Computational Annealing as Mechanism
In Eye Movement Desensitization and Reprocessing
(EMDR)

Steven A. Stwertka, Ph.D.

Eugene, Oregon

The author wishes to express his gratitude to Alexis Norelle, M.D. for her assistance in manuscript preparation.

sstwertka@gmail.com

Abstract

The computational annealing model offers a plausible neurophysiological mechanism to account for eye movement desensitization and reprocessing's (EMDR) psychotherapeutic effectiveness. The model is informed by analogy to the physical annealing of metals and the related computational method of simulated annealing. It proposes that observed instances of chaotic activity and criticality within the nervous system serve to loosen constraints within memory networks, allowing them to reorganize in a direction of optimal internal coherence and harmony. The role of eye movements is to generate corollary discharge within relevant brain areas, inducing transient increases in criticality within working memory; effectively raising the computational temperature and facilitating informational and energetic flow towards optimal resolution of trauma related memories. Raising the computational temperature overcomes constraints maintaining fragmented and discordant cognitive schemas, enabling fuller integration with the broader sense of self. Computational annealing provides an outline of a conceptual bridge between observations made at the microscopic neurophysiological level, and those made at the macroscopic, behavioral level of description.

Keywords: EMDR, eye movement desensitization and reprocessing, simulated annealing, computational psychiatry, criticality, computational annealing, chaos theory

Introduction

Eye movement desensitization and reprocessing (EMDR) is a psychotherapeutic technique shown to be effective in treating symptoms of psychological trauma. The technique was developed to reduce the emotional distress and intrusive recollections characterizing post-traumatic stress disorder (PTSD). The EMDR procedure has been conceived of as allowing insufficiently processed and dysfunctional traumatic memory structures to resolve themselves into an adaptive, less distressing configuration. Induced eye movements are thought to facilitate a natural process of information processing, allowing memories to reorganize themselves into a form congruent with the individual's inner experience and coherent sense of self. As the original developer of the technique, Shapiro (2007) describes it: "The pattern of recovery in EMDR treatment sessions allows clinicians to view a rapid progression of intrapsychic connections as emotions, insights, sensations, and memories surface and change with each new set of bilateral stimulation" (p. 69). The EMDR technique emphasizes the importance of eye movements in the individual's ability to rapidly integrate and adaptively resolve trauma related memories and their associated feelings, however it provides no detail on how this information processing is accomplished or what brain mechanisms might be involved. The computational annealing model addresses these issues in light of recent advances in computational psychiatry and the neurosciences.

Psychological trauma

Psychological trauma affects a large percentage of the world's population. It is estimated that over 70% of adults will experience a psychologically traumatic event at some point in their lives (Shalev et al., 2017). Much like physical trauma to bone or soft tissue, the experience of extreme psychological events such as those associated with sexual abuse, accidents, and violence, among others, can overwhelm the mind's natural ability to process and meaningfully integrate the experience in an acceptable manner (Yehuda et al., 2015). A psychologically traumatic experience associated either directly or indirectly with personal harm or violation of strongly held beliefs and values results in a cascade of interacting physical, emotional, and cognitive events (Pitman et al., 2012; Van der Kolk, 1994). The residual effects of psychological trauma are known to persist over time and may go on to comprise the syndrome of emotional, physical, and cognitive disturbances characterized as post-traumatic

stress disorder (Briere & Spinazzola, 2005; Van der Kolk, 2000). The relationship between various features of this post-traumatic syndrome continue to challenge a complete understanding of how particular symptoms interact to maintain the syndrome and complicate recovery (Yehuda, 2002). There is however consensus that memories of the trauma, as well as the cognitions and meanings attributed to them, play a major role in contributing to the distress and dysfunction characterizing the post-traumatic syndrome (Cason et al., 2002; Dalgleish, 2004; Ehlers & Clark, 2000).

Cognitive appraisals (Lazarus, 1984; Roseman & Smith, 2001; Smith & Lazarus, 1993) associated with the traumatic event may result in high levels of emotional distress and feelings of inner dissonance (Harmon-Jones, 2000; Harmon-Jones & Harmon-Jones, 2007). Recall of the trauma often violates long held core beliefs and assumptions, creating a sense of fragmentation, and threatening an individual's perception of autobiographical coherence. Traumatic memories contribute to a disjointed autobiographical narrative, irreconcilable within the larger meaning of a person's life and sense of self (Brewin, 2014; 2016; Engelhard et al., 2019; Kleim et al., 2008; Reese et al., 2011; Sachschaal et al., 2019; Vaile Wright et al., 2010). An early account of this phenomenon was offered by Freud and his collaborator Breuer in their work *Studies on Hysteria*, originally published in 1895, describing the psychological defense of repression resulting from trauma:

The basis for repression itself can only be a feeling of unpleasure, the incompatibility between the single idea that is to be repressed and the dominant mass of ideas constituting the ego. The repressed idea takes its revenge however, by becoming pathogenic. (Breuer & Freud, 1955, p. 116)

Although an intact, historically accurate memory and account of the trauma may be present (Rubin, 2011), recollection of the traumatic event and the meanings attributed to it, are incompatible within the broader context of an individual's life experience, creating feelings of distress and contributing to psychological distortions and defenses that are characteristic of PTSD. Foremost among these are persistent intrusive memories and flashbacks, as well as a sense of being stuck in the moment of the traumatic event (Michael et al., 2005; Pitman & Orr, 1990; Van der Kolk & McFarlane, 1996). Feelings of being stuck and fixated on the trauma have been described by Pitman & Orr (1990) as comprising *the black hole of trauma*. Like the astrophysical phenomenon of space and time being drawn into a field of gravitational collapse,

the trauma victim's thinking and current experience are drawn back into a web of associations of the traumatic event, creating barriers interfering with therapeutic integration and processing. Overcoming these informational and energetic barriers to facilitate integration and coherence, forms the theoretical basis of EMDR's therapeutic effectiveness; it is also a fundamental principle of the process of computational annealing, developed here as EMDR's proposed mechanism of action.

EMDR and trauma psychotherapy

The emphasis in much of the psychotherapeutic treatment of PTSD is to integrate memories and cognitions associated with the trauma in a manner that develops a sense of internal coherence and meaning which is more compatible with the individual's broader life experience, thereby reducing cognitive dissonance and restoring feelings of self consistency and control. As stated by Briere (2002):

Although it is likely that narrative coherence arises intrinsically from trauma recovery, it is also likely that the development of a "story" of one's trauma is salutary. In this regard, it is probable that a coherent trauma (or abuse) narrative increases the survivor's sense of control over his or her experience, reduces feelings of chaos, and increases the sense that the universe is predictable and orderly, if not beneficent. (p. 21)

The most consistently recognized evidence-based psychotherapies for PTSD are: cognitive processing therapy (CPT) (Kleim et al., 2013; Resick & Schnicke, 1992; Ehlers et al., 2005), emotional processing therapy (EPT) (Foa & Kozak, 1986; Rauch & Foa, 2006) and eye movement desensitization and reprocessing (EMDR). Although these approaches differ significantly in their technique, they share a common recognition of the importance of cognition and personal meaning in the therapeutic process (Schnyder et al., 2015).

Unlike CPT and EPT, where there is an explicit and intentional effort on the part of the therapist to alter dysfunctional cognitions and fear memories associated with the traumatic event, the technique of EMDR emphasizes a more spontaneous integration and resolution of the trauma, believed to rely on the nervous system's intrinsic information processing and healing abilities. The technique was originally developed by Shapiro to reduce the emotional distress and intrusive recollections characterizing PTSD relatively quickly and effectively. Although the complete clinical methodology of EMDR is a structured approach consisting of

several procedural components and phases, the essential features of the EMDR protocol are quite straightforward. The therapeutic client is instructed to produce a series of eye movements while simultaneously recalling details of the most distressing aspects of the traumatic event (Shapiro, 1995; 2014). Over the course of repeated sets of eye movements, which are evoked by instructing the client to follow the therapists hand movements as they sweep back and forth in front of the client's field of view, traumatic memories are consistently reported to become less distressing and intrusive.

Meta-analytic reviews (Bisson et al., 2007; Cusack et al., 2016; Watts et al., 2013) have shown that EMDR is effective in treating PTSD, and comparable in efficacy to both CPT and EMT, including cognitive behavioral therapy (Seidler & Wagner, 2006) and exposure therapies (Lee et al., 2002). Although the EMDR technique has elements in common with these techniques, the core feature distinguishing EMDR, is the reliance on induced eye movements to facilitate therapeutic improvement and diminish distress associated with the traumatic event. The precise role that eye movements play in facilitating therapeutic improvement has been the subject of considerable debate (Jeffries & Davis, 2013), however the preponderance of studies available support the conclusion that eye movements elicited during EMDR contribute a unique and fundamentally important component to the unfolding therapeutic process (De Jongh et al., 2013; Jeffries & Davis, 2013; Lee & Drummond, 2008; Lee & Cuijpers, 2013; Lilley et al., 2009). Although the skilled EMDR therapist may choose to incorporate cognitive or behavioral interventions into the unfolding psychotherapeutic process, the utilization of the induced eye movements is unique to the approach and considered to be essential in more rapidly facilitating clinical improvement and reduced symptomatology.

Whereas EMDR's effectiveness as a psychotherapy has been established in multiple clinical trials, the therapeutic practice has not been without its detractors (Herbert et al., 2000). Resistance to its acceptance has been contributed to in part, by the difficulty integrating the procedure theoretically into classical paradigms of psychotherapy (Perkins & Rouanzoin, 2002; Russell, 2008). EMDR's mechanism of action has remained elusive, and lack of an accepted understanding for EMDR's effectiveness is likely to have interfered with its more widespread adoption as a valid psychotherapeutic technique. Detractors seem often to invoke the argument, that whereas EMDR may be effective in practice, it is untenable in theory.

