidence is true. The formula describes how to update the probabilities of hypotheses in light of new evidence. It follows simply from the axioms of conditional probability but can be used to reason about a wide range of problems involving belief updates. If hypothesis is H and evidence

is E, then the probability that the hypothesis is true *before* considering any new evidence is written as $P(H)$. This is also known as the "prior probability" or "prior." The probability that the hypothesis remains true after considering the new evidence is written as $P(H \mid E)$, the vertical bar, |, denotes "given that." $P(H \mid E)$ is the "posterior probability" or "posterior." According to Bayes' theorem, this can be obtained by:

$$P(H \mid E) = \frac{P(H)P(E \mid H)}{P(E)}$$

$P(H \mid E)$ is the probability of the evidence being true given the hypothesis is true. This is known as the "likelihood."

Bayes' formula is perhaps more usefully written as:

$$P(H \mid E) = \frac{P(H)P(E \mid H)}{P(H)P(E \mid H) + P(\neg H)P(E \mid \neg H)}$$

$P(E \mid \neg H)$ is the probability of the evidence being true given the hypothesis is *not* true. In standard notation, ¬, signifies "not." The entire denominator is often written simply as $P(H)$, the total probability of seeing the evidence, but in order to calculate it, we need to break it down, as above, into cases where the hypothesis is true and cases where it is not true.

There has been mounting evidence over the past two decades to suggest that our brains may employ similar algorithms to process sensory information and update beliefs and predictions of the environment (Parr, Rees, & Friston, 2018) (Parr & Friston, 2018). Thus, the brain does not passively receive sensations converted into electric impulses by our sensory organs, but is, in fact, actively predicting the environment, preparing for the sensory input it is about to receive (Friston, 2009). This was, in part, fueled by the postulate that intrinsic brain activity represents millions of predictions of what one will encounter next in the world, $P(H \mid E)$, based on one's lifetime of past experiences, $P(H)$ (Ma, Beck, Latham, & Pouget, 2006) (Ma, Beck, & Pouget, 2008). Evidence suggests that perceptions, actions, memories, thoughts, language, attention, decision-making, belief-updating, executive functioning, and many other phenomena, historically treated as distinct brain processes, may all be influenced by predictions and prediction errors (Kaplan & Friston, 2018) (Parr & Friston, 2017) (Seth, 2013) (Parr & Friston, 2019).

The earliest conceptualization of predictive coding was in the late 19th century, with Helmholtz's concept of unconscious inference. Interest in this idea was renewed in the late 20th century, and there has been an explosion of both pre-clinical and clinical studies exploring this, along with a parallel explosion in the machine learning world that applies many of the same principles to improve AI.

We now understand that the brain encodes top-down generative models (based on experienced and evolutionarily prepared knowledge of world) at various temporal and spatial scales in order to predict and effectively suppress sensory inputs rising up from lower levels. A comparison between predictions (priors) and sensory input (likelihood) yields a degree

of surprise (also known as the “prediction error” or “free energy”). It is in our best interest (evolutionarily, to increase our chance of survival), to minimize this surprise (Friston, 2009). If the prediction error is low, it means that the generative model currently holds, and no change needs to occur. Thus, the activity at higher levels cancels out activity at lower levels, and the posterior probability of the model is increased. If, on the other hand, the prediction error is reliably larger than expected, the model updates are required so that predictions in the future are more accurate (Parr & Friston, 2019).

That is, the Bayesian brain assigns a weight to each of the prediction errors it encounters (based on their inverse variance or reliability), to denote confidence in the error. This is known as precision-weighting of the prediction error. If the confidence in the precision of the prediction error is high, then the prediction error is weighted highly and updates the generative model, and when the precision is low, the model is not updated.

PREDICTIVE PROCESSING FRAMEWORK IN PTSD

PTSD manifests after exposure to a traumatic event, and is characterized by four core clusters of symptoms: intrusive experiences and flashbacks, mood and cognitive disruptions, avoidance and numbing, and hyperarousal and reactivity symptoms (Armour, Mullerova, & Elhai, 2016). Auditory hallucinations have been associated with PTSD (Coronas et al., 2011) with a prevalence rate of about 50% (Anketell et al., 2010; Brewin & Patel, 2010a). We consider intrusive experiences and flashbacks as forms of visual hallucinations also.

The predictive processing framework as described by Sam Wilkinson et al (Wilkinson et al., 2017) previously views all encounters with the world as involving learning to some degree, with traumatic events influencing learning in a maladaptive way where excessive learning occurring during a specific context causes unwanted symptoms in other, more general contexts. While the symptoms can be life-preserving (for instance, increased vigilance so the agent can avoid the same traumatic event if it were to occur again), they can be present in unnecessary contexts, leading to emotional distress. We will explore how this relates to hallucinations.

Under predictive coding, we propose that an unexpected index traumatic event (in the case of type I trauma) or events (in the case of complex, type II trauma) (Terr, 1991; Wilkinson et al., 2017) could lead to a fundamental change in someone’s generative model of the world. In other words, the inevitable prediction errors generated during the traumatic event are assigned too much precision and induce profound belief updating. Subsequent inconsequential exposure to related sensory cues would leave trauma-related beliefs intact, because those cues and their consequences lack the requisite precision for updating. The ensuing shift of inference and memory towards these anomalous prior beliefs would – we suggest - manifest as flashbacks and hallucinations. Whilst we are considering all intrusive mnemonic/perceptual experiences together here, we appreciate there may be distinctions between them phenomenologically. Even within the category of hallucinations, there is variation in the sense of reality – with the visions experienced in the context of Parkinson’s disease and some closed head injuries reported as unreal, compared to the voices that attend psychosis which are often perceived as real. This sense of reality may be underwritten

by sensorimotor contingency and the counterfactual prediction errors that accompany perceptual changes with movement of the sensory organs (Seth, Suzuki, & Critchley, 2011). Perhaps if these reality monitoring mechanisms are intact, flashbacks ensue, and in their absence, hallucinations.

The brain encodes beliefs as probability distributions over states in the world that cause sensations (d'Acremont, Schultz, & Bossaerts, 2013) (Friston, Parr, & de Vries, 2017). These top-down predictions are compared with actual signals at lower levels (more proximal to sensory inputs), and the ensuing mismatch signal (prediction error) is passed back up to correct the higher representations. Prediction errors can be accommodated or assimilated depending on their reliability (or inverse variance; more precise errors garner new learning, imprecise ones are discounted and ignored) (Friston, 2005).

