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The interplay between subcortical and prefrontal brain structures in shaping ideological belief formation and updating

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History illustrates that economic crises and other sociopolitical threats often lead to a rise of polarization and radicalism, whereby people become more susceptible to intolerant political messages, including propaganda and ideological rhetoric. Political science, sociology, economics, and psychology have explored many dimensions of this phenomenon, yet a critical piece of the puzzle is still missing: what cognitive and neural mechanisms in the brain mediate between these threats and responsiveness to political messages? To answer this question, here, we present a theory that combines cognitive neuroscience theories, namely stress-induced memory shift and competitive cognitive processes, with political science. Our Threat-based Neural Switch Theory posits that the processing of political information, similarly to other information processing, is shaped by the competitive interaction between goal-directed and habitual processes. Threats, including resource overload or scarcity, can shift neural networks toward receptiveness to oversimplified political messages. This theory sets out a research program aimed at discovering the cognitive and neural underpinning of how situational factors alter brain functions and modify political information processing.

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Political scientists have long been fascinated by the construction of ideological opinions. The question of how new information modifies beliefs through learning is a central question not only of political psychology but also of education, philosophy, and biology. For example, ideological messages can reach the masses by providing oversimplified information or extreme solutions to complex crises, often while ignoring contextual nuance. Human responsiveness to these oversimplified political messages, such as propaganda and populist rhetoric, may catalyze societal polarization as well as individual radicalization, so it is essential that scientists investigate the causes and mechanisms of this phenomenon. Substantial scientific research has been carried out on political communication, political behavior, and ideological processes from sociological, political science, economics, and social-psychological perspectives [1–5]. Nevertheless, it is essential to emphasize that the neurocognitive explanatory level is equally vital in comprehending these phenomena (refer to the Neurocognitive Model of Ideological Thinking [6]). In this context, we introduce the Threat-based Neural Switch Theory, which seeks to offer insights into these inquiries from a neurocognitive stance.

The field of political neuroscience started to emerge during the 2000s [7–10] and subsequently experienced

notable growth and advancement throughout the 2010s, harnessing cognitive neuroscientific methodologies to study ideological attitudes, dogmatism, and political identity [6,11]. Most of these studies approach the problem by describing the psychological, cognitive, or neural correlates of political identities and ideologies. This dispositional *trait-like* research view can help us understand the relationship between neurocognitive functions and political ideologies. As an example, cognitive flexibility measured by the Wisconsin Card Sorting Task or drift rate in decision-making tasks can predict participants' levels of dogmatism [12,13]. Trait-like processes refer to "how cognitive dispositions — individual differences in the perception and processing of information — sculpt individuals' ideological worldviews, proclivities for extremist beliefs, and resistance (or receptivity) to evidence" [11]. In contrast, *state-like* processes refer to the effects of situations and contexts: an individual's level of responsiveness to oversimplified messages may be changed by external influences such as the threat of an economic crisis. Previous research has extensively investigated state-like issues, such as the influence of emotions on information processing in social psychology and their impact on political thinking [14–19]. Furthermore, various studies have explored the effects of economic threats on political thinking processes [20,21] and the influence of threat and anxiety on cognitive and brain processes [22–25]. Our theory aims to comprehensively address state-like effects in a complex manner by unveiling the intricate interplay among threat, cognition, brain processes, and political thinking. While previous research has tackled two, and possibly three, of these aspects, it has not simultaneously addressed the entirety of the fourfold interaction.