Theories of EMDR's mechanism of action

A number of investigators have developed theories suggesting brain mechanisms and psychological principals that might account for EMDR's effectiveness. Propper and Christman (2008) have proposed that bilateral eye movements increase interhemispheric interaction, thereby improving the recall of traumatic episodic memories and allowing for more effective processing of the memory content. The working memory hypothesis developed by Andrade et al. (1997) proposes that traumatic recollections become less distinct and distressing during eye movements. They suggest that the divided attention required by simultaneously holding the traumatic memory in awareness while performing eye movements degrades the memory trace, such that it is subsequently recalled in a less vivid and distressing manner. Stickgold (2002) has proposed that bilateral stimulation induced by eye movements produces a brain state similar to that occurring during rapid eye movement (REM) sleep, effectively facilitating cortical integration of traumatic memories. Excellent review articles of these theories, as well as others is offered by Bergman (2010), Gunter and Bodner (2009), and Landin-Romero et al. (2018).

Adaptive information processing model (AIP)

In order to provide a conceptual framework for the developing field and technique of eye movement desensitization, Shapiro outlined what she termed the adaptive information processing model (Shapiro 1995; 2007). The adaptive information processing (AIP) model was based largely on her observations and intuitions about what was changing during the unfolding therapeutic process. The model proposes that dysfunctional, traumatic memories become encoded and maintained in an isolated and essentially *frozen* condition, due to inadequate information processing. These inadequately assimilated memories create distress, cognitive dissonance, and intrusive re-experiencing as the individual struggles to make sense of and integrate the traumatic event with their broader inner experience. It proposes that eye movements somehow facilitate the nervous system's innate tendency towards adaptive information processing and psychological healing.

The EMDR protocol is conceived of as allowing insufficiently processed and dysfunctional traumatic memory structures to resolve themselves into a more adaptive and less subjectively distressing configuration. The eye movements themselves are considered to facilitate a natural process of intrapsychic information processing, allowing memories to

reorganize themselves into a form more congruent with the individual's broader inner experience and coherent sense of self. As Solomon and Shapiro (2008) describe it:

Processing generally occurs through a rapid progression of intrapsychic connections in the session as emotions, insights, sensations, and memories surface and change with each new set of bilateral stimulation. The proposed mechanisms of action include the assimilation of adaptive information found in other memory networks linking into the network holding the previously isolated disturbing event. After successful treatment, it is posited that the memory is no longer isolated, because it appears to be appropriately integrated within the larger memory network. (p. 316)

Shapiro (1995) goes on to say that during EMDR: "The traumatic event is transmuted to an adaptive resolution with appropriate affect, self-attribution, and overall assessment" (p. 47).

The AIP model emphasizes the importance of eye movements and the nervous system's ability to rapidly integrate and adaptively resolve trauma related memories, however it does not provide detail on how this information processing is accomplished or what brain mechanisms might be involved. Given the breadth and scope of the clinical use of EMDR, a more fully developed theory should ideally provide a plausible neurophysiological basis for EMDR's effectiveness and account for its unique methodology and range of clinical uses.

Computational Psychiatry

The computational annealing model of EMDR developed here is supported by the conceptual approach of computational psychiatry. Computational psychiatry, broadly conceived, is the attempt to account for psychopathology and its treatment in terms of a fundamental understanding of information processing in the nervous system (Huys et al., 2016; 2021; Montague et al., 2012; Mujica-Parodi & Strey, 2020). In distinction to classical psychiatric theories emphasizing psychodynamics, developmental processes, social context and chemical imbalances, the computational perspective emphasizes the informational processes supporting and governing behavior at the neural level of organization. In doing so, the approach attempts to establish a correspondence between features observed at the behavioral level and features existing either theoretically or observationally within the nervous system.

The computational approach maintains that information processing within physical systems in general, such as computers and nervous systems, may follow mathematically similar rules that can be applied to understanding aspects of observed behavior (Linson & Friston, 2019; Pitman & Orr, 1990).

Mathematical formulations and computational methods known to be applicable across a broad range of physical processes can offer a deeper understanding of brain-behavior relationships (Adams et al., 2016; Durstewitz et al., 2020). This approach might be expected to be well suited to extending and developing the theory of adaptive information processing, thought to underlie the mechanism of EMDR.

Annealing

The central idea of the computational annealing model is that induced eye movements contribute to a process similar to a computational method known as *simulated annealing* within the distributed memory systems comprising the recalled traumatic event. The computational method of simulated annealing was originally described by Kirkpatrick, et al. (1983) as a mathematical algorithm to find solutions to optimization problems consisting of many variables. The method was inspired and developed by analogy to the process of metallurgical annealing, which involves cycles of repeatedly heating, and then slowly cooling, a metal object. Over the course of repeated cycles of heating and cooling the metal becomes stronger, as internal flaws and defects present before the annealing are diminished, and the internal structure becomes more uniform and integrated.

The annealing model of EMDR developed here is offered as an extension and elaboration of the adaptive information processing (AIP) model proposed by Shapiro. It is conceptually congruent with AIP as well as with observations made at higher levels of behavioral organization. The process of annealing, in which informational barriers are overcome, allowing the system to move naturally towards greater coherence and order is consistent with AIP; conceptualized as helping the client to become unstuck and establishing greater autobiographical coherence between fragmented and dysfunctional memories. The annealing model can be shown to be neurophysiologically plausible, and offers several predictions in the field of memory and eye movement research which have received preliminary experimental support.

Physical Annealing

Within solid metals, constituent elements may be arrayed in a uniform and repeating spatial configuration, displaying crystalline regularity. Physically deforming the solid metal typically produces regions where there are internal defects in this uniformity, creating dislocations and misalignment of coherent ordering. These regions of local strain and fragmentation effectively weaken the material properties of the solid and contribute to internal stresses. To relieve these dislocations and restore greater internal order and coherence, the object can be repeatedly heated and slowly cooled. By increasing the temperature, the process of annealing brings the metal closer to a more fluid phase. Transiently increasing random internal disorder allows irregularities and dislocations trapped within the metal to diminish, resulting in a spontaneous rearrangement towards greater regularity and consistency. As cooling occurs, the metal again moves towards a solid phase, preserving the new order and forming a stronger, more malleable material.

The process of annealing has effectively *optimized* the internal order and coherence of the molecular structure. The metal has gone from being *frozen* in a sub-optimal state, and through the introduction of heat, has overcome structural constraints and barriers, allowing it to settle into a more optimally ordered configuration. By alternating between these two phases of molten disordered heat, and solid structured cold, the metal has in a crude sense, solved the problem of establishing its optimally energetic configuration.

Simulated annealing

In simulated annealing, the physical process of annealing is represented mathematically, and simulated on a computer. By substituting variables other than the physical location of constituents of a material solid, simulated annealing has been generalized to solving a wide variety of computational problems (Aarts et al., 2014; Rutenbar, 1989; Suman & Kumar, 2006). Instead of solutions to the problem being the physical location of elements in a material, various solutions correspond to the optimal configuration of variables of a defined problem. Computationally, the parameter of physical temperature is replaced by informational randomness, or chaos (Chen & Aihara, 1995). This parameter has been described in the literature as the *computational temperature* (Hofstadter, 1994; Smolensky, 1987; 1989). The greater the computational temperature, the greater the number of degrees of freedom and possible solutions to the problem. There are a great number of possible solutions when the

computational temperature is high and constraints relaxed, however as the computational temperature is reduced, degrees of freedom diminish until a best fit, or optimal solution is arrived at.

The computational annealing model proposes that informationally there is a corresponding process of neurophysiological annealing occurring during EMDR, and that the equivalent of the computational temperature is raised by induced eye movements. This process would allow for dysfunctional memories trapped in local sub-optimal configurations, to escape informational and energetic constraints maintaining its dissonance, and converge naturally towards a condition of greater internal order and coherence (Shultz & Lepper, 1996; Thagard & Verbeurgt, 1998).

Both simulated annealing and metallurgical annealing fundamentally rely on relaxing and overcoming physical and informational constraints, by subjecting the system to increased energy, temperature, and disorder. Shifting the *phase* of the system from an initially frozen solid state to a softer more fluid state, allows the system to overcome an energetically stuck condition, enabling it to spontaneously reorganize into one of greater global coherence and lower free energy. The annealing model proposes that there may be a similar process occurring within the brain, and that eye movements, in conjunction with the simultaneous recall of dysfunctional memories, are permitting those memory structures to optimally reorganize themselves towards greater global integration.

Recent advances in the neurosciences have provided compelling evidence that many of the anatomical and physiological features necessary to fulfill this process in fact exist. The brain may be similarly sensitively balanced between two distinct phases of activity: an ordered and a disordered phase. This balance between order and disorder is thought to facilitate information processing in the brain and may be a fundamental characteristic of its activity.

Chaos, Criticality and Corollary Discharge

Chaos

The computational method of simulated annealing relies on the deep physical association between concepts of temperature, and those of disorder or randomness. The idea that transiently increasing internal disorder or *chaos* within the nervous system could facilitate information processing might initially seem counterintuitive; however it has been shown to

offer advantages within distributed systems of neural information processing (Bertschinger & Natschläger, 2004; Langton, 1990). Chaos has properties that are similar to random activity but has several practical and mathematical differences (Rickles et al., 2007). Chaos may appear like completely random activity but can be purposefully generated within a system by the application of deterministic rules. As such, the degree of disorder can be controlled and utilized to facilitate and tune aspects of information processing (Shinbrot et al., 1993). Chaos has also been used as a computational temperature parameter within simulated annealing algorithms (Chen & Aihara, 1995; Tokuda et al., 1998; Wang et al., 2004).

Early insights into the role that chaos might play in the brain, emphasized that it was important in preventing previous learning from becoming fixed and inflexible; as perceptual and cognitive processes need to respond freshly to ever-changing environmental demands (Korn & Faure, 2003; Rabinovich & Abarbanel, 1998). This theme was more fully developed by the pioneering work of Skarda and Freeman (1987) in their publication: *How Brain's Make Chaos in Order to Make Sense of the World*. They noted how the presence of brief chaotic shifts could serve to prevent a repetitious cycle of previously generated activity. "Chaos provides the system with a deterministic 'I don't know' state within which new activity patterns can be generated" (p. 171). This chaotic perturbation within distributed *macrostates* of brain activity (Allefeld et al., 2009; Bressler & Menon, 2010), particularly during periods of sensory input - such as during eye movements - when the visual system is actively engaged in perceptual assessment, is thought to prevent informational convergence back to previously learned behavior, allow for greater sensitivity to novelty, and ultimately, more adaptable, flexible responding to novel environmental demands (Liljenström, 2003; Skarda & Freeman, 1990).