Extremely precise (strongly-weighted) priors as a result of traumatic experiences would lead to erroneous predictions, which in turn would increase subsequent prediction errors that demand to be reconciled. Also, as traumatic events occur, estimates of model reliability would decrease. The person experiencing the traumatic event would lose confidence in estimating prediction errors (precision weighting of the prediction error) when their past update mechanism had been proven to be catastrophically wrong (as in type 1 trauma) or consistently wrong (as in type 2 trauma). This would lead to reduced precision-weighting of sensory stimuli when they are subsequently encountered in potentially threatening situations, which in turn would result in the priors not getting updated, resulting in hallucinatory phenomena. In statistical terms, precision controls the width of the predictions. And, since the brain estimates precision at each level of the sensorimotor hierarchy (Kanai, Komura, Shipp, & Friston, 2015), its belief in the precision of its predictions changes, leading to the formation of "hyperpriors," where the brain retains prior beliefs about the precision of its predictions.

Additionally, whenever there are reminders to the fear memories, however weak the reminders may be, the brain could start generating aberrant predictions of the world. Weak reminders to the trauma would also elicit an emotional response. This could cause a sympathetic overdrive including norepinephrine (NE) and dopamine (DA), which can amplify the normal random discharges of sensory receptors and neurons. With a hyperprior expectation of the presence of a (threatening) stimulus, these random discharges get perceived as real stimulus, resulting in phenomena like flashbacks and hallucinations.

Negative emotional state stemming from the weak reminders may conform to the prior ("the fear I am feeling is justified because what I fear is actually happening"), initiating a vicious cycle of progressively strengthened posterior bias towards the prior, resulting in sustained anxiety, panic, and hyperarousal. There are magnetoencephalography data broadly consistent with this hypothesis - a narrower dynamic range of functional connectivity frequency couplings between regions that might underwrite the readiness with which merely distantly related stimuli can evoke re-experiencing of the trauma memory (Mišić et al., 2016).

There are, of course, applications of the predictive processing framework to affect and interoception (Barrett & Simmons, 2015), where in emotions are inferences to the best

explanation for interoceptive states – over variables like heart rate and blood pressure (Owens, Allen, Ondobaka, & Friston, 2018). Fear is what best explains the response of internal variables like heart rate, skin conductance and blood pressure, to the presence of some threatening external stimulus like a predator or to intrinsic volatility in those signals which may be ascribed to some external event. That is, these inferences and variables also influence exteroception, for example, inferences about visual stimuli are influenced by the phase of the cardiac cycle at which they are presented (Allen, Levy, Parr, & Friston, 2019). Thus, one's emotional state colors perceptual inferences about the external world, and it is our contention that under threat, when uncertainty (about self and world) is highest, one might rely most on ones' priors (Corlett et al., 2019; Powers et al., 2016; Powers, Mathys, & Corlett, 2017). Since reliance on priors subtends hallucinations, we posit that the extreme emotions associated with PTSD augur hallucinations.

Hypervigilance (for explanatory learning) is another potential means of reducing uncertainty (Peters, McEwen, & Friston, 2017). According to the social-psychological meaning-maintenance model, there is a natural tendency to construct mental representations of expected associations that organize one's beliefs and perceptions in order provide a general feeling that our lives make sense. This is hypothesized to arise from the interaction between perceptual input and context-dependent knowledge that is activated in long-term memory (Chassy, Calmès, & Prade, 2012a). Threats to aspects of meaning activate a meaning-maintenance motivation that may call upon any other available associations to restore a sense of meaning. Proulx and Heine demonstrated that unrelated meaning threats provoke an increased motivation to perceive patterns in the environment (Proulx & Heine, 2009).

In summary, we hypothesize that when the brain loses confidence in its priors (after the unexpected traumatic event), prediction errors are engendered, which will need to be explained somehow in order make sense of the world. Such prediction errors ultimately engage new explanatory priors, since unattenuated errors are aversive, and this aversion, given the magnitude of prediction error associated with index trauma, will shift inference and memory toward the explantory priors manifest ultimately as flashbacks and hallucinations (Powers et al., 2016) (Powers et al., 2016).

PREDICTIVE CODING, MEMORY, AND PERCEPTION

Our contention is that one would expect hallucinations in PTSD, given its mnemonic basis, because that basis – aberrant memory precision, lack of contextual modulation, poor extinction learning, are explicable in terms of predictive coding. In this account, priors are a form of long-term memory which optimize perception (Friston & Kiebel, 2009) by modulating anticipatory brain states (Stokes, Atherton, Patai, & Nobre, 2012). New learning can engender hallucinations in the laboratory, particularly in individuals who hallucinate in the real-world. These hallucinations are driven by strong learned priors (Powers et al., 2017). High-level memory for the colors of objects has been shown to significantly modulate the visual perception of their colors (Hansen, Olkkonen, Walter, & Gegenfurtner, 2006). Color perception is not determined by the incoming sensory data alone, memories of shape-color association contribute too, particularly as sensory inputs become more uncertain (Fan, Hutchinson, & Turk-Browne, 2016). Imagining a visual stimulus, presumably by retrieving

a prior representation of that stimulus, can influence subsequent visual perception of related visual stimuli (Ishai & Sagi, 1995; Kosslyn, Ganis, & Thompson, 2001).

We previously alluded to the fact that PTSD is typically conceptualized as a mnemonic problem (Lissek & van Meurs, 2015). Neuroscience studies indicate that memory is a reconstructive process that is susceptible to distortion (Lacy & Stark, 2013; Morey et al., 2015; Bouton, 1993). W. K. Estes proposed a basic framework for interpreting the various forms of memory distortions (Estes, 1997). He assumed that a learning experience is encoded in parallel in two distinct kinds of memory traces: one containing the perceptual attributes of objects and events which is basic to recognition, and one containing the reactions made to them which is basic to recall. The stored representations of both undergo random perturbations over time, which leads to both loss and distortions of memory. Retrieval from memory is accomplished by computing similarities of stimuli to stored representations. Recognition depends on the ratio between the total similarity of the stimuli to the relevant memory array; recall is accomplished by a form of pattern completion that depends on the same type of similarity computation (Estes, 1997). Routine information processing therefore involves “contextual integration” whereby detailed encoding of incoming stimuli takes place, which facilitates later memory recall.