For example, research has demonstrated that susceptibility to oversimplified political ideas might be heightened after economic crises. These threats may 'push' people in the direction of dogmatic, extreme, or nationalistic views, as evidenced by experimental work on worldview threat shifts [26–28]. The relationship between threats and politics is highly complex [29]. This complexity arises not only from the way perceptions are intertwined with emotions [30] but also from the fact that threats can influence people's political preferences, while their political preferences can also lead them to perceive issues and events as threatening and stressful. This phenomenon is described in the 'model of the reciprocal threat–politics relationship' [29]. To better understand this complexity, delving into the neural mechanisms underlying this connection could provide valuable insights. Yet, as laid out in the Neurocognitive Model of Ideological Thinking [6], it is essential to examine how changes in neural processes make an individual more susceptible to ideological messages and how these brain mechanisms mediate between situational factors and political ideology. To fill this gap, we must complement dispositional (*trait-*

like) approaches using situational (*state-like*) approaches. The main goal of this short review is to present the Threat-based Neural Switch Theory, which is based on cognitive neuroscience theories related to information processes, such as stress-related learning and memory systems, and the competition between goal-directed and habitual learning processes. This framework aims to uncover the neurocognitive processes underlying receptiveness to oversimplified political messages and to understand how this receptiveness changes within the individual over time. The theory suggests that the way political information is processed, much like nonpolitical information, is influenced by the interplay between processes related to goal-directed actions and habitual behaviors. An imbalance in these processes could potentially lead to a higher vulnerability to overly simplified political messages [31].

The nature and content of oversimplified political messages are in many ways context-dependent; however, we can hypothesize specific ideological outcomes that focus on the structure of ideological beliefs rather than their substance [32]. Here we propose that an imbalance toward habit-based behaviors, especially under conditions of stress, would skew preferences toward more extreme ideological solutions regardless of their content. In other words, oversimplification may exist in the realm of beliefs about national borders, environmental protection, economic policies, or gendered assumptions that are coupled with intolerance. When tested rigorously for both left-wing and right-wing issues, we suggest that oversimplified, extreme, and intolerant messages will be favored when habitual processes are activated. Here we focus on receptiveness to oversimplified messages, rather than the elaboration of ideological belief systems, and we expect that with additional data, we will be able to draw finer distinctions between the role of belief structure (e.g. extremity and dogmatism versus moderation and flexibility) and belief content (e.g. right- versus left-wing issues, religious versus atheistic issues, traditionally populist or neo-liberal). Through this framework, it will become possible to delineate the ways in which different ideological outcomes possess distinct neurocognitive signatures and may rely on different psychophysiological processes [6,12].

Building upon our Threat-based Neural Switch Theory, we can design empirical studies aimed at unraveling the cognitive and neural dynamics involved in how different situational factors, like economic crises, warfare, and sociopolitical stressors (as delineated by Blascovich et al. [33]), impact brain function. These investigations seek to shed light on the modulation of stress-related brain networks, leading to the downregulation of executive networks and the upregulation of salience and basal ganglia networks during the processing of political information.

Theoretical background

The brain continuously extracts patterns and regularities from the information stream originating from our physical and social environments. It constructs models to utilize this knowledge for predicting and anticipating future events [34–36]. The processes of acquisition and model-building, along with the complexity of the models, play a crucial role in our adaptation to the environment and our understanding of the world around us. These brain models are also integral to information processing (top-down, model-based learning, predictive brain) [37]. In this context, the present theoretical framework follows new approaches that consider the processing of political information as governed by the general processes of information acquisition and model-building [38]. Therefore, it is intertwined with the cognitive neuroscientific theories of learning and memory.

For concision, simplified terminology is used. Here, ‘goal-directed processes’ denote executive functions, controlled model-based processes, working memory, and declarative memory. In contrast, ‘habit-related processes’ encompass habit learning, automatic behaviors, statistical learning, model-free, and nondeclarative processes. However, the theoretical framework will adopt a more sophisticated process-level perspective to investigate the cooperative and competitive interactions among these processes.

Going beyond classical models of learning and memory, our framework is constructed upon two relatively recent theoretical approaches. These approaches are employed to develop our Threat-based Neural Switch Theory: *competitive memory systems* framework and *stress-induced memory shift* theory.