Criticality

By maintaining a balance between stability and instability - order and disorder - nerve networks are thought to achieve a greater flexibility in responding to both inner conditions and environmental demands. This balance has been identified in the brain and termed, *criticality* (Heiney, et al., 2021; Plenz & Thiagarajan, 2007; Yu et al., 2013). Criticality is thought to be a general operational principle of healthy cortical functioning (Hesse & Gross, 2014). By briefly destabilizing cortical regions through transient criticality, the brain is able to overcome informational biases established by previous experience; becoming optimally poised to

respond with novel modes of activity and more accurately reflecting changing demands of the internal and external environment.

Criticality has been described by Shew and Plenz (2013) as optimizing information processing, and by Tsuda (2015) as potentially contributing to the formation of associative memory networks. Of relevance in support of the annealing model, Hahn et al. (2017), have described cortical activity in the visual cortex “poised towards criticality”. Rajkai et al. (2008), have reported increased activity in the visual cortex associated with eye movements. These findings have been interpreted as potentially reflecting higher levels of excitability, effectively enhancing and priming the visual system for optimal sensitivity; an observation consistent with the idea that cortical regions become quickly and adaptively tuned towards criticality to broaden their dynamic range of sensitivity, facilitate metastability (Werner, 2007) and optimize information processing (Beggs, 2008; Haldeman & Beggs, 2005; Kinouchi & Copelli, 2006; Palva & Palva, 2018; Shew et al., 2015; Tomen & Ernst, 2019). Review articles by Shriki and Yellin (2016), Wilting and Priesemann (2019) and Zimmerman (2020) offer excellent summaries of the role of criticality and its significance in the behavioral neurosciences.

Criticality describes the point where two *phases* of activity: ordered and disordered, begin to transition and lose their distinctive properties. The system can be referred to as being *metastable* (Tognoli & Kelso, 2014) or capable of rapidly shifting from one phase of activity to the other (Bertschinger & Natschläger, 2004; Kelso et al., 1992; Plenz, 2013). The term phase is generally used in the material sciences to describe the state of a material depending largely on its temperature, either a liquid phase or a solid phase. As outlined previously, alternating between a high temperature phase of relative disorder, and subsequent cooling to a lower temperature phase of greater stability and order, precisely describes the method of annealing; the computational mechanism proposed to be central to the process of adaptive information processing in EMDR.

Corollary Discharge

Insights and observations of criticality have emphasized that edge of chaos activity, induced at or around the time of perceptual search and orienting, serves to facilitate information processing and prepare the brain to assimilate and adaptively respond to the current environment. The visual system and cortical association areas have long been recognized to display activity that anticipates sensory input from brain regions initiating eye

movements. This feature of classical neurophysiology is termed *corollary discharge* (Poulet & Hedwig, 2007). Redirecting visual attention with eye movements generates two distinct streams of activity, a process referred to as corollary discharge. One stream of neural activity is directed towards the cranial nerves innervating muscles of the eyes. The other, a corollary stream of activity, is directed internally, towards the visual and association cortex. (Duhamel et al., 1992; Nakamura & Colby, 2002; Sommer & Wurtz, 2004). Corollary discharge is thought to fulfill several functions throughout the animal kingdom: stabilizing the apparent motion caused by displacement of the visual scene on the retina and priming cortical areas towards optimal sensitivity to anticipated sensory input (Crapse & Sommer, 2008).

Corollary discharge originating in brain stem regions initiating eye movements and directed towards higher cortical areas is thought to facilitate the interpretation and analysis of sensory information and provide a context for generating a meaningful response to sensory input (Bansal et al., 2018). It is known that regions active during eye movements overlap anatomically with areas thought to subserve autobiographical memory. Activating these overlapping areas toward a phase change to criticality with eye movement induced corollary discharge, while simultaneously recalling traumatic memories, forms the core premise of the computational annealing model and the presumed basis for adaptive information processing in EMDR. The computational annealing model maintains that during EMDR, eye movements are transiently increasing the computational temperature of the representational system encoding recalled information, effectively unfreezing it and temporarily reducing energetic constraints that have been a neural as well as behavioral obstacle to adaptive integration and change.

Computational Annealing and EMDR

Trauma related distress is thought to result in part from inconsistency and lack of integration between the experience of trauma, and thoughts and beliefs existing prior to the traumatic event. Computational annealing describes the process of facilitating greater internal self-consistency and coherence. It maintains that eye movements induce the energetic equivalent of computational heat into trauma related memory networks, and that these networks overcome a frozen dysfunctional form to reorganize themselves adaptively towards better integration with those comprising the global sense of self. The annealing process overcomes energetic barriers allowing for resetting and refreshing of perceptual and cognitive systems that have remained effectively frozen and trapped in intrusive and perseverative

loops of re-experiencing. The annealing facilitates an optimal integration of memory networks and *schemas*. Schema in this context is understood in the manner described by Cason et al. (2002) in their review of schemas in PTSD: ““schema” is meant to encompass all working models of the cognitive and affective processes undergone by trauma survivors, as they integrate traumatic events into their overall conceptual systems” (p.132). The concept has played a central role as an organizing principal in the field of traumatology and cognitive psychology (Horowitz, 1986; 1991; 2003).

The annealing model proposes that corollary discharge from induced eye movements biases relevant brain areas toward criticality by increasing the computational temperature in recalled memory systems; thereby supporting an informational environment with properties formally equivalent to those in which simulated annealing algorithms have been demonstrated. Raising the computational temperature within distributed memory systems allows for reorganization and optimization consistent with the principles of annealing outlined earlier. Annealing increases informational degrees of freedom and relaxes constraints, supporting a search within an informational space containing a wider range of options for finding optimal integration. Expressed in terms of dynamical systems theory: the system is lifted from being trapped in an attractor basin of local energy minima, to search the state space for a globally optimal energy minima (Tank & Hopfield, 1987). Partial or suboptimal solutions which may have energetically limited alternative solutions, are overcome by the annealing process, and the system eventually converges on a best-fit or optimal outcome.

Computational annealing catalyzes a transition from a condition of dysfunctional order, into disorder, from which arises a more global integration of experience. Eye movement related activity induces the equivalent of a phase change within relevant memory networks, allowing them to become more fluid and flexible. As connection strengths within neural states and memories are relaxed, it allows for greater associational flow and reorganization along lines of energy minimization as directed by the annealing process. As eye movements cease, the representational system, having overcome barriers within its internal energy landscape and having escaped from basins of local energy minima, can begin reorganization more effectively satisfying the constraints of the totality of schemas comprising a more harmonious sense of self. Clinically, this is accompanied by an overall reduction in intrusive symptomatology, emotional distress, and a greater sense of personal integration.

Anatomical Plausibility

The plausibility of the annealing model requires that brain regions activated during eye movements, are also active during mental imagery, recall of episodic autobiographical memory, or both. Several neuroimaging studies have revealed distinct cortical areas overlapping in precisely this manner (Pagani et al., 2013). The parietal eye field (Muri, et al., 1996), corresponding roughly to *Brodmann areas 39 and 40*, have been shown to be activated during eye movements (Konen et al., 2004; Petit & Haxby, 1999; Pierrot-Deseilligny et al., 2004; Tanabe et al., 2002). These same cortical regions have also been shown to be activated during imagery (Ganis et al., 2004) or recall of episodic autobiographical memories (Graham et al., 2003; Levine, et al., 2004; Svoboda et al., 2006; Wagner et al., 2005). These parietal regions have also been reported by Pearson (2009) as being of unique relevance during EMDR.

Similar organization is displayed in areas of the temporal lobe. Neuroimaging performed by Ganis et al. (2004) and Kosslyn et al. (1997), have shown activation of the temporal lobe associated with the generation of mental imagery and memory retrieval (Cabeza & Nyberg, 2000; Ranganath et al., 2004). These same areas are activated during eye movements (Petit & Haxby, 1999; Tanabe, et al., 2002). These results, coupled with the fact that memory recall has been shown to entail actual re-activation of the same brain regions involved during encoding (Danker & Anderson, 2010; Kuhl et al., 2010) support the claim that EMDR's protocol of recalling events and imagery during sets of eye movements is exposing associated memory networks directly to eye movement induced neural activation.

As EMDR modifies memory networks and their associated cognitions and schemas in the direction of greater integration and coherence, cognitive dissonance and perceived threat are diminished, reducing the hyper-arousal and emotional over-reactivity previously established by the traumatic event. The cognitive as well as the emotional texture and content of the recalled event would be influenced given their mutual interdependence. This relationship is described by Phelps (2006):

As our understanding of the cognitive neuroscience of emotion and cognition grows, it is increasingly apparent that the division of human behavior into emotion and cognition is not as clear as previous philosophical and psychological investigations have suggested. The mechanisms of emotion and cognition appear to be intertwined at all stages of stimulus processing and their distinction can be difficult. (p. 46)

Heightened arousal and affect during the EMDR procedure itself, would be expected to facilitate improved access to memory networks consolidated in an emotionally state dependent manner, allowing them freer expression to be more widely integrated into the unfolding therapeutic gestalt.

EMDR's beneficial effects have been characterized in the literature using a variety of terms and descriptions, including: unfreezing dysfunctional memories, facilitating linkages, hastening integration, diminishing cognitive dissonance, overcoming rigidity, becoming unblocked, and accomplishing transmutation, among others. Intuitively these observations have a strong resemblance to the actual process of physical and simulated annealing, offering additional support for the plausibility of the computational annealing model.

Discussion

The computational annealing model attempts to provide a detailed and plausible account of what may be one of the mechanisms underlying the improvement of symptoms in PTSD. The computational process of annealing reviewed in this paper could be considered as much an expression of a physical principle, an unfolding of a natural process, as it is a specific method or technique. The concept of minimization of free energy, derived from the physics of thermodynamics, is foundational in both physical, as well as simulated annealing. This principle has been developed in the pioneering work by Friston, as it may apply to information processing in the brain (Friston, et al., 2006; Friston & Stephan, 2007). Friston has described how energy minimization can be seen as a general principle in the neurosciences and productively applied to understanding aspects of perception, memory, and decision making. The field of computational science is increasingly committed to the idea that computation is deeply embedded in the physical and biological sciences, and that what is commonly referred to as "information processing" can be represented in many overlapping ways, and implemented within a diverse number of physical systems, often with a parallel conceptual basis (Chalmers, 2011; Denning, 2007; Hopfield & Tank, 1985; Mitchell, 2011).

