

Review



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Author for correspondence:

Bianca Acevedo

e-mail: bianca.acevedo@lifesci.ucsb.edu

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The functional highly sensitive brain: a review of the brain circuits underlying sensory processing sensitivity and seemingly related disorders

Bianca Acevedo¹, Elaine Aron², Sarah Pospos¹ and Dana Jessen¹

¹Neuroscience Research Institute, University of California, Santa Barbara, CA, USA

²Department of Psychology, Stony Brook University, Stony Brook, NY, USA

BA, 0000-0001-6603-7218

During the past decade, research on the biological basis of sensory processing sensitivity (SPS)—a genetically based trait associated with greater sensitivity and responsiveness to environmental and social stimuli—has burgeoned. As researchers try to characterize this trait, it is still unclear how SPS is distinct from seemingly related clinical disorders that have overlapping symptoms, such as sensitivity to the environment and hyper-responsiveness to incoming stimuli. Thus, in this review, we compare the neural regions implicated in SPS with those found in fMRI studies of—Autism Spectrum Disorder (ASD), Schizophrenia (SZ) and Post-Traumatic Stress Disorder (PTSD) to elucidate the neural markers and cardinal features of SPS versus these seemingly related clinical disorders. We propose that SPS is a stable trait that is characterized by greater empathy, awareness, responsiveness and depth of processing to salient stimuli. We conclude that SPS is distinct from ASD, SZ and PTSD in that in response to social and emotional stimuli, SPS differentially engages brain regions involved in reward processing, memory, physiological homeostasis, self-other processing, empathy and awareness. We suggest that this serves species survival via deep integration and memory for environmental and social information that may subserve well-being and cooperation.

This article is part of the theme issue ‘Diverse perspectives on diversity: multi-disciplinary approaches to taxonomies of individual differences’.

1. Introduction

Clinically, sensory processing issues manifest as inappropriate responses to stimuli that involve emotional and behavioural disruptions, and interfere with an individual’s daily functioning [1]. As such, ‘sensitivity’ to sensory input may be defined positively as the ability to perceive small changes in stimulus intensity [2], or as a negative reaction to a low-threshold stimulus [3]. Correspondingly, neural ‘hyper’-responsiveness is ‘over-reactivity’ to a stimulus, while ‘hypo’-responsiveness is the absence of a typical response [4,5].

However, a variety of factors affect how individuals express their ‘sensitivity’ to a stimulus, such as their childhood environment, their predisposition to ‘sensitivity’, as well as other individual factors (including co-occurring disorders), and the context in which a particular stimulus occurs. In this review, we will focus on the specific ‘sensitivity’ trait termed ‘sensory processing sensitivity’ (SPS) or ‘high environmental sensitivity’ (ES) as measured by the HSP Scale [6]. Environmental sensitivity is considered a fundamental trait found on a spectrum and is defined as the degree to which an individual may register, process and respond to external factors [7]. Based on the Highly Sensitive Child scale, a reliable self-report measure of SPS or

environmental sensitivity, there appear to be three distinct groups of unique levels of environmental sensitivity: low, medium and high, with high sensitivity making up about 20–35% of a UK sample ranging in age from 8–19 years [8]. The three levels of environmental sensitivity are maintained across childhood, adolescence and adulthood, and appear to be comprised of the same neurophysiological and psychological factors but are manifested in varying degrees within individuals, appearing as ‘high sensitivity’ in roughly 30% of adults [9]. High sensitivity is mediated via neural and genetic factors [10–12] that are thought to predispose individuals to adverse conditions (such as stress, poor health and disorders) in harsh environments [13], as well as bestowing benefits in supportive ones [7,14,15].

According to SPS theory, the trait is characterized by greater depth of processing, cognizance of subtleties in the environment, being easily overstimulated, having stronger emotional responses (both positive and negative), and empathy to others’ affective cues [6,10,11,16–18]. Found in over 100 other species [11], including primates [18], SPS is thought to be a survival strategy that may facilitate behaviours to garner resources, provide responsive care to others, and avoid threats through careful observation of each situation and then comparing it to past observations. However, high sensitivity is not adapted by all organisms within a given species because it has cognitive and physiological costs. Furthermore, if all organisms were equally sensitive, there would be no advantage to it. Hence, high sensitivity is thought to be ‘negative frequency dependent’, found only in a minority of individuals within a given species.

Similarly, differential susceptibility (DS) and biological sensitivity to context (BSC) theories propose that individuals vary in their degree of sensitivity, and thus highly sensitive persons are more susceptible both to the detrimental effects of harsh environments, and the benefits of positive and nurturing ones [6,14,15,19–21].