The competitive memory systems framework

Prior research has shown that neurocognitive networks underlying learning and memory can engage in either cooperative or competitive interactions [39,40]. Specifically, a substantial body of evidence has demonstrated that weak prefrontal lobe-dependent executive and control functions are associated with enhanced performance in statistical learning (extracting the regularities from an information stream), a form of learning that underlies habit formation [41–43]. This finding suggests a competitive, antagonist relationship between controlled, goal-directed, hypothesis-testing, and automatic, stimulus-driven learning processes. This competition implies that a greater engagement of the former could hinder the extraction of statistical properties from the environment [34,44]. In contrast, executive functions exhibit positive correlations with other learning and memory functions, such as working memory and declarative memory [45,46].

Competitive memory systems framework from a computational neuroscience perspective

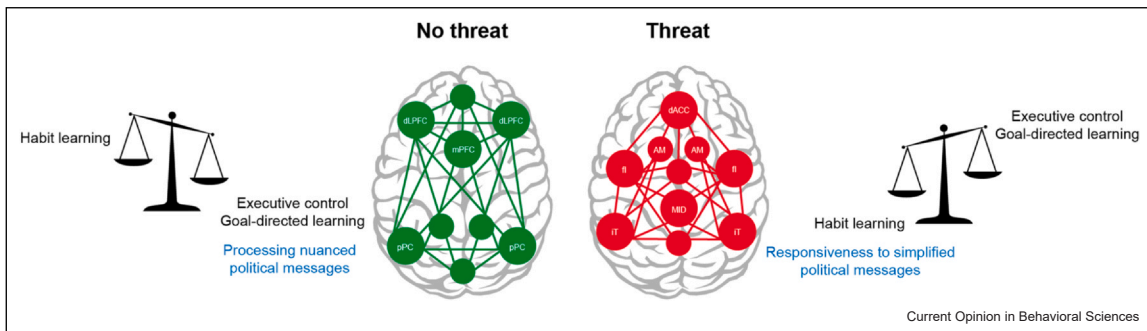
The accumulating evidence from computational neuroscience suggests that the interactions between learning and memory functions are driven by specific cognitive processes. In particular, a widely recognized computational model [47] postulates the existence of model-based and model-free processes underlying learning and, more generally, behavior. The central distinction between the two processes lies in whether an internal model or representation of the task at hand was formed during learning, characterizing model-based versus model-free processes, respectively. Since these processes appear to be relevant in a wide range of learning situations, they could potentially shed further light on the competition observed both on the neural and behavioral levels [36,47–49]. Based on existing theoretical and empirical work, model-based and model-free processes are posited to compete for control over behavior [36,47]. Moreover, the reliance on model-free versus model-based learning processes changed dynamically according to the concurrent executive function demands [49].

In summary, the antagonistic relationship between learning systems affects information processes and model-building. When the prefrontal functions are ‘weaker’, it could lead to more efficient habit-learning performance and result in the construction of less complex models. These findings have implications for the processing of political information; the imbalance in neurocognitive networks (habit versus goal-directed learning) can lead to ‘weaker’ PFC functioning and ‘stronger’ habit learning, potentially resulting in a higher receptivity to simplistic political messages. This could lead to a reduced inclination to develop a nuanced understanding of the political landscape and a reluctance to update this model with additional information. Conversely, when the PFC performs ‘strongly’ — involving computational level model-based processes — it could facilitate the creation of an accessible and nuanced model of the political landscape stored in declarative memory. This neurocognitive mechanism could play a role in mediating between situational factors and responsiveness to political messages.