Daniel Hoffman argues that since evolution optimizes fitness, often at the expense of features that might be better valued under different circumstances (Mark, Marion, & Hoffman, 2010), they might rapidly apprehend and perceive a gist-like approximation of reality that portends survival better than a more veridical (but slow and expensive) representation. Traumatic events, especially, demand rapid behavioral responses and similarly speedy information processing. A temporary decrease in contextual integration would enable a quick response based on basic perceptual processing. Such a decrease in mnemonic context processing may be consistent with accounts of perception based on predictive coding and Bayesian inference (Aitchison & Lengyel, 2017b), which assume that the brain maintains probabilistic models of sensory experience that are updated by new information in a Bayesian fashion (Kording, 2014; De Ridder, Vanneste, & Freeman, 2014; Vilares & Kording, 2011), that is, predictions are compared to data, and prediction errors are either accommodated or assimilated based on their precision (or inverse variance). This calculus entails hyper-priors – beliefs about precision of priors and prediction errors that render inferences (and, we posit, memories) contextually sensitive. We contend that stressful situations demand quicker responses for which such contextually rich processing with hyper-priors is too sluggish and energetically expensive. Since context facilitates recall, memories encoded under such conditions become difficult to recall on a voluntary basis. However, these engrams may be triggered involuntarily by stimuli which overlap to some extent the traumatic event, resulting in re-experiences, flashbacks and hallucinations (Steel, 2015).

In one of the largest population studies to date, Alsawy et al. showed a linear correlation between reliving trauma symptoms and auditory hallucinations. More relevantly, those who were upset by reminders of their trauma had a four-times higher chance of also experiencing auditory hallucinations (Aitchison & Lengyel, 2017a). Reduced levels of contextual integration may be central to the development of trauma-related intrusive

memories. Some people who experience a traumatic event do believe they have a vivid memory for the event and their reactions to it, a so-called flashbulb memory (Brown & Kulik, 1977). However, despite high confidence in these memories, they may not actually be accurate, and they degrade over time (Hirst & Phelps, 2016; Hirst et al., 2015).

Trauma-related intrusive memories, flashbacks and hallucinations may invoke fear each time they are recalled. This may be a combination of a recollection of the fear experienced at the time of the traumatic event and fear evoked by memory recall in the present moment. Memory reconsolidation theory holds that each time a previously consolidated memory is recalled, it will become labile and undergo a process of active consolidation which will maintain, strengthen or modify the memory (Tronson & Taylor, 2007). This has significant implications in the courtroom as memory distortions can occur simply from misleading questions posed when the memory is in a malleable state after being recalled (Lacy & Stark, 2013). In prior work, we suggested that aberrant reconsolidation-mediated belief strengthening could be the basis for delusion fixity (Chassy, Calmès, & Prade, 2012b), for which we provided some preliminary evidence (Corlett et al., 2013). Here we suggest hallucinations, themselves somewhat inflexible, may also be related to similar mechanisms of belief fixity, for which there is also preliminary evidence (Powers et al., 2017). McCarthy-Jones and Longden argue that each time such reconsolidation occurs, the current cognitive and affective state of the person may be embedded as well (McCarthy-Jones & Longden, 2015). During stress, neuromodulation amplifies the precision of sensory prediction errors endowing sensory information with greater weight in relation to prior expectations (Peters et al., 2017). Thus, an intrusive memory invokes fear, self-reinforces and may vitiate perception to the point of hallucination (Powers et al., 2016).

Fear memories thus formed and reinforced are difficult to over-ride through extinction training alone. Extinction involves the formation of a new memory that competes for expression with the original memory, rather than a weakening of that original memory. Gradually reducing the contingency between cues and aversive outcomes resulted in sustained elimination of cue-induced fear whereas abruptly removing the aversive stimuli resulted in spontaneous cued fear recovery (Gershman, Jones, Norman, Monfils, & Niv, 2013). Abrupt removal of aversive stimuli is surprising, it engenders a prediction error, which drives the inference that a new latent cause is responsible for the new observed data, this new learning competes with the original learning, which is sustained – facilitating later spontaneous renewal. In Gershman et al's experiments, the small prediction errors engendered by the gradual decrease in contingency modifies the original fear memory while the larger prediction error engendered by the abrupt change in contingency induces the competitive extinction memory. We suggest that trauma-induced changes in prediction error processing weaken extinction memory and enhance memory reconsolidation (Corlett, Krystal, Taylor, & Fletcher, 2009).

PHENOMENOLOGY OF HALLUCINATIONS IN PTSD VERSUS SCHIZOPHRENIA

Auditory hallucinations seen in PTSD may share features with the auditory hallucinations seen in schizophrenia (McCarthy-Jones & Longden, 2015), but they also differ in certain ways (see table 1). They may manifest as discrete flashbacks, but they may also be continuous (Butler, Mueser, Sprock, & Braff, 1996; Braakman, Kortmann, & van den Brink, 2009). Occasionally, the hallucinations share the content and theme of the inciting trauma, but more commonly they share only the theme, or have no identifiable relation at all (Hardy et al., 2005).

Command-auditory hallucinations may also be present, but they are less common in PTSD than they are in schizophrenia (Scott, Nurcombe, Sheridan, & McFarland, 2007). Internally-located voices, where voices are perceived to originate from within (Scott et al., 2007), and ego-syntonic hallucinations, where hallucinatory content is more acceptable to self (Brewin & Patel, 2010b; McCarthy-Jones et al., 2014), may be more common in PTSD. These differences derived from quantitative studies are summarized in table 1. Additionally, there are several case reports available that provide a rich illustration of this hallucinatory phenomena in PTSD (Ivezic, Oruc, & Bell, 1999; Waldfogel & Mueser, 1988; Mueser & Butler, 1987; Norredam, Jensen, & Ekstrom, 2011).

15% of patients with schizophrenia may also meet criteria for PTSD. However, correlation does not imply causation, therefore we could not be certain if the history of trauma is coincidental, confounding, or causative (Achim et al., 2011). That said, a meta-analysis of 29 studies exploring associations between childhood trauma and severity of psychosis found that childhood trauma was significantly correlated with severity of hallucinations and delusions, but not with severity of negative symptoms (Bailey et al., 2018).

There are few studies directly linking hallucinations to traumatic events (Conway & Pleydell-Pearce, 2000). In a study of 199 patients with AH, 12% reported that they heard voices which were identical replays of memories of previous conversations that they had heard, whilst 31% reported that the relationship was similar but not identical (McCarthy-Jones et al., 2014). In another study of 40 patients with psychosis, the study authors extracted details of the main traumatic event and hallucination content. These were then rated as either having a direct link, an indirect/emotional link, or no link. 12.5% of hallucinations contained content which was a direct replication of trauma content, and 45% rated as having an emotional link (Hardy et al., 2005).