The technique of simulated annealing has proven to be a particularly useful and robust methodology for finding solutions to questions that can be framed as optimization problems. Inspired by the natural process of developing coherence and order within crystals, the method of annealing has been adapted for use in the computer sciences and is currently one of the computational techniques used in *quantum annealing* computers, being developed as the next

phase in the evolution of computer technology (Ruiz, 2014; Seddiqi & Humble, 2014; Venegas-Andraca, 2018). Quantum computers exploit many of the same principles of energy minimization used in the simulated annealing algorithm, utilizing the unique properties of the quantum states of atoms to embody the energy levels of the evolving informational system. That the brain might support a similar computational process seems plausible. Interestingly, areas of the cortex itself, may be functionally organized in a regularly ordered manner, with a lattice structure of receptive fields (Bressloff & Cowan, 2002) similar to those seen in the crystal structures that were the original inspiration for the annealing algorithm.

In the field of engineering, simulated annealing has been generalized to solve a variety of problems requiring finding an optimal solution within complex systems consisting of a great number of variables and potential outcomes, but only one best or optimal solution (Suman & Kumar, 2006). The method has been productively applied in areas as diverse as computer object recognition (Betke & Makris, 1995) and the reconstruction of degraded stored images (Geman & Geman, 1984; Robini et al., 1999).

Based on the optimization search properties of the annealing process, the current model would predict that repetitive eye movements might similarly improve memory search. There is evidence that it does, particularly in the recall of episodic memory. (Brunyé et al., 2009; Christman et al., 2003; Nieuwenhuis et al., 2013; Parker et al., 2018; 2020). There are however, also studies showing no effect of eye movements on a test of free-recall (Matzke et al., 2015; Roberts et al., 2020). These contradictory results may reflect an important distinction between short term free-recall, and the deep and distributed processing required of truly episodic memory as characterized by Tulving (2002) as entailing true “recollective experience” (p. 4).

The annealing model also predicts facilitated problem solving resulting from induced eye movements due to their presumptive role in pushing certain brain areas closer to criticality and metastability (Tognoli & Kelso, 2014). Transiently relaxing informational and energetic constraints at a neuronal level should correspondingly relax constraints at a behavioral level, allowing for greater flexibility and creative problem solving. Research supporting these inferences is suggestive but inconclusive (Thomas & Lleras, 2007). The strongest direct support for an eye movement effect on creativity and problem solving, is work published by Shobe et al. (2009) as well as Fleck and Braun (2015) showing an enhancement on measures of creativity by bilateral eye movements.

The recognition that the concept of simulated annealing may have something to offer psychology is not entirely new. Several authors have described how creative problem solving could potentially be facilitated by a process like simulated annealing (Cagan & Kotovsky, 1997; Gabora, 2010; Gopnik et al., 2017; Howard-Jones & Murray, 2003; Martindale, 1995). In their view, an annealing process would be expected to temporarily overcome constraints in how a problem was being represented and conceptualized by the cognitive system, providing greater flexibility in generating possible solutions. Through an internal mechanism similar to annealing, the problem-solving process would have access to a broader range of outcomes and creative alternatives, allowing for the development of more integrative and novel solutions.

The computational annealing model is distinct from both the working memory hypothesis and the rapid eye movement hypothesis of EMDR, in that it proposes a unique process of neurophysiological information processing as the basis for EMDR's effectiveness. Instead of EMDR rendering the traumatic memory trace degraded and therefore less vivid and emotionally salient, the annealing model maintains that the memory is less emotionally salient because it has been optimally integrated into the broader and more inclusive memory structure. The memory has not been effectively masked, but creatively incorporated. This conclusion is more congruent with Shapiro's (2014) intuitions regarding EMDR's effectiveness, in which she states: "Completed processing is posited to involve an alteration of the originally stored memory through a process of integration and reconsolidation" (p. 74). If rapid eye movement sleep and dreaming bear functional similarities to the EMDR protocol as has been suggested by Stickgold (2002), it would be interesting to speculate that both these phenomena may share annealing as a common mechanism of action.

It should be acknowledged that induced eye movements have not been the only sensory modality recognized to facilitate therapeutic change with distressing memories. Both tones as well as other distractor tasks have been shown to be beneficial, however to a lesser degree than eye movements (De Jongh et al., 2013; Van den Hout et al., 2012). This fact was addressed by an earlier model of EMDR's effectiveness developed by Armstrong and Vaughn (1996), termed the *orienting response model*. According to this model, hand movements or other sources of distraction evoke a physiological orienting towards the stimulus, while the simultaneous attentional focus on trauma related memories leads to an extinction of the elicited fear response and effective desensitization of the memory. While recognizing the behavioral importance of the orienting response, the annealing model interprets this effect

differently. Instead of viewing orienting within a classical stimulus response habituation paradigm, behavioral orienting is seen as preparing the sensory system to accept, integrate and adaptively respond to new environmental information. According to the neural criticality viewpoint outlined earlier, eye movements would transiently destabilize existing memory networks to prepare the system to react to novel input without prior activation biases. This property allows the system to overcome *functional fixedness* and encourages creative responding, better suited to behavioral adaptation. This is consistent within the framework of the annealing model which views the therapeutic resolution of trauma as an active and creative process of problem solving.

Any event or technique which subtly destabilizes existing dysfunctional patterns of behavior, sets the stage for potential reintegration into more coherent and harmonious forms of activity. As Skarda and Freeman (1987) describe it, referring to perception:

We think that the notion of “destabilization” provides a better description of the essentials of neural functioning than the concept of pattern completion. In an alert, motivated animal, input destabilizes the system, leading to further destabilization and a bifurcation to a new form of patterned activity. (p.172)

A consistent theme in the development of the annealing model is the presumed role that a degree of disorder assumes at the neural level of organization. This disorder is considered to play a significant role in what unfolds during EMDR and the process of annealing, during which memory systems converge towards optimal integration of what had been previously a dysfunctional network of traumatic content. This movement from discord to relative internal coherence, is the fundamental aim of most psychotherapeutic approaches. During EMDR, the mental and neurophysiological constraints contributing to cognitive dissonance and distress are relaxed, allowing for the development of optimal coherence and integration. In a sense, the premise of the black hole of trauma introduced by Pittman and Orr (1990) has been fulfilled. In the annealing model, energy barriers representing constraints imposed by local energy minima are overcome, allowing cognitive schema to escape their attractor basins and converge instead toward a more globally integrated state space, identified by Smolensky (1987; 1989) as the configuration of an informational system displaying optimal overall coherence: a condition he terms “harmony”. Computational annealing essentially describes the process of facilitating greater internal consistency and coherence. As such, its

relevance potentially extends to those areas in which EMDR has been described and developed as holding out hope as a fully integrative psychotherapy (Shapiro, 2002), whose applicability extends beyond the treatment of trauma to other clinical conditions.

References

- Aarts, E., Korst, J., & Michiels, W. (2014). Simulated annealing. In E. K. Burke, & G. Kendall, *Search methodologies, introductory tutorials in optimization and decision support techniques, 2nd Edition* (pp. 265-285). Boston, MA: Springer.
- Adams, R. A., Huys, Q. J., & Roiser, J. P. (2016). Computational psychiatry: Towards a mathematically informed understanding of mental illness. *Journal of Neurology, Neurosurgery & Psychiatry*, 87(1), 53-63. <https://dx.doi.org/10.1136/jnnp-2015-310737>.
- Allefeld, C., Atmanspacher, H., & Wackermann, J. (2009). Mental states as macrostates emerging from brain electrical dynamics. *Chaos: An Interdisciplinary Journal of Nonlinear Science*, 19(1), 015102. <https://doi.org/10.1063/1.3072788>.
- Andrade, J., Kavanagh, D., & Baddeley, A. (1997). Eye-movements and visual imagery: A working memory approach to the treatment of post-traumatic stress disorder. *British Journal of Clinical Psychology*, 36(2), 209-223. <https://doi.org/10.1111/j.2044-8260.1997.tb01408.x>.
- Armstrong, M. S., & Vaughan, K. (1996). An orienting response model of eye movement desensitization. *Journal of Behavior Therapy and Experimental Psychiatry*, 27(1), 21-32. [https://doi.org/10.1016/0005-7916\(95\)00056-9](https://doi.org/10.1016/0005-7916(95)00056-9).
- Bansal, S., Ford, J. M., & Sperling, M. (2018). The function and failure of sensory predictions. *Annals of the New York Academy of Sciences*, 1426(1), 199-220. <https://doi.org/10.1111/nyas.13686>.
- Beggs, J. M. (2008). The criticality hypothesis: How local cortical networks might optimize information processing. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 366(1864), 329-343. <https://doi.org/10.1098/rsta.2007.2092>.