Stress-induced memory shift

Acute stress leads to changes in both cognitive and affective processes [50–53]. Previous studies have shown the significant impact of stress on learning and memory systems. Glucocorticoid hormones are released in stressful situations and can induce a shift from cognitively demanding, goal-directed forms of learning to habitual forms of learning [54–57]. Stress-induced memory shift has been widely demonstrated on both the behavioral and neural levels. Schwabe et al. [58] were the pioneers in providing evidence for the shift in humans; psychosocial stress increased the use of habitual

Figure 1



The stress-induced shift in brain networks promotes habit memory-related processes such as statistical learning, model-free learning, and habit learning at the cost of goal-directed learning. In situations without stress, the executive control network is more prominent, supporting cognitive control and goal-directed learning processes. The nodes of this executive control network are the dLPFC, mPFC, and pPC. Acute stress downregulates the executive networks (dLPFC, mPFC, pPC) and upregulates the salience network (dACC, AM, fI, MID), which promotes a shift toward habit-based memory. In the context of processing political information, stress induces a shift from processing nuanced political messages toward higher responsiveness to simplified political messages.

Illustration adapted from figures presented in Hermans, Henckens, Joëls, & Fernández [63]; [64], and Schwabe [65].

strategies at the expense of goal-directed strategies in spatial learning. Significantly, however, stress may also alter habit learning [59]. Studies investigating the effect of stress on the habitual processes in humans have shown that stress could modify habit learning performance [53,60,61]. In a recent study, Tóth-Fáber et al. [62] investigated statistical learning, an essential component of habit learning under stress induction, and found improved regularity extraction (enhanced habit learning) under the stress condition compared with the nonstress condition. In the present work, we might focus on a somewhat more precise term, threat, that is related to the appraisal of the stressful situation in which the demands exceed the resources.

On the neural level, the prefrontal cortex (PFC), hippocampus, dorsal striatum, and amygdala seem to play an essential role in the shift. Studies [63,66] proposed a model that explains how stress changes large-scale networks in the brain (Figure 1). In a no-stress situation, the PFC inhibits habitual responses when necessary, utilizes top-down control, and regulates emotional responses in the amygdala. Following stress, however, changes occur in these brain areas and networks; acute stress downregulates the executive networks (dorsolateral prefrontal cortex [dLPFC], medial prefrontal cortex [mPFC], posterior parietal cortex [pPC]) and upregulates the salience network (dorsal anterior cingulate cortex [dACC], amygdala [AM], frontal insula [fI], midbrain [MID]) and basal ganglia, which promotes a shift toward habit-based memory. Their findings corroborate the behavioral evidence of the stress-induced memory shift, which entails the enhancement of habitual behavior at the expense of goal-directed behavior in response to acute stress [55]. In this framework, studies have consistently shown that

stress creates a bias that favors dorsal striatum-dependent habitual behavior over PFC-dependent goal-directed behavior [67,68]. To sum up, converging evidence suggests that stress induces large-scale network changes from the executive control network to the salience network, orchestrating a shift from goal-directed to habitual control of learning.

Therefore, stress can alter information processing by shifting learning and memory systems from goal-directed, declarative memory processes toward habit and statistical learning. The processing of simple statistics and regularities becomes more effective than dealing with more complex patterns. Translating this to political information processing, stress can enhance receptiveness to oversimplified political messages, as opposed to a preference for more complex and sophisticated information (Figure 2).

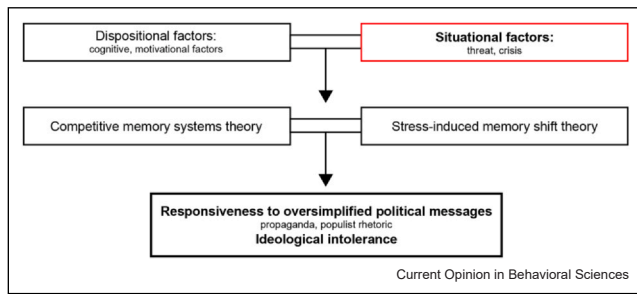
In a similar vein, Houshofer and Fehr [69] suggest that poverty induces stress and negative emotional states. These states, in turn, can result in making decisions that are focused on immediate outcomes and avoiding risks. This might occur because poverty can restrict attention and prioritize habitual behaviors over purposeful, goal-oriented actions [69].