In recent times, there has been increased attention to sensory processing disorders and Autism Spectrum Disorders (ASD), particularly in children, which are also characterized by hyper- or hypo-sensitivity to tactile, auditory and visual stimuli [22]. However, in contrast to SPS, individuals with ASD typically show social communicative difficulties, impaired empathy, restricted interests and repetitive behaviours [23,24]. In children with ASD, social deficits—such as difficulty in making eye contact, facial recognition, responding to others’ emotional cues and reciprocating intentions—appear as early as a few months to 2–3 years of age [25–32]. Indeed, a large body of work, including diagnostic tools, suggests that social impairments in ASD are largely mediated by deficient responsiveness of neural structures involved in emotion, facial processing, empathy and reflective thinking [33–37]. By contrast, fMRI research on SPS has tended to show prominent brain activation of regions that are implicated in empathy, social processing and reflective thinking [10,20].

Somewhat similarly, post-traumatic stress disorder (PTSD) is also characterized by maladaptive responses to triggering stimuli that are misperceived as harmful due to their similarity to stimuli present during the original trauma. This also leads to a generalized vigilance for threats and difficulty in properly evaluating sensory stimuli. These impairments manifest in one of two ways: as hyperarousal to stimuli or as dissociation that may appear as under-response to the triggering stimulus [38]. These disruptions often result in

the inability to properly integrate memories and a fixation on the past [39]. Correspondingly, brain imaging studies suggest that PTSD is associated with dysregulated response in neural regions that process emotion, attention, memory and self-control [40–44]. These studies suggest there is a general increase in emotional and vigilance-related brain activation in the amygdala; and diminished self-control, shown as PFC deactivation [45]; while remediation from PTSD shows the reverse [44]. Interestingly, some PTSD studies have shown diminished activation in sensory and temporal areas, supporting ideas that PTSD may also manifest as dissociation or lack of present-moment awareness [46].

Schizophrenia (SZ) and other psychosis-related disorders are also characterized by the inability to inhibit irrelevant information, from stimuli, along with difficulties in social cognition and interactions, which are mediated by impaired theory of mind, emotion-processing, and agency judgments [33]. SZ also manifests as hyper-distractibility and marked deficits in working memory. Its active symptoms include auditory and/or visual hallucinations without corresponding sources in the external world [47]. As such, neuroimaging studies that have compared SZ patients’ (versus healthy subjects) response to emotional stimuli (facial expressions) indicate abnormal activation of brain regions involved in emotion, memory, attention, empathy, multisensory integration, reflective thinking and self-control [33,48–53]. Clearly, these various disorders have overlapping symptoms, as ASD is also characterized by marked impairments in empathic and social processes and behaviours [29]; and all seem to show maladaptive responsiveness to incoming emotional stimuli. They are also well known and include a broad symptom of categories, therefore, motivating our selection for comparisons.

As evidence suggests that there are behavioural, conceptual and perceptual differences across SPS, ASD, PTSD and SZ—typically with regard to empathy, social interactions and emotional responsiveness to salient stimuli—we conducted a systematic review of functional MRI studies examining response to emotional and perceptual tasks across these fields to better understand the similarities and differences, as well as underlying neural correlates, for these conditions that involve ‘sensitivity’ to stimuli. We based this review on fMRI literature even though there are only four fMRI studies of SPS. However, we believe the comparison these allow, although only preliminary, will be useful because of the clear differences across these conditions.

2. Methods

First, we retrieved the four fMRI studies of SPS, and meta-analyses and review papers investigating ASD, PTSD and SZ with fMRI that involved tasks similar to those in the SPS studies: for example, studies examining responses to affective or social stimuli, emotion recognition or perceptual tasks. For ASD, PTSD and SZ, we focused on systematic reviews and meta-analyses, as the body of work on these are abundant. However, we also reviewed two individual fMRI studies of ASD that examined neural response to positive social stimuli and familiar versus unfamiliar faces [10,11], which very directly aligned with a study examining empathy as a function of SPS [1]. Moreover, we only included studies of marked ASD and excluded milder forms of the disorder, such as High-Functioning Autism (HFA) to make for a strong comparison with SPS, as studies

have tended to find differing results for samples low on Autism or with experimental paradigms that were not truly measuring empathy.