- Bergmann, U. (2010). EMDR's neurobiological mechanisms of action: A survey of 20 years of searching. *Journal of EMDR Practice and Research*, 4(1), 22-42.
<https://doi.org/10.1891/1933-3196.4.1.22>.
- Bertschinger, N., & Natschläger, T. (2004). Real-time computation at the edge of chaos in recurrent neural networks. *Neural Computation*, 16(7), 1413-1436.
<https://doi.org/10.1162/089976604323057443>.
- Betke, M., & Makris, N. C. (1995). Fast object recognition in noisy images using simulated annealing. *Proceedings of IEEE International Conference on Computer Vision*, 523-530.
- Bisson, J. I., Ehlers, A., Matthews, R., Pilling, S., Richards, D., & Turner, S. (2007). Psychological treatments for chronic post-traumatic stress disorder: Systematic review and meta-analysis. *The British Journal of Psychiatry*, 190(2), 97-104. [https://doi: 10.1192/bjp.bp.106.021402](https://doi.org/10.1192/bjp.bp.106.021402).
- Bressler, S. L., & Menon, V. (2010). Large-scale brain networks in cognition: Emerging methods and principles. *Trends in Cognitive Sciences*, 14(6), 277-290.
<https://doi.org/10.1016/j.tics.2010.04.004>.
- Bressloff, P. C., & Cowan, J. D. (2002). The visual cortex as a crystal. *Physica D: Nonlinear Phenomena*, 173(3-4), 226-258. [https://doi.org/10.1016/S0167-2789\(02\)00677-2](https://doi.org/10.1016/S0167-2789(02)00677-2).
- Breuer, J., & Freud, S. (1955). *Studies on hysteria*. (J. Strachey, & A. Freud, Eds.) New York: Basic Books.
- Brewin, C. R. (2014). Episodic memory, perceptual memory, and their interaction: foundations for a theory of posttraumatic stress disorder. *Psychological Bulletin*, 140(1), 69-97.
<https://doi.org/10.1037/a0033722>.
- Brewin, C. R. (2016). Coherence, disorganization, and fragmentation in traumatic memory reconsidered: A response to Rubin et al. (2016). *Journal of Abnormal Psychology*, 125(7), 1011-1017. <https://doi.org/10.1037/abn0000154>.
- Briere, J. (2002). Treating adult survivors of severe childhood abuse and neglect: Further development of an integrative model. In J. E. Myers, L. Berliner, J. Briere, C. T. Hendrix, T. Reid, & C. Jenny, *The APSAC handbook on child maltreatment, 2nd Edition* (pp. 1-26). Newbury Park, CA: Sage Publications.

- Briere, J., & Spinazzola, J. (2005). Phenomenology and psychological assessment of complex posttraumatic states. *Journal of Traumatic Stress: Official Publication of The International Society for Traumatic Stress Studies*, 18(5), 401-412.
<https://doi.org/10.1002/jts.20048>.
- Brunyé, T. T., Mahoney, C. R., Augustyn, J. S., & Taylor, H. A. (2009). Horizontal saccadic eye movements enhance the retrieval of landmark shape and location information. *Brain and Cognition*, 70(3), 279-288. <https://doi.org/10.1016/j.bandc.2009.03.003>.
- Cabeza, R., & Nyberg, L. (2000). Imaging cognition II: An empirical review of 275 PET and fMRI studies. *Journal of Cognitive Neuroscience*, 12(1), 1-47.
<https://doi.org/10.1162/08989290051137585>.
- Cagan, J., & Kotovsky, K. (1997). Simulated annealing and the generation of the objective function: A model of learning during problem solving. *Computational Intelligence*, 13(4), 534-581. <https://doi.org/10.1111/0824-7935.00051>.
- Cason, D. R., Resick, P. A., & Weaver, T. L. (2002). Schematic integration of traumatic events. *Clinical Psychology Review*, 22(1), 131-153. [https://doi.org/10.1016/S0272-7358\(01\)00085-X](https://doi.org/10.1016/S0272-7358(01)00085-X).
- Chalmers, D. J. (2011). A computational foundation for the study of cognition. *Journal of Cognitive Science*, 12(4), 325-359.
- Chen, L., & Aihara, K. (1995). Chaotic simulated annealing by a neural network model with transient chaos. *Neural Networks*, 8(6), 915-930. [https://doi.org/10.1016/0893-6080\(95\)00033-V](https://doi.org/10.1016/0893-6080(95)00033-V).
- Christman, S. D., Garvey, K. J., Propper, R. E., & Phaneuf, K. A. (2003). Bilateral eye movements enhance the retrieval of episodic memories. *Neuropsychology*, 17(2), 221-229.
<https://doi.org/10.1037/0894-4105.17.2.221>.
- Crapse, T. B., & Sommer, M. A. (2008). Corollary discharge across the animal kingdom. *Nature Reviews Neuroscience*, 9, 587-600. <https://doi.org/10.1038/nrn2457>.
- Cusack, K., Jonas, D. E., Forneris, C. A., Wines, C., Sonis, J., Middleton, J. C., . . . Gaynes, B. N. (2016). Psychological treatments for adults with posttraumatic stress disorder: A systematic review and meta-analysis. *Clinical Psychology Review*, 43, 128-141.
<https://doi.org/10.1016/j.cpr.2015.10.003>.

- Dalgleish, T. (2004). Cognitive approaches to posttraumatic stress disorder: The evolution of multirepresentational theorizing. *Psychological Bulletin*, 130(2), 228-260.
<https://doi:10.1037/0033-2909.130.2.228>.
- Danker, J. F., & Anderson, J. R. (2010). The ghosts of brain states past: Remembering reactivates the brain regions engaged during encoding. *Psychological Bulletin*, 136(1), 87-102. <https://doi.org/10.1037/a0017937>.
- De Jongh, A., Ernst, R., Marques, L., & Hornsvelt, H. (2013). The impact of eye movements and tones on disturbing memories involving PTSD and other mental disorders. *Journal of Behavior Therapy and Experimental Psychiatry*, 44(4), 477-483.
<https://doi.org/10.1016/j.jbtep.2013.07.002>.
- Denning, P. J. (2007). Computing is a natural science. *Communications of the Association for Computing Machinery*, 50(7), 13-18. <https://doi.org/10.1145/1272516.1272529>.
- Duhamel, J. R., Colby, C. L., & Goldberg, M. E. (1992). The updating of the representation of visual space in parietal cortex by intended eye movements. *Science*, 255(5040), 90-92.
<https://doi:10.1126/science.1553535>.
- Durstewitz, D., Huys, Q. J., & Koppe, G. (2020). Psychiatric illnesses as disorders of network dynamics. *Biological Psychiatry: Cognitive Neuroscience and Neuroimaging*, ,
<https://doi.org/10.1016/j.bpsc.2020.01.001>.
- Ehlers, A., & Clark, D. M. (2000). A cognitive model of posttraumatic stress disorder. *Behaviour Research and Therapy*, 38(4), 319-345. [https://doi.org/10.1016/S0005-7967\(99\)00123-0](https://doi.org/10.1016/S0005-7967(99)00123-0).
- Ehlers, A., Clark, D. M., Hackmann, A., McManus, F., & Fennell, M. (2005). Cognitive therapy for post-traumatic stress disorder: Development and evaluation. *Behaviour Research and Therapy*, 43(4), 413-431. <https://doi.org/10.1016/j.brat.2004.03.006>.
- Engelhard, I. M., McNally, R. J., & van Schie, K. (2019). Retrieving and modifying traumatic memories: Recent research relevant to three controversies. *Current Directions in Psychological Science*, 28(1), 91-96. <https://doi.org/10.1177/0963721418807728>.
- Fleck, J. I., & Braun, D. A. (2015). The impact of eye movements on a verbal creativity task. *Journal of Cognitive Psychology*, 27(7), 866-881.
<https://doi.org/10.1080/20445911.2015.1036057>.

- Foa, E. B., & Kozak, M. J. (1986). Emotional processing of fear: Exposure to corrective information. *Psychological Bulletin*, 99(1), 20-35. <https://doi.org/10.1037/0033-2909.99.1.20>.
- Friston, K. J., & Stephan, K. E. (2007). Free-energy and the brain. *Synthese*, 159, 417-458. <https://doi.org/10.1007/s11229-007-9237-y>.
- Friston, K., Kilner, J., & Harrison, L. (2006). A free energy principle for the brain. *Journal of Physiology-Paris*, 100(1-3), 70-87. <https://doi.org/10.1016/j.jphysparis.2006.10.001>.
- Gabora, L. (2010). Revenge of the “neurds”: Characterizing creative thought in terms of the structure and dynamics of memory. *Creativity Research Journal*, 22(1), 1-13. <https://doi.org/10.1080/10400410903579494>.
- Ganis, G., Thompson, W. L., & Kosslyn, S. M. (2004). Brain areas underlying visual mental imagery and visual perception: An fMRI study. *Cognitive Brain Research*, 20(2), 226-241. <https://doi.org/10.1016/j.cogbrainres.2004.02.012>.
- Geman, S., & Geman, D. (1984). Stochastic relaxation, Gibbs distributions, and the Bayesian restoration of images. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 6(6), 721-741. <https://doi.org/10.1109/TPAMI.1984.4767596>.
- Gopnik, A., O’Grady, S., Lucas, C. G., Griffiths, T. L., Wente, A., Bridgers, S., . . . Dahl, R. E. (2017). Changes in cognitive flexibility and hypothesis search across human life history from childhood to adolescence to adulthood. *Proceedings of the National Academy of Sciences*, 114(30), 7892-7899. <https://doi.org/10.1073/pnas.1700811114>.
- Graham, K. S., Lee, A. C., Brett, M., & Patterson, K. (2003). The neural basis of autobiographical and semantic memory: New evidence from three PET studies. *Cognitive, Affective, & Behavioral Neuroscience*, 3(3), 234-254. <https://doi.org/10.3758/CABN.3.3.234>.
- Gunter, R. W., & Bodner, G. E. (2009). EMDR works... but how? Recent progress in the search for treatment mechanisms. *Journal of EMDR Practice and Research*, 3(3), 161-168. <https://doi.org/10.1891/1933-3196.3.3.161>.
- Hahn, G., Ponce-Alvarez, A., Monier, C., Benvenuti, G., Kumar, A., Chavane, F., . . . Frégnac, Y. (2017). Spontaneous cortical activity is transiently poised close to criticality. *PLoS Computational Biology*, 13(5), 1-29. <https://doi.org/10.1371/journal.pcbi.1005543>.
- Haldeman, C., & Beggs, J. M. (2005). Critical branching captures activity in living neural networks and maximizes the number of metastable states. *Physical Review Letters*, 94(5), 058101. <https://doi.org/10.1103/PhysRevLett.94.058101>.