Dissociation appears to mediate the effect of childhood trauma on hallucination-proneness within individuals diagnosed with schizophrenia spectrum disorders (Pearce et al., 2017; Pilton, Varese, Berry, & Bucci, 2015; Varese, Barkus, & Bentall, 2012). Based on their finding that all thirty PTSD-AVH patients they interviewed regarded their AVH (Auditory and Visual Hallucinations) as a manifestation of their own thoughts, Brewin and Patel argue that PTSD-AVH are a dissociative phenomenon, distinct from the “psychotic processes” that result in SZ-AVH (Brewin & Patel, 2010a). However, dissociation is a common feature of PTSD, and a correlate of AVH. Using dynamic causal modeling of resting state fMRI data to

discern directional relationships between brain regions, Nicholson and colleagues found that dissociation in PTSD is associated with greater top-down connectivity of prefrontal cortex onto amygdala, consistent with our contentions regarding priors and hallucinations in PTSD (Nicholson et al., 2017).

CLINICAL IMPLICATIONS

Rather than an arcane academic exercise, we believe the application of predictive coding to explain hallucinations in PTSD might have clinical implications. For example, the efficacy of exposure-based treatments for PTSD might be improved by making the exposure as gradual as possible, thereby minimizing the predictive error. Grounding techniques, which also lower predictive error by reorienting the person to reality, might work to alleviate PTSD symptoms as well.

Eye Movement Desensitization and Reprocessing (EMDR) is a psychotherapy treatment that was originally designed to alleviate the distress associated with traumatic memories. It involves following a slowly oscillating target with the eyes and, through the lens of predictive processing, is thought to increase sensory precision (Chamberlin, 2019). EMDR has been successful in reducing the severity of posttraumatic stress symptoms in psychosis (de Bont, van Minnen, & de Jongh, 2013; de Bont et al., 2016). Under our account, increasing sensory precision would decrease uncertainty, rendering the imposition of strong hallucinatory priors unnecessary.

There are few clinical trials of antipsychotics to treat hallucinations in PTSD. One trial (olanzapine vs fluphenazine) (Pivac, Kozaric-Kovacic, & Muck-Seler, 2004) did include PANSS, but it was not reported in the original manuscript. Reduced levels of PTSD symptoms alone were not associated with a reduction in hallucinatory experiences, according to van der Gaag, M. in a 2015 presentation: “The effects of trauma treatment on comorbid symptoms in PTSD in psychotic patients,” in Proceedings of the 43rd Annual Conference of the British Association for Behavioural and Cognitive Psychotherapy, Warwick. However, this does not appear to have been published in a peer reviewed journal. Also, while the patients included did have hallucinations, whether or not this reduced with treatment is unfortunately not reported (van den Berg et al., 2015).

If the symptoms characteristic of PTSD and hallucinations share a pathophysiology, then treatments that resolve standard PTSD symptoms ought to mollify hallucinations also. Given what we know about the machinery of predictive coding and priors, are there pharmacological, psychological, or combination treatments that we might consider for hallucinations in the context of PTSD? E.g. Cognitive behavioral therapy for psychosis with a glutamatergic agent (D-cycloseriene) that would promote extinction of the maladaptive prior (Gottlieb et al., 2011).

Could we repurpose the pharmacological agents effective in the lab at disrupting fear memory reconsolidation, like propranolol (Kindt, Soeter, & Vervliet, 2009), as as-needed medication for flashbacks in PTSD? This would be impractical if the flashbacks are severe, but it might be worth attempting in those that retain some level of awareness.

Are there clinical means – experimental or phenomenological – that we might use to distinguish hallucinations in schizophrenia from those in PTSD? One proposition is that PTSD-AVH are ego-syntonic (recognized as one's own cognitions), whereas SZ-AVH are ego-dystonic hallucinations (experienced as externally generated) (McCarthy-Jones & Longden, 2015). Based on their finding that all thirty PTSD-AVH patients they interviewed regarded their AVH as a manifestation of their own thoughts, Brewin and Patel argue that PTSD-AVH are a dissociative phenomenon, distinct from the "psychotic processes" that result in SZ-AVH (Brewin & Patel, 2010a). There appear to be few other differences phenomenologically (McCarthy-Jones & Longden, 2015). However, there are ego-dystonic AVH in PTSD and ego-syntonic AVH in psychosis on occasion.

In recent work, we used a multi-sensory conditioning procedure to engender hallucinations. All participants were susceptible to this lab effect, however, voice-hearers (regardless of clinical diagnosis) were five times more susceptible to this effect and those with psychosis (regardless of whether they were hallucinators) evinced a deficit in belief updating when that conditioning was extinguished. Given the dearth of extinction learning in PTSD, we predict that people with PTSD would likewise show a deficit in belief updating in the task, particularly if they experience hallucinations.

We should be cautious though. The predictive processing account and its extension to biology and the living non-living distinction, the free energy principle, is powerful and broadly applicable (Friston, 2013). Indeed, it may be unfalsifiable (Colombo & Wright, 2018), which dents its credibility as a scientific theory. We believe its specific implementation and departures from those implementations in clinical settings will be key to falsifying theory and its extension to the clinic. For example, if we have a measure of top-down priors (like our conditioned hallucinations task (Powers et al., 2017), and that measure is not augmented in people with PTSD who hallucinate, then our strong prior theory does not explain hallucinations in PTSD.

To summarize, we have suggested a predictive coding-based account of hallucinations in PTSD and made predictions about treatments that may target a predictive-processing-mediated deficit and should, theoretically, mollify hallucinations. More broadly, we believe the presence of hallucinations in PTSD underlines the intimate associations between memory and perception, which are readily understood in the predictive coding framework, may provide new insights into the treatment of hallucinations in PTSD.