3. Results

This review included 27 peer-reviewed fMRI research articles, meta-analyses and review papers examining neural responsiveness to emotional, social or salient stimuli: four regarding SPS, eight ASD, nine SZ and seven PTSD (one meta-analysis reported on social cognition studies for both SZ and ASD [33]). Brain region results and sample characteristics for SPS and ASD studies are shown in the electronic supplementary material, tables S1 and S2, respectively.

We compared patterns of activation and deactivation for SPS, ASD, SZ and PTSD studies. Common activations across all four were shown in the precentral gyrus. Activations unique to SPS were shown in neural structures associated with reward processing (VTA and SN, for positive stimuli only), physiological homeostasis and pain-control (hypothalamus and PAG); self-other processing and empathy (IFG and insula), awareness and reflective thinking (TPJ) and self-control (PFC)—while they showed deactivations or lack of results for ASD, PTSD and SZ in the context of emotional, social and perceptual tasks. However, SZ was dissimilar from SPS, ASD and PTSD in its showing deactivations in the caudate, thalamus, amygdala, cingulate/anterior cingulate cortex (ACC), superior frontal gyrus (SFG), precuneus, medial temporal gyrus and superior temporal lobe/gyrus (STL/STG)—while these areas were activated for SPS, ASD and PTSD (with some variability).

Comparison of SPS and ASD studies showed common neural activations in the caudate, thalamus, STG/STL, supra-marginal gyrus and precuneus. However, SPS showed clear activations, whereas ASD showed deactivations, in the VTA/SN (for positive stimuli only); amygdala (emotion), hippocampus (memory), hypothalamus and PAG; as well as regions involved in empathy and self-other processing (insula, AI, IFG, FG); self-control and executive function (MFG and PFC); and the default mode network (DMN) including the temporal, TPJ, parietal and angular gyrus (AG).

4. Discussion

The present review highlights common and unique neural circuits reported for SPS as compared to ASD, PTSD and SZ—disorders that involve sensory issues and hyper- or hypo-responsiveness to stimuli. A common brain activation reported in the literature across these four conditions was the precentral gyrus; a primary site of motor command that is involved in conscious movement [54]. Common activations for SPS, ASD and PTSD (showing deactivation or lack of activation for SZ) were the caudate (reward processing), thalamo-cingulate circuit (attention) and areas of the DMN (SFG, precuneus and temporal areas) involved in reflective thinking, motor and cognitive control. These results highlight some neural structures that may coordinate hyper-sensitivity symptoms displayed in SPS, ASD and PTSD, and also suggests how SPS may be correlated with some of these conditions. For example, individuals with high (versus low) SPS may be more susceptible to PTSD and other adverse reactions following trauma exposure [55].

Neural activations that appeared for SPS, but showed deactivations or lack of activations for ASD, PTSD and SZ, were shown in regions that mediate reward (to positive stimuli only), hormonal balance, calm, empathy, self-reflective thinking and self-control (hypothalamus, PAG, IFG, insula, TPJ and PFC). These brain structures highlight some of the primary features that differentiate SPS from the disorders reviewed herein, such as enhanced conscientiousness, empathy and depth of processing [6]. Highly sensitive individuals do experience hyperarousal to some stimuli, such as when feeling empathy towards others' distress or in the presence of unusually loud noises, but these may be moderated in at least some individuals, if not most, by increased physiological calm and homeostasis, as well as cognitive and emotional control. This requires regulating unpleasant emotional states to optimize outcomes for the self and others as seen by prominent activation of the PFC, involved in self-regulation. SPS is characterized by a deep integration of information and intricate memory processing. These two neural signatures of SPS processing are facilitated when the organism remains calm in the presence of a stimulus while engaging other emotional, cognitive and sensory systems.

However, for ASD, PTSD and SZ, dysregulated responses in the hippocampus, insula and DMN are typical [52,56], disrupting memory and integration of information. Also in ASD, PTSD and SZ, decreased reward to positive stimuli plus a lack of empathy, calmness and self-control coincide with disruptions in social behaviours, as seemingly benign stimuli may be perceived as threats.

For ASD specifically, the reward, emotional and calming-inducing nature of social stimuli appear to be impaired, as manifested in diminished VTA, amygdala, hippocampal, hypothalamic and PAG activations. This results in lessened self-other processing and decreased empathy (deactivation of the IFG, FG and insula, and AG) that are cardinal features of ASD as confirmed by many studies [29,33]. We suggest that these differences in response to social stimuli for ASD (compared with SPS) may also be due to the diminished calm and reward inducing elements that are typically evoked for social/affective events in neuro-typical individuals. This suggests perhaps that a key divergence for SPS and ASD may be the extent to which individuals find social/emotional stimuli rewarding and are able to physiologically/hormonally and behaviourally respond adaptively to both positive and negative social stimuli.