- Harmon-Jones, E. (2000). Cognitive dissonance and experienced negative affect: Evidence that dissonance increases experienced negative affect even in the absence of aversive consequences. *Personality and Social Psychology Bulletin*, 26(12), 1490-1501.
<https://doi.org/10.1177/01461672002612004>.
- Harmon-Jones, E., & Harmon-Jones, C. (2007). Cognitive dissonance theory after 50 years of development. *Zeitschrift für Sozialpsychologie*, 38(1), 7-16.
<https://doi.org/10.1024/0044-3514.38.1.7>.
- Heiney, K., Huse Ramstad, O., Fiskum, V., Christiansen, N., Sandvig, A., Nichele, S., & Sandvig, I. (2021). Criticality, connectivity, and neural disorder: A multifaceted approach to neural computation. *Frontiers in Computational Neuroscience*, 15(611183), 1-19.
<https://doi.org/10.3389/fncom.2021.611183>.
- Herbert, J. D., Lilienfeld, S. O., Lohr, J. M., Montgomery, R. W., O'Donohue, W. T., Rosen, G. M., & Tolin, D. F. (2000). Science and pseudoscience in the development of eye movement desensitization and reprocessing: Implications for clinical psychology. *Clinical Psychology Review*, 20(8), 945-971. [https://doi.org/10.1016/S0272-7358\(99\)00017-3](https://doi.org/10.1016/S0272-7358(99)00017-3).
- Hesse, J., & Gross, T. (2014). Self-organized criticality as a fundamental property of neural systems. *Frontiers in Systems Neuroscience*, 8(166), 1-14.
<https://doi.org/10.3389/fnsys.2014.00166>.
- Hofstadter, D. (1994). How could a copycat ever be creative? In T. Dartnall, *Artificial intelligence and creativity. Studies in cognitive systems, vol 17* (pp. 405-424). Dordrecht: Springer.
- Hopfield, J. J., & Tank, D. W. (1985). "Neural" computation of decisions in optimization problems. *Biological Cybernetics*, 52(3), 141-152.
<https://doi.org/10.1007/BF00339943>.
- Horowitz, M. J. (1986). Stress response syndromes: A review of posttraumatic and adjustment disorders. *Hospital and Community Psychiatry*, 37(3), 241-249.
- Horowitz, M. J. (1991). Person schemas. In M. J. Horowitz (Ed.), *Person schemas and maladaptive interpersonal patterns*. (pp. 13-31). Chicago, IL: University of Chicago Press.

- Horowitz, M. J. (2003). *Treatment of Stress Response Syndromes*. Washington, DC: American Psychiatric Publishing, Inc.
- Howard-Jones, P. A., & Murray, S. (2003). Ideational productivity, focus of attention, and context. *Creativity Research Journal*, 15(2-3), 153-166.
<https://doi.org/10.1080/10400419.2003.9651409>.
- Huys, Q. J., Maia, T. V., & Frank, M. J. (2016). Computational psychiatry as a bridge from neuroscience to clinical applications. *Nature Neuroscience*, 19(3), 404-413.
<https://doi.org/10.1038/nn.4238>.
- Huys, Q., Browning, M., Paulus, M. P., & Frank, M. J. (2021). Advances in the computational understanding of mental illness. *Neuropsychopharmacology*, 46, 3-19.
<https://doi.org/10.1038/s41386-020-0746-4>.
- Jeffries, F. W., & Davis, P. (2013). What is the role of eye movements in eye movement desensitization and reprocessing (EMDR) for post-traumatic stress disorder (PTSD)? A review. *Behavioural and Cognitive Psychotherapy*, 41(3), 290-300.
<https://doi.org/10.1017/S1352465812000793>.
- Kelso, J. S., Bressler, S. L., Buchanan, S., DeGuzman, G. C., Ding, M. A., Fuchs, A., & Holroyd, T. (1992). A phase transition in human brain and behavior. *Physics Letters A*, 169(3), 134-144. [https://doi.org/10.1016/0375-9601\(92\)90583-8](https://doi.org/10.1016/0375-9601(92)90583-8).
- Kinouchi, O., & Copelli, M. (2006). Optimal dynamical range of excitable networks at criticality. *Nature Physics*, 2(5), 348-351. <https://doi.org/10.1038/nphys289>.
- Kirkpatrick, S., Gelatt, C. D., & Vecchi, M. P. (1983). Optimization by simulated annealing. *Science*, 220(4958), 671-680. <https://doi:10.1126/science.220.4598.671>.
- Kleim, B., Grey, N., Wild, J., Nussbeck, F. W., Stott, R., Hackmann, A., . . . Ehlers, A. (2013). Cognitive change predicts symptom reduction with cognitive therapy for posttraumatic stress disorder. *Journal of Consulting and Clinical Psychology*, 81(3), 383-393. <https://doi:10.1037/a0031290>.
- Kleim, B., Wallott, F., & Ehlers, A. (2008). Are trauma memories disjointed from other autobiographical memories in posttraumatic stress disorder? An experimental investigation. *Behavioural and Cognitive Psychotherapy*, 36(2), 221-234.
<https://doi.org/10.1017/S1352465807004080>.

- Konen, C. S., Kleiser, R., Wittsack, H. J., Bremmer, F., & Seitz, R. J. (2004). The encoding of saccadic eye movements within human posterior parietal cortex. *Neuroimage*, 22(1), 304-314. <https://doi.org/10.1016/j.neuroimage.2003.12.039>.
- Korn, H., & Faure, P. (2003). Is there chaos in the brain? II. Experimental evidence and related models. *Comptes Rendus Biologies*, 326(9), 787-840. <https://doi.org/10.1016/j.crvi.2003.09.011>.
- Kosslyn, S. M., Thompson, W. L., & Alpert, N. M. (1997). Neural systems shared by visual imagery and visual perception: A positron emission tomography study. *NeuroImage*, 6(4), 320-334. <https://doi.org/10.1006/nimg.1997.0295>.
- Kuhl, B. A., Bainbridge, W. A., & Chun, M. M. (2012). Neural reactivation reveals mechanisms for updating memory. *The Journal of Neuroscience*, 32(10), 3453-3461. <https://doi.org/10.1523/JNEUROSCI.5846-11.2012>.
- Landin-Romero, R., Moreno-Alcazar, A., Pagani, M., & Amann, B. L. (2018). How does eye movement desensitization and reprocessing therapy work? A systematic review on suggested mechanisms of action. *Frontiers in Psychology*, 9(1395), 1-23. <https://doi.org/10.3389/fpsyg.2018.01395>.
- Langton, C. G. (1990). Computation at the edge of chaos: Phase transitions and emergent computation. *Physica D: Nonlinear Phenomena*, 42(1-3), 12-37. [https://doi.org/10.1016/0167-2789\(90\)90064-V](https://doi.org/10.1016/0167-2789(90)90064-V).
- Lazarus, R. S. (1984). On the primacy of cognition. *American Psychologist*, 39(2), 124-129. <https://doi.org/10.1037/0003-066X.39.2.124>.
- Lee, C. W., & Cuijpers, P. (2013). A meta-analysis of the contribution of eye movements in processing emotional memories. *Journal of Behavior Therapy and Experimental Psychiatry*, 44(2), 231-239. <https://doi.org/10.1016/j.jbtep.2012.11.001>.
- Lee, C. W., & Drummond, P. D. (2008). Effects of eye movement versus therapist instructions on the processing of distressing memories. *Journal of Anxiety Disorders*, 22(5), 801-808. <https://doi.org/10.1016/j.janxdis.2007.08.007>.
- Lee, C., Gavriel, H., Drummond, P., Richards, J., & Greenwald, R. (2002). Treatment of PTSD: Stress inoculation training with prolonged exposure compared to EMDR. *Journal of Clinical Psychology*, 58(9), 1071-1089. <https://doi.org/10.1002/jclp.10039>.

- Levine, B., Turner, G. R., Tisserand, D., Hevenor, S. J., Graham, S. J., & McIntosh, A. R. (2004). The functional neuroanatomy of episodic and semantic autobiographical remembering: A prospective functional MRI study. *Journal of Cognitive Neuroscience*, 16(9), 1633-1646. <https://doi.org/10.1162/0898929042568587>.
- Liljenström, H. (2003). Neural stability and flexibility: A computational approach. *Neuropsychopharmacology*, 28(1), S64-S73. <https://doi.org/10.1038/sj.npp.1300137>.
- Lilley, S. A., Andrade, J., Turpin, G., Sabin-Farrell, R., & Holmes, E. A. (2009). Visuospatial working memory interference with recollections of trauma. *British Journal of Clinical Psychology*, 48(3), 309-321. <https://doi.org/10.1348/014466508X398943>.
- Linson, A., & Friston, K. (2019). Reframing PTSD for computational psychiatry with the active inference framework. *Cognitive Neuropsychiatry*, 24(5), 347-368. <https://doi.org/10.1080/13546805.2019.1665994>.
- Martindale, C. (1995). Creativity and connectionism. In S. M. Smith, T. B. Ward, & R. A. Finke, *The Creative Cognition Approach* (pp. 249-268.). Cambridge Massachusetts: MIT Press.
- Matzke, D., Nieuwenhuis, S., van Rijn, H., Slagter, H. A., van der Molen, M. W., & Wagenmakers, E. J. (2015). The effect of horizontal eye movements on free recall: A preregistered adversarial collaboration. *Journal of Experimental Psychology: General*, 144(1), e1-e5. <https://doi.org/10.1037/xge0000038>.
- Michael, T., Ehlers, A., Halligan, S. L., & Clark, D. M. (2005). Unwanted memories of assault: What intrusion characteristics are associated with PTSD? *Behaviour Research and Therapy*, 43(5), 613-628. <https://doi.org/10.1016/j.brat.2004.04.006>.
- Mitchell, M. (2011). What is computation? Biological computation. *Ubiquity*, 3, 1-7. <https://doi.org/10.1145/1940721.1944826>.
- Montague, P. R., Dolan, R. J., Friston, K. J., & Dayan, P. (2012). Computational psychiatry. *Trends in Cognitive Sciences*, 16(1), 72-80. <https://doi.org/10.1016/j.tics.2011.11.018>.
- Mujica-Parodi, L. R., & Strey, H. H. (2020). Making sense of computational psychiatry. *International Journal of Neuropsychopharmacology*, 23(5), 339-347. <https://doi.org/10.1093/ijnp/pyaa013>.