GRANTS:

Neurocomputational Models of Auditory Hallucinations R21MH116258

Predictive coding as a framework for understanding psychosis R01MH112887

BIBLIOGRAPHY

Achim AM, Maziade M, Raymond E, Olivier D, Mérette C, & Roy MA (2011). How prevalent are anxiety disorders in schizophrenia? A meta-analysis and critical review on a significant association. Schizophr Bull, 37(4), 811–821. doi:10.1093/schbul/sbp148 [PubMed: 19959704]

Adams RA, Stephan KE, Brown HR, Frith CD, & Friston KJ (2013). The computational anatomy of psychosis. Front Psychiatry, 4, 47. doi:10.3389/fpsyt.2013.00047 [PubMed: 23750138]

Aitchison L, & Lengyel M. (2017a). With or without you: predictive coding and Bayesian inference in the brain. Curr Opin Neurobiol, 46, 219–227. doi:10.1016/j.conb.2017.08.010 [PubMed: 28942084]

Aitchison L, & Lengyel M. (2017b). With or without you: predictive coding and Bayesian inference in the brain. Curr Opin Neurobiol, 46, 219–227. doi:10.1016/j.conb.2017.08.010 [PubMed: 28942084]

Allen M, Levy A, Parr T, & Friston KJ (2019). In the Body's Eye: The Computational Anatomy of Interoceptive Inference. BioRxiv, 603928. Retrieved from https://www.biorxiv.org/content/biorxiv/early/2019/04/10/603928.full.pdf

Anketell C, Dorahy MJ, Shannon M, Elder R, Hamilton G, Corry M, . . . O'Rawe B. (2010). An exploratory analysis of voice hearing in chronic PTSD: potential associated mechanisms. J Trauma Dissociation, 11(1), 93–107. doi:10.1080/15299730903143600 [PubMed: 20063251]

Armour C, Mullerova J, & Elhai JD (2016). A systematic literature review of PTSD's latent structure in the Diagnostic and Statistical Manual of Mental Disorders: DSM-IV to DSM-5. Clin Psychol Rev, 44, 60–74. doi:10.1016/j.cpr.2015.12.003 [PubMed: 26761151]

Bailey T, Alvarez-Jimenez M, Garcia-Sanchez AM, Hulbert C, Barlow E, & Bendall S. (2018). Childhood Trauma Is Associated With Severity of Hallucinations and Delusions in Psychotic Disorders: A Systematic Review and Meta-Analysis. Schizophr Bull, 44(5), 1111–1122. doi:10.1093/schbul/sbx161 [PubMed: 29301025]

Barrett LF, & Simmons WK (2015). Interoceptive predictions in the brain. Nat Rev Neurosci, 16(7), 419–429. doi:10.1038/nrn3950 [PubMed: 26016744]

Bouton ME (1993). Context, time, and memory retrieval in the interference paradigms of Pavlovian learning. Psychol Bull, 114(1), 80–99. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/8346330 [PubMed: 8346330]

Braakman MH, Kortmann FA, & van den Brink W. (2009). Validity of 'post-traumatic stress disorder with secondary psychotic features': a review of the evidence. Acta Psychiatr Scand, 119(1), 15–24. doi:10.1111/j.1600-0447.2008.01252.x [PubMed: 18764840]

Brewin CR, & Patel T. (2010a). Auditory pseudohallucinations in United Kingdom war veterans and civilians with posttraumatic stress disorder. J Clin Psychiatry, 71(4), 419–425. doi:10.4088/JCP.09m05469blu [PubMed: 20361915]

Brewin CR, & Patel T. (2010b). Auditory pseudohallucinations in United Kingdom war veterans and civilians with posttraumatic stress disorder. J Clin Psychiatry, 71(4), 419–425. doi:10.4088/JCP.09m05469blu [PubMed: 20361915]

Brewin CR, Dalgleish T, & Joseph S. (1996). A dual representation theory of posttraumatic stress disorder. Psychol Rev, 103(4), 670–686. doi:10.1037/0033-295x.103.4.670 [PubMed: 8888651]

Brewin CR, Gregory JD, Lipton M, & Burgess N. (2010). Intrusive images in psychological disorders: characteristics, neural mechanisms, and treatment implications. Psychol Rev, 117(1), 210–232. doi:10.1037/a0018113 [PubMed: 20063969]

Brown R, & Kulik J. (1977). Flashbulb memories. Cognition, 5(1), 73–99. doi:10.1016/00100277(77)90018-x

Butler RW, Mueser KT, Sprock J, & Braff DL (1996). Positive symptoms of psychosis in posttraumatic stress disorder. Biol Psychiatry, 39(10), 839–844. doi:10.1016/00063223(95)00314-2 [PubMed: 9172704]

Chamberlin DE (2019). The Predictive Processing Model of EMDR. Front Psychol, 10, 2267. doi:10.3389/fpsyg.2019.02267 [PubMed: 31636594]

Chassy P, Calmès MD, & Prade H. (2012a). Making sense as a process emerging from perception-memory interaction: A model. International Journal of Intelligent Systems, 27(8), 757–775. doi:10.1002/int.21545

Chassy P, Calmès MD, & Prade H. (2012b). Making sense as a process emerging from perception-memory interaction: A model. International Journal of Intelligent Systems, 27(8), 757–775. doi:10.1002/int.21545

Colombo M, & Wright C. (2018). First principles in the life sciences: the free-energy principle, organicism, and mechanism. Synthese, 1–26. Retrieved from https://link.springer.com/article/10.1007/s11229-018-01932-w [PubMed: 30872868]

Conway MA, & Pleydell-Pearce CW (2000). The construction of autobiographical memories in the self-memory system. Psychol Rev, 107(2), 261–288. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/10789197 [PubMed: 10789197]

Corlett PR, Cambridge V, Gardner JM, Piggot JS, Turner DC, Everitt JC, . . . Fletcher PC (2013). Ketamine effects on memory reconsolidation favor a learning model of delusions. PLoS One, 8(6), e65088. doi:10.1371/journal.pone.0065088

Corlett PR, Horga G, Fletcher PC, Alderson-Day B, Schmack K, & Powers AR (2019). Hallucinations and Strong Priors. Trends Cogn Sci, 23(2), 114–127. doi:10.1016/j.tics.2018.12.001 [PubMed: 30583945]

Corlett PR, Krystal JH, Taylor JR, & Fletcher PC (2009). Why do delusions persist. Front Hum Neurosci, 3, 12. doi:10.3389/neuro.09.012.2009 [PubMed: 19636384]