Implication of the Threat-based Neural Switch Theory

The main goal of this theoretical framework is to help understand responsiveness to dogmatic political messages, including its behavioral, cognitive, and neural components.

- 1) This theory can help to identify the relationship between learning, memory systems, and responsiveness

Figure 2



Threat-based Neural Switch Theory.

to oversimplified political messages. We suppose that this responsiveness correlates not only with executive functions and goal-directed memory processes [12] but also with habit-like learning processes, such as statistical learning.

- 2) The theory proposes the potential to determine the brain regions and networks that underlie political information processing in terms of dynamic functional connectivity. We suppose that weakening the functioning of specific PFC areas by noninvasive brain stimulation results in altered dynamic functional connectivity in frontoparietal and fronto-temporal circuits, leading to a heightened preference for dogmatic political messages.
- 3) Threats like financial crises and wars can increase receptiveness to oversimplified political messages, including propaganda and ideological rhetoric. The framework suggests that stress-related learning and memory shifts are the key mechanisms mediating this relationship. To empirically test this, we need to model the psychological impact of economic instability and other threats with experimental stress induction in the laboratory. We hypothesize that this stress induction will alter dynamic functional connectivity in the brain and result in a preference for simpler political messages. Future research can focus on the effect of acute stress, as reflected by rapidly changing salivary cortisol levels and sympathetic nervous system activity, as well as the effect of long-lasting stress based on hair cortisol levels [70]

Conclusion

The Threat-based Neural Switch Theory and the resulting empirical research can facilitate a deeper understanding of ideological intolerance and evidence-resistant beliefs. Rather than describing these as a malfunction of singular cognitive systems or brain networks, we aim to consider the susceptibility to ideological messages from a situation-based neuroscientific perspective as reflecting an interactive imbalance between cognitive systems, such as habitual and goal-directed behavior. The theory can also contribute to theoretically

integrating trait- and state-based processes, thereby allowing us to develop a more holistic and nuanced understanding of how to counter dogmatic ideological thinking.

Declaration of Competing Interest

The authors declare no conflicts of interest.

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References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- of special interest
 - of outstanding interest.
1. Hoffman L: **Psychoanalytic perspectives on populism**. *Contemp Psychoanal* 2018, **54**:266-289.
 2. Fiedler K, Forgas JP, Crano WD: **The Psychology of Populism: The Tribal Challenge to Liberal Democracy**. Routledge; 2021.
 3. Levitsky S, Ziblatt D: **How Democracies Die**. Crown; 2019.
 4. Norris P, Inglehart R: **Cultural Backlash: Trump, Brexit, and Authoritarian Populism**. Cambridge University Press; 2019.
 5. Rodrik D: **Populism and the economics of globalization**. *J Int Bus Policy* 2018, **1**:12-33.
 6. Zmigrod L: **A neurocognitive model of ideological thinking**. *Polit Life Sci* 2021, **40**:224-238.
 7. Westen D: **The Political Brain: How We Make up Our Minds without Using Our Heads**. PublicAffairs; 2007.
 8. Westen D, Blagov PS, Harenski K, Kilts C, Hamann S: **Neural bases of motivated reasoning: an fMRI study of emotional constraints on partisan political judgment in the 2004 US presidential election**. *J Cogn Neurosci* 2006, **18**:1947-1958.
 9. Cacioppo JT, Visser PS: **Political psychology and social neuroscience: strange bedfellows or comrades in arms?** *Polit Psychol* 2003, **24**:647-656.
 10. Jost JT, Nam HH, Amodio DM, Van Bavel JJ: **Political neuroscience: the beginning of a beautiful friendship**. *Polit Psychol* 2014, **35**:3-42.
 11. Zmigrod L, Tsakiris M: **Computational and neurocognitive approaches to the political brain: key insights and future avenues for political neuroscience**. *Philos Trans R Soc Lond B Biol Sci* 2021, **376**:20200130.
 12. Zmigrod L, Eisenberg IW, Bissett PG, Robbins TW, Poldrack RA: **The cognitive and perceptual correlates of ideological attitudes: a data-driven approach**. *Philos Trans R Soc Lond B Biol Sci* 2021, **376**:20200424.
 13. Zmigrod L, Rentfrow PJ, Robbins TW: **The partisan mind: is extreme political partisanship related to cognitive inflexibility?** *J Exp Psychol Gen* 2020, **149**:407.
 14. Marcus GE, Neuman WR, MacKuen M: **Affective Intelligence and Political Judgment**. University of Chicago Press; 2000.
 15. Marcus GE, Sullivan JL, Theiss-Morse E, Stevens D: **The emotional foundation of political cognition: the impact of extrinsic anxiety on the formation of political tolerance judgments**. *Polit Psychol* 2005, **26**:949-963.
 16. McGregor I: **Offensive defensiveness: toward an integrative neuroscience of compensatory zeal after mortality salience**,