- Muri, R. M., Iba-Zizen, M. T., Derosier, C., Cabanis, E. A., & Pierrot-Deseilligny, C. (1996). Location of the human posterior eye field with functional magnetic resonance imaging. *Journal of Neurology, Neurosurgery & Psychiatry*, 60(4), 445-448. <https://dx.doi.org/10.1136/jnnp.60.4.445>.
- Nakamura, K., & Colby, C. L. (2002). Updating of the visual representation in monkey striate and extrastriate cortex during saccades. *Proceedings of the National Academy of Sciences*, 99(6), 4026-4031. <https://doi.org/10.1073/pnas.052379899>.
- Nieuwenhuis, S., Elzinga, B. M., Ras, P. H., Berends, F., Duijs, P., Samara, Z., & Slagter, H. A. (2013). Bilateral saccadic eye movements and tactile stimulation, but not auditory stimulation, enhance memory retrieval. *Brain and Cognition*, 81(1), 52-56. <https://doi.org/10.1016/j.bandc.2012.10.003>.
- Pagani, M., Högberg, G., Fernandez, I., & Siracusano, A. (2013). Correlates of EMDR therapy in functional and structural neuroimaging: A critical summary of recent findings. *Journal of EMDR Practice and Research*, 7(1), 29-38. <https://doi.org/10.1891/1933-3196.7.1.29>.
- Palva, S., & Palva, J. M. (2018). Roles of brain criticality and multiscale oscillations in temporal predictions for sensorimotor processing. *Trends in Neurosciences*, 41(10), 729-743. <https://doi.org/10.1016/j.tins.2018.08.008>.
- Parker, A., Poole, J., & Dagnall, N. (2020). Saccade-induced retrieval enhancement and the recovery of perceptual item-specific information. *Cognitive Processing*, 21, 223-237. <https://doi.org/10.1007/s10339-019-00943-w>.
- Parker, A., Powell, D., & Dagnall, N. (2018). Effects of saccade induced retrieval enhancement on conceptual and perceptual tests of explicit & implicit memory. *Brain and Cognition*, 121, 1-10. <https://doi.org/10.1016/j.bandc.2017.12.002>.
- Pearson, H. J. (2009). Present and accounted for: Sensory stimulation and parietal neuroplasticity. *Journal of EMDR Practice and Research*, 3(1), 39-49. <https://doi.org/10.1891/1933-3196.3.1.39>.
- Perkins, B. R., & Rouanzoin, C. C. (2002). A critical evaluation of current views regarding eye movement desensitization and reprocessing (EMDR): Clarifying points of confusion. *Journal of Clinical Psychology*, 58(1), 77-97. <https://doi.org/10.1002/jclp.1130>.

- Petit, L., & Haxby, J. V. (1999). Functional anatomy of pursuit eye movements in humans as revealed by fMRI. *Journal of Neurophysiology*, 82(1), 463-471.
<https://doi.org/10.1152/jn.1999.82.1.463>.
- Phelps, E. A. (2006). Emotion and cognition: Insights from studies of the human amygdala. *Annual Review of Psychology*, 57(1), 27-53.
<https://doi.org/10.1146/annurev.psych.56.091103.070234>.
- Pierrot-Deseilligny, C., Milea, D., & Müri, R. M. (2004). Eye movement control by the cerebral cortex. *Current Opinion in Neurology*, 17(1), 17-25. <https://doi.org/10.1097/00019052-200402000-00005>.
- Pitman, R. K., & Orr, S. P. (1990). The black hole of trauma. *Biological Psychiatry*, 27(5), 469-471. [https://doi.org/10.1016/0006-3223\(90\)90437-7](https://doi.org/10.1016/0006-3223(90)90437-7).
- Pitman, R. K., Rasmusson, A. M., Koenen, K. C., Shin, L. M., Orr, S. P., Gilbertson, M. W., . . . Liberzon, I. (2012). Biological studies of post-traumatic stress disorder. *Nature reviews. Neuroscience*, 13(11), 769-787. <https://doi.org/10.1038/nrn3339>.
- Plenz, D. (2013). The critical brain. *Physics*, 6(47), 1-3.
<https://link.aps.org/doi/10.1103/Physics.6.47>.
- Plenz, D., & Thiagarajan, T. C. (2007). The organizing principles of neuronal avalanches: Cell assemblies in the cortex? *Trends in Neurosciences*, 30(3), 101-110.
<https://doi.org/10.1016/j.tins.2007.01.005>.
- Poulet, J. F., & Hedwig, B. (2007). New insights into corollary discharges mediated by identified neural pathways. *Trends in Neurosciences*, 30(1), 14-21.
<https://doi.org/10.1016/j.tins.2006.11.005>.
- Propper, R. E., & Christman, S. D. (2008). Interhemispheric interaction and saccadic horizontal eye movements implications for episodic memory, EMDR, and PTSD. *Journal of EMDR Practice and Research*, 2(4), 269-281. <https://doi.org/10.1891/1933-3196.2.4.269>.
- Rabinovich, M. I., & Abarbanel, H. D. (1998). The role of chaos in neural systems. *Neuroscience*, 87(1), 5-14. [https://doi.org/10.1016/S0306-4522\(98\)00091-8](https://doi.org/10.1016/S0306-4522(98)00091-8).
- Rajkai, C., Lakatos, P., Chen, C. M., Pincze, Z., Karmos, G., & Schroeder, C. E. (2008). Transient cortical excitation at the onset of visual fixation. *Cerebral Cortex*, 18(1), 200-209.
<https://doi.org/10.1093/cercor/bhm046>.

- Ranganath, C., Cohen, M. X., Dam, C., & D'Esposito, M. (2004). Inferior temporal, prefrontal, and hippocampal contributions to visual working memory maintenance and associative memory retrieval. *Journal of Neuroscience*, 24(16), 3917-3925.
<https://doi.org/10.1523/JNEUROSCI.5053-03.2004>.
- Rauch, S., & Foa, E. (2006). Emotional processing theory (EPT) and exposure therapy for PTSD. *Journal of Contemporary Psychotherapy*, 36(2), 61-65.
<https://doi.org/10.1007/s10879-006-9008-y>.
- Reese, E., Haden, C. A., Baker-Ward, L., Bauer, P., Fivush, R., & Ornstein, P. A. (2011). Coherence of personal narratives across the lifespan: A multidimensional model and coding method. *Journal of Cognition and Development*, 12(4), 424-462.
<https://doi.org/10.1080/15248372.2011.587854>.
- Resick, P. A., & Schnicke, M. K. (1992). Cognitive processing therapy for sexual assault victims. *Journal of Consulting and Clinical Psychology*, 60(5), 748-756.
<https://doi.org/10.1037/0022-006X.60.5.748>.
- Rickles, D., Hawe, P., & Shiell, A. (2007). A simple guide to chaos and complexity. *Journal of Epidemiology & Community Health*, 61(11), 933-937.
<https://jech.bmj.com/content/61/11/933>.
- Roberts, B. R., Fernandes, M. A., & MacLeod, C. M. (2020). Re-evaluating whether bilateral eye movements influence memory retrieval. *PLoS ONE*, 15(1), e0227790.
<https://doi.org/10.1371/journal.pone.0227790>.
- Robini, M. C., Rastello, T., & Magnin, I. E. (1999). Simulated annealing, acceleration techniques, and image restoration. *IEEE Transactions on Image Processing*, 8(10), 1374-1387.
doi:10.1109/83.791963.
- Roseman, I. J., & Smith, C. A. (2001). Appraisal theory overview, assumptions, varieties, controversies. In K. R. Scherer, A. Schorr, & T. Johnstone, *Appraisal Processes in Emotion: Theories, methods, research* (pp. 3-19). Oxford University Press.
- Rubin, D. C. (2011). The coherence of memories for trauma: Evidence from posttraumatic stress disorder. *Consciousness and Cognition*, 20(3), 857-865.
<https://doi.org/10.1016/j.concog.2010.03.018>.
- Ruiz, A. D. (2014). Quantum annealing. 1404(2465), <https://arxiv.org/abs/1404.2465>.

- Russell, M. C. (2008). Scientific resistance to research, training and utilization of eye movement desensitization and reprocessing (EMDR) therapy in treating post-war disorders. *Social Science & Medicine*, 67(11), 1737-1746.
<https://doi.org/10.1016/j.socscimed.2008.09.025>.
- Rutenbar, R. A. (1989). Simulated annealing algorithms: An overview. *IEEE Circuits and Devices Magazine*, 5(1), 19-26. <https://doi.org/10.1109/101.17235>.
- Sachschaal, J., Woodward, E., Wichelmann, J. M., Haag, K., & Ehlers, A. (2019). Differential effects of poor recall and memory disjointedness on trauma symptoms. *Clinical Psychological Science*, 7(5), 1032-1041. <https://doi.org/10.1177/2167702619847195>.
- Schnyder, U., Ehlers, A., Ehlers, T., Foa, E. B., Gersons, B. P., Resick, P. A., . . . Cloitre, M. (2015). Psychotherapies for PTSD: what do they have in common? *European Journal of Psychotraumatology*, 6(1), 28186. <https://doi.org/10.3402/ejpt.v6.28186>.
- Seddiqi, H., & Humble, T. S. (2014). Adiabatic quantum optimization for associative memory recall. *Frontiers in Physics*, 2(79), 1-12. <https://doi.org/10.3389/fphy.2014.00079>.
- Seidler, G. H., & Wagner, F. E. (2006). Comparing the efficacy of EMDR and trauma-focused cognitive-behavioral therapy in the treatment of PTSD: A meta-analytic study. *Psychological Medicine*, 36(11), 1515-1522. <https://doi.org/10.1017/S0033291706007963>.
- Shalev, A., Liberzon, I., & Marmar, C. (2017). Post-traumatic stress disorder. *New England Journal of Medicine*, 376(25), 2459-2469. <https://doi.org/10.1056/NEJMra1612499>.
- Shapiro, F. (1995). *Eye movement desensitization and reprocessing; Basic principles, protocols and procedures*. New York, NY: Guilford Press.
- Shapiro, F. E. (2002). *EMDR as an integrative psychotherapy approach: Experts of diverse orientations explore the paradigm prism*. Washington, DC: American Psychological Association.
- Shapiro, F. (2007). EMDR, adaptive information processing, and case conceptualization. *Journal of EMDR Practice and Research*, 1(2), 68-87. <https://doi.org/10.1891/1933-3196.1.2.68>.
- Shapiro, F. (2014). The role of eye movement desensitization and reprocessing (EMDR) therapy in medicine: Addressing the psychological and physical symptoms stemming from adverse life experiences. *The Permanente Journal*, 18(1), 71-77.
<https://doi.org/10.7812/TPP/13-098>.
- Shew, W. L., & Plenz, D. (2013). The functional benefits of criticality in the cortex. *The Neuroscientist*, 19(1), 88-100. <https://doi.org/10.1177/1073858412445487>.