Coronas R, Gallardo O, Moreno MJ, Suárez D, García-Parés G, & Menchón JM (2011). Heart rate measured in the acute aftermath of trauma can predict post-traumatic stress disorder: a prospective study in motor vehicle accident survivors. Eur Psychiatry, 26(8), 508–512. doi:10.1016/j.eurpsy.2010.06.006 [PubMed: 20813504]

d'Acremont M, Schultz W, & Bossaerts P. (2013). The human brain encodes event frequencies while forming subjective beliefs. J Neurosci, 33(26), 10887–10897. doi:10.1523/JNEUROSCI.5829-12.2013 [PubMed: 23804108]

de Bont PA, van den Berg DP, van der Vleugel BM, de Roos C, de Jongh A, van der Gaag M, & van Minnen AM (2016). Prolonged exposure and EMDR for PTSD v. a PTSD waiting-list condition: effects on symptoms of psychosis, depression and social functioning in patients with chronic psychotic disorders. Psychol Med, 46(11), 2411–2421. doi:10.1017/S0033291716001094 [PubMed: 27297048]

de Bont PA, van Minnen A, & de Jongh A. (2013). Treating PTSD in patients with psychosis: a within-group controlled feasibility study examining the efficacy and safety of evidence-based PE and EMDR protocols. Behav Ther, 44(4), 717–730. doi:10.1016/j.beth.2013.07.002 [PubMed: 24094795]

De Ridder D, Vanneste S, & Freeman W. (2014). The Bayesian brain: phantom percepts resolve sensory uncertainty. Neurosci Biobehav Rev, 44, 4–15. doi:10.1016/j.neubiorev.2012.04.001 [PubMed: 22516669]

Ehlers A, & Clark DM (2000). A cognitive model of posttraumatic stress disorder. Behaviour research and therapy, 38(4), 319–345. Retrieved from http://kognitifterapi.com/cbtistanbul/wp-content/uploads/2014/04/Ehlers_Clark_2000_ptsd.pdf [PubMed: 10761279]

Elsey JWB, Van Ast VA, & Kindt M. (2018). Human memory reconsolidation: A guiding framework and critical review of the evidence. Psychol Bull, 144(8), 797–848. doi:10.1037/bul0000152 [PubMed: 29792441]

Estes WK (1997). Processes of memory loss, recovery, and distortion. Psychol Rev, 104(1), 148–169. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/9009883 [PubMed: 9009883]

Fan JE, Hutchinson JB, & Turk-Browne NB (2016). When past is present: Substitutions of long-term memory for sensory evidence in perceptual judgments. J Vis, 16(8), 1. doi:10.1167/16.8.1

Foa EB, & Kozak MJ (1986). Emotional processing of fear: exposure to corrective information. Psychological bulletin, 99(1), 20. Retrieved from https://www.researchgate.net/profile/Edna_Foa2/publication/20283831_Foa_EB_Kozak_MJ_Emotional_processing_of_fear_Exposure_to_corrective_information_Psychol_Bull_99_20-35/links/0046351e8425bb5748000000.pdf [PubMed: 2871574]

Friston K. (2009). The free-energy principle: a rough guide to the brain. Trends Cogn Sci, 13(7), 293–301. doi:10.1016/j.tics.2009.04.005 [PubMed: 19559644]

Friston K. (2013). Life as we know it. J R Soc Interface, 10(86), 20130475. doi:10.1098/rsif.2013.0475

Friston K. (2005). A theory of cortical responses. Philos Trans R Soc Lond B Biol Sci, 360(1456), 815–836. doi:10.1098/rstb.2005.1622 [PubMed: 15937014]

Friston K, & Kiebel S. (2009). Predictive coding under the free-energy principle. Philos Trans R Soc Lond B Biol Sci, 364(1521), 1211–1221. doi:10.1098/rstb.2008.0300 [PubMed: 19528002]

Friston KJ, Parr T, & de Vries B. (2017). The graphical brain: Belief propagation and active inference. Netw Neurosci, 1(4), 381–414. doi:10.1162/NETN_a_00018 [PubMed: 29417960]

Gershman SJ, Jones CE, Norman KA, Monfils MH, & Niv Y. (2013). Gradual extinction prevents the return of fear: implications for the discovery of state. Front Behav Neurosci, 7, 164. doi:10.3389/fnbeh.2013.00164 [PubMed: 24302899]

Gottlieb JD, Cather C, Shanahan M, Creedon T, Macklin EA, & Goff DC (2011). D-cycloserine facilitation of cognitive behavioral therapy for delusions in schizophrenia. Schizophrenia research, 131(1–3), 69–74. Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3389827 [PubMed: 21723096]

Hamner MB, Frueh BC, Ulmer HG, Huber MG, Twomey TJ, Tyson C, & Arana GW (2000). Psychotic features in chronic posttraumatic stress disorder and schizophrenia: comparative severity. J Nerv Ment Dis, 188(4), 217–221. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/10789998 [PubMed: 10789998]

Hansen T, Olkkonen M, Walter S, & Gegenfurtner KR (2006). Memory modulates color appearance. Nat Neurosci, 9(11), 1367–1368. doi:10.1038/nn1794 [PubMed: 17041591]

Hardy A, Fowler D, Freeman D, Smith B, Steel C, Evans J, . . . Dunn, G. (2005). Trauma and hallucinatory experience in psychosis. J Nerv Ment Dis, 193(8), 501–507. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/16082293 http://ovidsp.tx.ovid.com/ovftpdfs/FPDDNCLBLDIHOK00/fs046/ovft/live/gv023/00005053/00005053-200508000-00001.pdf [PubMed: 16082293]

Haubrich J, & Nader K. (2018). Memory Reconsolidation. Curr Top Behav Neurosci, 37, 151-176. doi:10.1007/7854_2016_463

Hirst W, & Phelps EA (2016). Flashbulb Memories. Curr Dir Psychol Sci, 25(1), 36–41. doi:10.1177/0963721415622487 [PubMed: 26997762]

Hirst W, Phelps EA, Meksin R, Vaidya CJ, Johnson MK, Mitchell KJ, . . . Olsson A. (2015). A ten-year follow-up of a study of memory for the attack of September 11, 2001: Flashbulb memories and memories for flashbulb events. J Exp Psychol Gen, 144(3), 604-623. doi:10.1037/xge0000055

Ishai A, & Sagi D. (1995). Common mechanisms of visual imagery and perception. Science, 268(5218), 1772–1774. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/7792605 [PubMed: 7792605]

Ivezic S, Oruc L, & Bell P. (1999). Psychotic symptoms in post-traumatic stress disorder. Mil Med, 164(1), 73–75. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/9922651 [PubMed: 9922651]

Jessop M, Scott J, & Nurcombe B. (2008). Hallucinations in adolescent inpatients with post-traumatic stress disorder and schizophrenia: similarities and differences. Australas Psychiatry, 16(4), 268–272. doi:10.1080/10398560801982580 [PubMed: 18608156]

Kanai R, Komura Y, Shipp S, & Friston K. (2015). Cerebral hierarchies: predictive processing, precision and the pulvinar. Philos Trans R Soc Lond B Biol Sci, 370(1668). doi:10.1098/rstb.2014.0169