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- personal uncertainty, and other poignant self-threats. *Psychol Inq* 2006, **17**:299-308.
17. McGregor I, Nash K, Mann N, Phillips CE: **Anxious uncertainty and reactive approach motivation (RAM)**. *J Pers Soc Psychol* 2010, **99**:133.
 18. Haas IJ, Cunningham WA: **The uncertainty paradox: perceived threat moderates the effect of uncertainty on political tolerance**. *Polit Psychol* 2014, **35**:291-302.
 19. Clifford S, Jerit J: **Disgust, anxiety, and political learning in the face of threat**. *Am J Political Sci* 2018, **62**:266-279.
 20. Sales SM: **Economic threat as a determinant of conversion rates in authoritarian and nonauthoritarian churches**. *J Pers Soc Psychol* 1972, **23**:420.
 21. Sales SM: **Threat as a factor in authoritarianism: an analysis of archival data**. *J Pers Soc Psychol* 1973, **28**:44.
 22. Bishop S, Duncan J, Brett M, Lawrence AD: **Prefrontal cortical function and anxiety: controlling attention to threat-related stimuli**. *Nat Neurosci* 2004, **7**:184-188.
 23. Bishop SJ, Duncan J, Lawrence AD: **State anxiety modulation of the amygdala response to unattended threat-related stimuli**. *J Neurosci* 2004, **24**:10364-10368.
 24. Lavric A, Rippon G, Gray JR: **Threat-evoked anxiety disrupts spatial working memory performance: an attentional account**. *Cogn Ther Res* 2003, **27**:489-504.
 25. Sheldon KM, Kasser T: **Psychological threat and extrinsic goal striving**. *Motiv Emot* 2008, **32**:37-45.
 26. Duckitt J: **Introduction to the special section on authoritarianism in societal context: the role of threat**. *Int J Psychol* 2013, **48**:1-5.
 27. Karwowski M, Kowal M, Groyecka-Bernard A, Bialek M, Lebuda I, Sorokowska A, Sorokowski P: **When in Danger, Turn Right: Does COVID-19 Threat Promote Social Conservatism and Right-wing Presidential Candidates?**; 2020.
 28. Thornhill R, Fincher CL, Aran D: **Parasites, democratization, and the liberalization of values across contemporary countries**. *Biol Rev* 2009, **84**:113-131.
 29. Brandt MJ, Bakker BN: **The complicated but solvable threat-politics relationship**. *Trends Cogn Sci* 2022, **26**:368-370.
 30. Brandt MJ, Bakker BN: **Threat-politics perceptions are intertwined with emotional processes**. *Trends Cogn Sci* 2022, **26**:733-734.
 31. Zmigrod L, Rentfrow PJ, Robbins TW: **Cognitive underpinnings of nationalistic ideology in the context of Brexit**. *Proc Natl Acad Sci* 2018, **115**:E4532-E4540.
 32. Zmigrod L: **A psychology of ideology: unpacking the psychological structure of ideological thinking**. *Perspect Psychol Sci* 2022, **17**:1072-1092.
 33. Blascovich J, Mendes WB, Hunter SB, Salomon K: **Social "facilitation" as challenge and threat**. *J Pers Soc Psychol* 1999, **77**:68.
 34. Conway CM: **How does the brain learn environmental structure? Ten core principles for understanding the neurocognitive mechanisms of statistical learning**. *Neurosci Biobehav Rev* 2020, **112**:279-299.
 35. Janacsek K, Nemeth D: **Predicting the future: from implicit learning to consolidation**. *Int J Psychophysiol* 2012, **83**:213-221.
 36. Lee SW, Shimojo S, O'Doherty JP: **Neural computations underlying arbitration between model-based and model-free learning**. *Neuron* 2014, **81**:687-699.
 37. Schapiro AC, Gregory E, Landau B, McCloskey M, Turk-Browne NB: **The necessity of the medial temporal lobe for statistical learning**. *J Cogn Neurosci* 2014, **26**:1736-1747.
 38. Zmigrod L, Burnell R, Hameleers M: **The misinformation receptivity framework: political misinformation and disinformation as cognitive Bayesian inference problems**. *Eur Psychol* 2023, **28**:173.