- Shew, W. L., Clawson, W. P., Pobst, J., Karimipناه, Y., Wright, N. C., & Wessel, R. (2015). Adaptation to sensory input tunes visual cortex to criticality. *Nature Physics*, 11(8), 659-663. <https://doi.org/10.1038/nphys3370>.
- Shinbrot, T., Grebogi, C., Yorke, J. A., & Ott, E. (1993). Using small perturbations to control chaos. *Nature*, 363(6428), 411-417. <https://doi.org/10.1038/363411a0>.
- Shobe, E. R., Ross, N. M., & Fleck, J. I. (2009). Influence of handedness and bilateral eye movements on creativity. *Brain and Cognition*, 71(3), 204-214. <https://doi.org/10.1016/j.bandc.2009.08.017>.
- Shriki, O., & Yellin, D. (2016). Optimal information representation and criticality in an adaptive sensory recurrent neuronal network. *PLoS Computational Biology*, 12(2), 1-19. <https://doi.org/10.1371/journal.pcbi.1004698>.
- Shultz, T. R., & Lepper, M. R. (1996). Cognitive dissonance reduction as constraint satisfaction. *Psychological Review*, 103(2), 219-240. <https://doi.org/10.1037/0033-295X.103.2.219>.
- Skarda, C. A., & Freeman, W. J. (1987). How brains make chaos in order to make sense of the world. *Behavioral and Brain Sciences*, 10(2), 161-195. <https://doi:10.1017/S0140525X00047336>.
- Skarda, C. A., & Freeman, W. J. (1990). Chaos and the new science of the brain. In G. Shaw, *Concepts in neuroscience* (pp. 275-285). World Scientific.
- Smith, C. A., & Lazarus, R. S. (1993). Appraisal components, core relational themes, and the emotions. *Cognition and Emotion*, 7(3/4), 233-269. <https://doi.org/10.1080/02699939308409189>.
- Smolensky, P. (1987). Connectionist AI, symbolic AI, and the brain. *Artificial Intelligence Review*, 1(2), 95-109. <https://doi.org/10.1007/BF00130011>.
- Smolensky, P. (1989). Information processing in dynamical systems: Foundations of harmony theory. In D. E. Rumelhart, J. L. McClelland, & PDP Research Group, *Parallel distributed processing; Explorations in the microstructure of cognition. 1*, (pp. 194-263). Cambridge, MA: MIT Press.
- Solomon, R. M., & Shapiro, F. (2008). EMDR and the adaptive information processing model potential mechanisms of change. *Journal of EMDR Practice and Research*, 2(4), 315-325. <https://doi:10.1891/1933-3196.2.4.315>.

- Sommer, M. A., & Wurtz, R. H. (2004). What the brain stem tells the frontal cortex. II. Role of the SC-MD-FEF pathway in corollary discharge. *Journal of Neurophysiology*, 91, 1403-1423. <https://doi.org/10.1152/jn.00740.2003>.
- Stickgold, R. (2002). EMDR: A putative neurobiological mechanism of action. *Journal of Clinical Psychology*, 58(1), 61-75. <https://doi.org/10.1002/jclp.1129>.
- Suman, B., & Kumar, P. (2006). A survey of simulated annealing as a tool for single and multiobjective optimization. *Journal of the Operational Research Society*, 57(10), 1143-1160. <https://doi.org/10.1057/palgrave.jors.2602068>.
- Svoboda, E., McKinnon, M. C., & Levine, B. (2006). The functional neuroanatomy of autobiographical memory: A meta-analysis. *Neuropsychologia*, 44(12), 2189-2208. <https://doi.org/10.1016/j.neuropsychologia.2006.05.023>.
- Tanabe, J., Tregellas, J., Miller, D., Ross, R. G., & Freedman, R. (2002). Brain activation during smooth-pursuit eye movements. *NeuroImage*, 17(3), 1315-1324. <https://doi.org/10.1006/nimg.2002.1263>.
- Tank, D. W., & Hopfield, J. J. (1987). Collective computation in neuronlike circuits. *Scientific American*, 257(6), 104-115. <https://www.jstor.org/stable/24979583>.
- Thagard, P., & Verbeurgt, K. (1998). Coherence as constraint satisfaction. *Cognitive Science*, 22(1), 1-24. [https://doi.org/10.1016/S0364-0213\(99\)80033-0](https://doi.org/10.1016/S0364-0213(99)80033-0).
- Thomas, L. E., & Lleras, A. (2007). Moving eyes and moving thought: On the spatial compatibility between eye movements and cognition. *Psychonomic Bulletin & Review*, 14(4), 663-668. <https://doi.org/10.3758/BF03196818>.
- Tognoli, E., & Kelso, J. S. (2014). The metastable brain. *Neuron*, 81(1), 35-48. <https://doi.org/10.1016/j.neuron.2013.12.022>.
- Tokuda, I., Aihara, K., & Nagashima, T. (1998). Adaptive annealing for chaotic optimization. *Physical Review E*, 58(4), 5157-5160. <https://doi.org/10.1103/PhysRevE.58.5157>.
- Tomen, N., & Ernst, U. (2019). The role of criticality in flexible visual information processing. In N. Tomen, & U. Ernst, (Eds.). *The functional role of critical dynamics in neural systems* (pp. 233-264) Springer. https://doi.org/10.1007/978-3-030-20965-0_12.
- Tsuda, I. (2015). Chaotic itinerancy and its roles in cognitive neurodynamics. *Current Opinion in Neurobiology*, 31, 67-71. <https://doi.org/10.1016/j.conb.2014.08.011>.
- Tulving, E. (2002). Episodic memory: From mind to brain. *Annual Review of Psychology*, 53(1), 1-25. <https://doi.org/10.1146/annurev.psych.53.100901.135114>.

- Vaile Wright, C., Collinsworth, L. L., & Fitzgerald, L. F. (2010). Why did this happen to me? Cognitive schema disruption and posttraumatic stress disorder in victims of sexual trauma. *Journal of Interpersonal Violence*, 25(10), 1801-1814.
<https://doi.org/10.1177/0886260509354500>.
- Van den Hout, M. A., Rijkeboer, M. M., Engelhard, I. M., Klugkist, I., Hornsveld, H., Toffolo, M. J., & Cath, D. C. (2012). Tones inferior to eye movements in the EMDR treatment of PTSD. *Behaviour Research and Therapy*, 50(5), 275-279.
<https://doi.org/10.1016/j.brat.2012.02.001>.
- Van der Kolk, B. (2000). Posttraumatic stress disorder and the nature of trauma. *Dialogues in Clinical Neuroscience*, 2(1), 7-22. <https://doi:10.31887/DCNS.2000.2.1/bvdkolk>.
- Van der Kolk, B. A. (1994). The body keeps the score: Memory and the evolving psychobiology of posttraumatic stress. *Harvard Review of Psychiatry*, 1(5), 253-265.
<https://doi:10.3109/10673229409017088>.
- Van der Kolk, B. A., & McFarlane, A. C. (1996). The black hole of trauma. In B. A. Van der Kolk, A. C. McFarlane, & L. Weisaeth, *Traumatic stress: The effects of overwhelming experience on mind, body, and society*. (pp. 3-23). New York, NY: The Guilford Press.
- Venegas-Andraca, S. E., Cruz-Santos, W., McGeoch, C., & Lanzagorta, M. (2018). A cross-disciplinary introduction to quantum annealing-based algorithms. *Contemporary Physics*, 59(2), 174-197. <https://doi.org/10.1080/00107514.2018.1450720>.
- Wagner, A. D., Shannon, B. J., Kahn, I., & Buckner, R. L. (2005). Parietal lobe contributions to episodic memory retrieval. *Trends in Cognitive Sciences*, 9(9), 445-453.
<https://doi.org/10.1016/j.tics.2005.07.001>.
- Wang, L., Li, S., Tian, F., & Fu, X. (2004). A noisy chaotic neural network for solving combinatorial optimization problems: Stochastic chaotic simulated annealing. *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)*, 34(5), 2119-2125.
<https://doi:10.1109/TSMCB.2004.829778>.
- Watts, B. V., Schnurr, P. P., Mayo, L., Young-Xu, Y., Weeks, W. B., & Friedman, M. J. (2013). Meta-analysis of the efficacy of treatments for posttraumatic stress disorder. *The Journal of Clinical Psychiatry*, 74(6), 541-550. <https://doi:10.4088/JCP.12r08225>.
- Werner, G. (2007). Metastability, criticality and phase transitions in brain and its models. *Biosystems*, 90(2), 496-508. <https://doi.org/10.1016/j.biosystems.2006.12.001>.

- Wilting, J., & Priesemann, V. (2019). 25 years of criticality in neuroscience—established results, open controversies, novel concepts. *Current Opinion in Neurobiology*, 58, 105-111. <https://doi.org/10.1016/j.conb.2019.08.002>.
- Yehuda, R. (2002). Post-traumatic stress disorder. *New England Journal of Medicine*, 346(2), 108-114. <https://doi.org/10.1056/NEJMr012941>.
- Yehuda, R. C., Hoge, C. W., McFarlane, A. C., Vermetten, E., Lanius, R. A., Nievergelt, C. M., . . . Hyman, S. E. (2015). Post-traumatic stress disorder. *Nature Reviews Disease Primers*, 1(15057), 1-22. <https://doi.org/10.1038/nrdp.2015.57>.
- Yu, S., Yang, H., Shriki, O., & Plenz, D. (2013). Universal organization of resting brain activity at the thermodynamic critical point. *Frontiers in Systems Neuroscience*, 7(42), 1-17. <https://doi.org/10.3389/fnsys.2013.00042>.
- Zimmern, V. (2020). Why brain criticality is clinically relevant: A scoping review. *Frontiers in Neural Circuits*, 14(54), 1-34. <https://doi.org/10.3389/fncir.2020.00054>.