Kaplan R, & Friston KJ (2018). Planning and navigation as active inference. Biol Cybern, 112(4), 323–343. doi:10.1007/s00422-018-0753-2 [PubMed: 29572721]

Kindt M, Soeter M, & Vervliet B. (2009). Beyond extinction: erasing human fear responses and preventing the return of fear. Nature neuroscience, 12(3), 256. Retrieved from https://www.psychiatry.wisc.edu/courses/Nitschke/seminar/Kindt_Erasingfearresponses-suppl_NatNS2009.pdf [PubMed: 19219038]

Kording KP (2014). Bayesian statistics: relevant for the brain? Curr Opin Neurobiol, 25, 130–133. doi:10.1016/j.conb.2014.01.003 [PubMed: 24463330]

Kosslyn SM, Ganis G, & Thompson WL (2001). Neural foundations of imagery. Nat Rev Neurosci, 2(9), 635–642. doi:10.1038/35090055 [PubMed: 11533731]

Lacy JW, & Stark CEL (2013). The neuroscience of memory: implications for the courtroom. Nat Rev Neurosci, 14(9), 649–658. doi:10.1038/nrn3563 [PubMed: 23942467]

Lee JLC, Nader K, & Schiller D. (2017). An Update on Memory Reconsolidation Updating. Trends Cogn Sci, 21(7), 531–545. doi:10.1016/j.tics.2017.04.006 [PubMed: 28495311]

Lissek S, & van Meurs B. (2015). Learning models of PTSD: Theoretical accounts and psychobiological evidence. Int J Psychophysiol, 98(3 Pt 2), 594–605. doi:10.1016/j.ijpsycho.2014.11.006 [PubMed: 25462219]

Ma WJ, Beck JM, Latham PE, & Pouget A. (2006). Bayesian inference with probabilistic population codes. Nat Neurosci, 9(11), 1432–1438. doi:10.1038/nn1790 [PubMed: 17057707]

Ma WJ, Beck JM, & Pouget A. (2008). Spiking networks for Bayesian inference and choice. Curr Opin Neurobiol, 18(2), 217–222. doi:10.1016/j.conb.2008.07.004 [PubMed: 18678253]

Macpherson F. (2017). The relationship between cognitive penetration and predictive coding. Conscious Cogn, 47, 6–16. doi:10.1016/j.concog.2016.04.001 [PubMed: 27114093]

Mark JT, Marion BB, & Hoffman DD (2010). Natural selection and veridical perceptions. J Theor Biol, 266(4), 504–515. doi:10.1016/j.jtbi.2010.07.020 [PubMed: 20659478]

McCarthy-Jones S, & Longden E. (2015). Auditory verbal hallucinations in schizophrenia and post-traumatic stress disorder: common phenomenology, common cause, common interventions? Front Psychol, 6, 1071. doi:10.3389/fpsyg.2015.01071 [PubMed: 26283997]

McCarthy-Jones S, Trauer T, Mackinnon A, Sims E, Thomas N, & Copolov DL (2014). A new phenomenological survey of auditory hallucinations: evidence for subtypes and implications for theory and practice. Schizophr Bull, 40(1), 231–235. doi:10.1093/schbul/sbs156 [PubMed: 23267192]

Mišić B, Dunkley BT, Sedge PA, Da Costa L, Fatima Z, Berman MG, . . . Taylor MJ (2016). Post-Traumatic Stress Constrains the Dynamic Repertoire of Neural Activity. J Neurosci, 36(2), 419–431. doi:10.1523/JNEUROSCI.1506-15.2016 [PubMed: 26758834]

Morey RA, Dunsmoor JE, Haswell CC, Brown VM, Vora A, Weiner J, . . . LaBar KS (2015). Fear learning circuitry is biased toward generalization of fear associations in posttraumatic stress disorder. Transl Psychiatry, 5, e700. doi:10.1038/tp.2015.196 [PubMed: 26670285]

Mowrer O. (1947). On the dual nature of learning—a re-interpretation of" conditioning" and" problem-solving.". Harvard educational review.

Mueser KT, & Butler RW (1987). Auditory hallucinations in combat-related chronic posttraumatic stress disorder. Am J Psychiatry, 144(3), 299–302. doi:10.1176/ajp.144.3.299 [PubMed: 3826427]

Nicholson AA, Friston KJ, Zeidman P, Harricharan S, McKinnon MC, Densmore M, . . . Lanius RA (2017). Dynamic causal modeling in PTSD and its dissociative subtype: Bottom-up versus top-down processing within fear and emotion regulation circuitry. Hum Brain Mapp, 38(11), 5551–5561. doi:10.1002/hbm.23748 [PubMed: 28836726]

Norredam M, Jensen M, & Ekstrom M. (2011). Psychotic symptoms in refugees diagnosed with PTSD: a series of case reports. Nord J Psychiatry, 65(4), 283–288. doi:10.3109/08039488.2010.533385 [PubMed: 21087093]

Owens AP, Allen M, Ondobaka S, & Friston KJ (2018). Interoceptive inference: From computational neuroscience to clinic. Neurosci Biobehav Rev, 90, 174–183. doi:10.1016/j.neubiorev.2018.04.017 [PubMed: 29694845]

Parr T, & Friston KJ (2017). Working memory, attention, and salience in active inference. Sci Rep, 7(1), 14678. doi:10.1038/s41598-017-15249-0 [PubMed: 29116142]

Parr T, & Friston KJ (2018). The Anatomy of Inference: Generative Models and Brain Structure. Front Comput Neurosci, 12, 90. doi:10.3389/fncom.2018.00090 [PubMed: 30483088]

Parr T, & Friston KJ (2019). Generalised free energy and active inference. Biol Cybern, 113(5–6), 495–513. doi:10.1007/s00422-019-00805-w [PubMed: 31562544]

Parr T, Rees G, & Friston KJ (2018). Computational Neuropsychology and Bayesian Inference. Front Hum Neurosci, 12, 61. doi:10.3389/fnhum.2018.00061 [PubMed: 29527157]

Pearce J, Simpson J, Berry K, Bucci S, Moskowitz A, & Varese F. (2017). Attachment and dissociation as mediators of the link between childhood trauma and psychotic experiences. Clin Psychol Psychother, 24(6), 1304–1312. doi:10.1002/cpp.2100 [PubMed: 28653442]

Peters A, McEwen BS, & Friston K. (2017). Uncertainty and stress: Why it causes diseases and how it is mastered by the brain. Prog Neurobiol, 156, 164–188. doi:10.1016/j.pneurobio.2017.05.004 [PubMed: 28576664]