 39. Poldrack RA, Clark J, Pare-Blagoev EJ, Shohamy D, Creso Moyano J, Myers C, Gluck MA: **Interactive memory systems in the human brain**. *Nature* 2001, **414**:546-550.
 40. Poldrack RA, Packard MG: **Competition among multiple memory systems: converging evidence from animal and human brain studies**. *Neuropsychologia* 2003, **41**:245-251.
 41. Poldrack RA: **Hard to Break: Why Our Brains Make Habits Stick**. Princeton University Press; 2022.
 42. Virag M, Janacsek K, Horvath A, Bujdoso Z, Fabo D, Nemeth D: **Competition between frontal lobe functions and implicit sequence learning: evidence from the long-term effects of alcohol**. *Exp Brain Res* 2015, **233**:2081-2089.
 43. Pedraza F, Farkas BC, Vékony T, Haesebaert F, Janacsek K, Anders R, Tillmann B, Plancher G, Nemeth D: **Evidence for a competitive relationship between executive functions and statistical learning**. *bioRxiv* 2023,524710.
This empirical study shows that processing new information (re-presentational learning) could be better in the case of weaker executive functions.
 44. Ambrus GG, Vékony T, Janacsek K, Trimbom ABC, Kovács G, Nemeth D: **When less is more: enhanced statistical learning of non-adjacent dependencies after disruption of bilateral DLPFC**. *J Mem Lang* 2020, **114**:104144.
 45. Ruchkin D, Grafman J, Cameron K, Berndt D: **Working memory retention systems: a state of activated long-term memory**. *Behav Brain Sci* 2004, **26**:709-728.
 46. Van der Linden M, Meulemans T, Marczewski P, Collette F: **The relationships between episodic memory, working memory, and executive functions: the contribution of the prefrontal cortex**. *Psychol Belg* 2000, **40**:275-297.
 47. Daw ND, Niv Y, Dayan P: **Uncertainty-based competition between prefrontal and dorsolateral striatal systems for behavioral control**. *Nat Neurosci* 2005, **8**:1704-1711.
 48. Decker JH, Otto AR, Daw ND, Hartley CA: **From creatures of habit to goal-directed learners: tracking the developmental emergence of model-based reinforcement learning**. *Psychol Sci* 2016, **27**:848-858.
 49. Otto AR, Raio CM, Chiang A, Phelps EA, Daw ND: **Working-memory capacity protects model-based learning from stress**. *Proc Natl Acad Sci* 2013, **110**:20941-20946.
 50. Dolfen N, King BR, Schwabe L, Swinnen S, Albouy G: **Glucocorticoid response to stress induction prior to learning is negatively related to subsequent motor memory consolidation**. *Neurobiol Learn Mem* 2019, **158**:32-41.
 51. Ehlers MR, Todd RM: **Acute psychophysiological stress impairs human associative learning**. *Neurobiol Learn Mem* 2017, **145**:84-93.
 52. Joëls M, Fernandez G, Roozendaal B: **Stress and emotional memory: a matter of timing**. *Trends Cogn Sci* 2011, **15**:280-288.
 53. Schwabe L, Joëls M, Roozendaal B, Wolf OT, Oitzl MS: **Stress effects on memory: an update and integration**. *Neurosci Biobehav Rev* 2012, **36**:1740-1749.
 54. Fournier M, d'Arripe-Longueville F, Radel R: **Effects of psychosocial stress on the goal-directed and habit memory systems during learning and later execution**. *Psychoneuroendocrinology* 2017, **77**:275-283.
 55. Schwabe L, Wolf OT: **Stress and multiple memory systems: from 'thinking' to 'doing'**. *Trends Cogn Sci* 2013, **17**:60-68.
 56. Schwabe L, Wolf OT: **Stress-induced modulation of instrumental behavior: from goal-directed to habitual control of action**. *Behav Brain Res* 2011, **219**:321-328.
 57. Wirz L, Bogdanov M, Schwabe L: **Habits under stress: mechanistic insights across different types of learning**. *Curr Opin Behav Sci* 2018, **20**:9-16.