Pilton M, Varese F, Berry K, & Bucci S. (2015). The relationship between dissociation and voices: A systematic literature review and meta-analysis. Clin Psychol Rev, 40, 138–155. doi:10.1016/j.cpr.2015.06.004 [PubMed: 26117061]

Pivac N, Kozaric-Kovacic D, & Muck-Seler D. (2004). Olanzapine versus fluphenazine in an open trial in patients with psychotic combat-related post-traumatic stress disorder. Psychopharmacology (Berl), 175(4), 451–456. doi:10.1007/s00213-004-1849-z [PubMed: 15064916]

Powers AR, Kelley M, & Corlett PR (2016). Hallucinations as top-down effects on perception. Biol Psychiatry Cogn Neurosci Neuroimaging, 1(5), 393–400. doi:10.1016/j.bpsc.2016.04.003 [PubMed: 28626813]

Powers AR, Mathys C, & Corlett PR (2017). Pavlovian conditioning-induced hallucinations result from overweighting of perceptual priors. Science, 357(6351), 596–600. doi:10.1126/science.aan3458 [PubMed: 28798131]

Proulx T, & Heine SJ (2009). Connections from Kafka: exposure to meaning threats improves implicit learning of an artificial grammar. Psychol Sci, 20(9), 1125–1131. doi:10.1111/j.1467-9280.2009.02414.x [PubMed: 19656338]

Rubin DC, Berntsen D, & Bohni MK (2008). A memory-based model of posttraumatic stress disorder: evaluating basic assumptions underlying the PTSD diagnosis. Psychological review, 115(4), 985. Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/pmc2762652 [PubMed: 18954211]

Scott JG, Nurcombe B, Sheridan J, & McFarland M. (2007). Hallucinations in adolescents with post-traumatic stress disorder and psychotic disorder. Australas Psychiatry, 15(1), 44-48. doi:10.1080/10398560601083084 [PubMed: 17464634]

Seth AK (2013). Interoceptive inference, emotion, and the embodied self. Trends Cogn Sci, 17(11), 565–573. doi:10.1016/j.tics.2013.09.007 [PubMed: 24126130]

Seth AK, Suzuki K, & Critchley HD (2011). An interoceptive predictive coding model of conscious presence. Front Psychol, 2, 395. doi:10.3389/fpsyg.2011.00395 [PubMed: 22291673]

Steel C. (2015). Hallucinations as a trauma-based memory: implications for psychological interventions. Front Psychol, 6, 1262. doi:10.3389/fpsyg.2015.01262 [PubMed: 26441698]

Sterzer P, Adams RA, Fletcher P, Frith C, Lawrie SM, Muckli L, . . . Corlett PR (2018). The Predictive Coding Account of Psychosis. Biol Psychiatry, 84(9), 634–643. doi:10.1016/j.biopsych.2018.05.015 [PubMed: 30007575]

Stokes MG, Atherton K, Patai EZ, & Nobre AC (2012). Long-term memory prepares neural activity for perception. Proc Natl Acad Sci U S A, 109(6), E360–7. doi:10.1073/pnas.1108555108 [PubMed: 22109554]

Terr LC (1991). Childhood traumas: an outline and overview. Am J Psychiatry, 148(1), 10–20. doi:10.1176/ajp.148.1.10 [PubMed: 1824611]

Tronson NC, & Taylor JR (2007). Molecular mechanisms of memory reconsolidation. Nat Rev Neurosci, 8(4), 262–275. doi:10.1038/nrn2090 [PubMed: 17342174]

van den Berg DP, de Bont PA, van der Vleugel BM, de Roos C, de Jongh A, Van Minnen A, & van der Gaag M. (2015). Prolonged exposure vs eye movement desensitization and reprocessing vs waiting list for posttraumatic stress disorder in patients with a psychotic disorder: a randomized clinical trial. JAMA Psychiatry, 72(3), 259–267. doi:10.1001/jamapsychiatry.2014.2637 [PubMed: 25607833]

Varese F, Barkus E, & Bentall RP (2012). Dissociation mediates the relationship between childhood trauma and hallucination-proneness. Psychol Med, 42(5), 1025–1036. doi:10.1017/S0033291711001826 [PubMed: 21896238]

Vilares I, & Kording K. (2011). Bayesian models: the structure of the world, uncertainty, behavior, and the brain. Ann N Y Acad Sci, 1224, 22–39. doi:10.1111/j.1749-6632.2011.05965.x [PubMed: 21486294]

Waldfogel S, & Mueser KT (1988). Another case of chronic PTSD with auditory hallucinations. Am J Psychiatry, 145(10), 1314. doi:10.1176/ajp.145.10.1314b

Wearne D, & Genetti A. (2015). Pseudohallucinations versus hallucinations: wherein lies the difference. Australas Psychiatry, 23(3), 254–257. doi:10.1177/1039856215586150 [PubMed: 25948509]

Wilkinson S, Dodgson G, & Meares K. (2017). Predictive Processing and the Varieties of Psychological Trauma. Front Psychol, 8, 1840. doi:10.3389/fpsyg.2017.01840 [PubMed: 29089916]

Table 1.

Characteristics of Auditory Hallucinations in PTSD and Schizophrenia

	PTSD	**Schizophrenia**
Presence (Braakman et al., 2009; Butler et al., 1996)	Discrete flashbacks or continuous	Often continuous
Theme (Hardy et al., 2005; Wearne & Genetti, 2015)	Often no relation to trauma, but occasionally share the content and theme. Negative voices are more common than in schizophrenia.	Negative voices tend to have predominantly shaming themes, while positive voices are associated with greater control and positive attribution.
Associated delusions (Wearne & Genetti, 2015; Hamner et al., 2000)	Less common and less intense – more delusion-like beliefs rather than true delusions	More common and more intense
Ego-syntonic hallucinations (Brewin & Patel, 2010a; McCarthy-Jones et al., 2014)	More common	Less common
Subjective distress from the hallucinations (Jessop, Scott, & Nurcombe, 2008)	Higher	Lower
Command auditory hallucinations (Scott et al., 2007)	Less common	More common
Perceived locus (Scott et al., 2007; Jessop et al., 2008)	Often internal	Internal or external
Ability to identify the person whose voice is heard (Brewin & Patel, 2010a; Anketell et al., 2010; McCarthy-Jones et al., 2014)	More common	Less common
History of abuse (Wearne & Genetti, 2015)	Much more common	Less common