58. Schwabe L, Hermans EJ, Joëls M, Roozendaal B: **Mechanisms of memory under stress.** *Neuron* 2022, **110**:1450-1467.
59. Wood W, Rünger D: **Psychology of habit.** *Annu Rev Psychol* 2016, **67**:289-314.
60. Guenzel FM, Wolf OT, Schwabe L: **Sex differences in stress effects on response and spatial memory formation.** *Neurobiol Learn Mem* 2014, **109**:46-55.
61. Kirschbaum C, Wolf OT, May M, Wippich W, Hellhammer DH: **Stress- and treatment-induced elevations of cortisol levels associated with impaired declarative memory in healthy adults.** *Life Sci* 1996, **58**:1475-1483.
62. Tóth-Fáber E, Janacsek K, Szöllösi Á, Kéri S, Németh D: **Regularity •• detection under stress: faster extraction of probability-based regularities.** *PLoS One* 2021, **16**:e0253123.
- This study shows that stress induction in humans can boost information processing and statistical learning.
63. Hermans EJ, Henckens MJ, Joëls M, Fernández G: **Dynamic adaptation of large-scale brain networks in response to acute stressors.** *Trends Neurosci* 2014, **37**:304-314.
64. Vogel S, Schwabe L: **Learning and memory under stress: implications for the classroom.** *NPJ Sci Learn* 2016, **1**:16011.
65. Schwabe L: **Memory under stress: from single systems to network changes.** *Eur J Neurosci* 2017, **45**:478-489.
66. Arnsten AF: **Stress signalling pathways that impair prefrontal cortex structure and function.** *Nat Rev Neurosci* 2009, **10**:410-422.
67. Hermans EJ, Van Marle HJ, Ossewaarde L, Henckens MJ, Qin S, Van Kesteren MT, Schoots VC, Cousijn H, Rijpkema M, Oostenveld R: **Stress-related noradrenergic activity prompts large-scale neural network reconfiguration.** *Science* 2011, **334**:1151-1153.
68. Schwabe L, Wolf OT: **Socially evaluated cold pressor stress after instrumental learning favors habits over goal-directed action.** *Psychoneuroendocrinology* 2010, **35**:977-986.
69. Haushofer J, Fehr E: **On the psychology of poverty.** *Science* 2014, **344**:862-867.
70. Berger M, Taylor S, Harriss L, Campbell S, Thompson F, Jones S, Sushames A, Amminger GP, Sarnyai Z, McDermott R: **Hair cortisol, allostatic load, and depressive symptoms in Australian Aboriginal and Torres Strait Islander people.** *Stress* 2019, **22**:312-320.