The present review highlights some of the principal features of SPS, ASD, SZ and PTSD; and provides some key neural patterns that may serve to distinguish SPS from clinical disorders with sensory symptoms. They also help to clarify practical issues around SPS and neurodiversity perspectives on ASD which otherwise have suggested that all sensory issues are clear indications of ASDs. It is important to note that ASD is a spectrum showing varying degrees of symptoms with some individuals having HFA or Asperger's. However, the present review only included studies of diagnosed ASD, and excluded studies in which the majority of subjects were HFA.

With only four fMRI studies involved in SPS, it is clear that more research is needed on this topic. Although this review may seem preliminary, it seemed warranted to begin to clarify how SPS is distinct from disorders that may seem related due to symptoms and hyperarousal to stimuli. However, as shown by fMRI studies, SPS is clearly different

with respect to empathy, emotional responsiveness, self-reflection, physiological calm and self-regulation. Thus, this review may serve as a basis for clarification of diagnoses, practical questions, and further research and developments.

5. Conclusion

SPS is distinct from seemingly related clinical disorders—such as ASD, PTSD and SZ—that have overlapping symptoms such as sensitivity to the environment and hyper- or hypo-responsiveness to stimuli. Consistent with research suggesting that SPS is associated with greater empathy and awareness in response to social, emotional and perceptual tasks, we found that SPS differentially engages brain regions involved in reward processing (for positive stimuli), memory, physiological homeostasis, self-other processing and awareness. We suggest that adaptive SPS strategies involving empathy, awareness, calmness and physiological and cognitive self-control may serve a species by facilitating deep integration and memory for environmental

and social information, which may ultimately foster survival, well-being and cooperation.

Ethics. The articles reviewed provided approval statements for research with human subjects and informed consent.

Data accessibility. All data gathered for this review may be available upon request to the corresponding author.

Authors' contributions. B.A., PhD contributed to the conception and design of this review, making decisions about inclusion criteria for articles, interpretation of the data, drafting and revising the article, and final approval of the version to be published. E.A., PhD contributed to making decisions about the inclusion criteria and revising the article. S.P. contributed to gathering and organizing research articles for the review, drafting and organizing the tables, and revising the article. D.J. contributed to gathering and organizing research articles for the review, drafting and organizing the tables, and revising the article.

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References

- Miller LJ, Schoen SA, James K, Schaaf RC. 2007 Lessons learned: a pilot study on occupational therapy effectiveness for children with sensory modulation disorder. *Am. J. Occup. Ther.* **61**, 161–169. (doi:10.5014/ajot.61.2.161)
- Engen T. 1988 Psychophysics. In *States of brain and mind* (ed. JA Hobson), pp. 89–91. Berlin, Germany: Springer.
- Dunn W. 1997 The impact of sensory processing abilities on the daily lives of young children and their families: a conceptual model. *Infants Young Child.* **9**, 23–35. (doi:10.1097/00001163-199704000-00005)
- McCormick C, Hepburn S, Young GS, Rogers SJ. 2016 Sensory symptoms in children with autism spectrum disorder, other developmental disorders and typical development: a longitudinal study. *Autism* **20**, 572–579. (doi:10.1177/1362361315599755)
- Ben-Sasson A, Hen L, Fluss R, Cermak SA, Engel-Yeger B, Gal E. 2009 A meta-analysis of sensory modulation symptoms in individuals with autism spectrum disorders. *J. Autism Dev. Disord.* **39**, 1–11. (doi:10.1007/s10803-008-0593-3)
- Aron EN, Aron A. 1997 Sensory-processing sensitivity and its relation to introversion and emotionality. *J. Pers. Soc. Psychol.* **73**, 345–368. (doi:10.1037/0022-3514.73.2.345)
- Pluess M. 2015 Individual differences in environmental sensitivity. *Child Dev. Perspect.* **9**, 138–143. (doi:10.1111/cdep.12120)
- Pluess M, Assary E, Lionetti F, Lester KJ, Krapohl E, Aron EN, Aron A. 2017 Environmental sensitivity in children: development of the highly sensitive child scale and identification of sensitive groups. *Dev. Psychol.* **54**, 51–70. (doi:10.1037/dev0000406)
- Lionetti F, Aron A, Aron E, Burns GL, Jagiellowicz J, Pluess M. In press. Dandelions, tulips, and orchids: evidence for the existence of low, medium, and high sensitive individuals in the general population. *Translational Psychiatry*.
- Acevedo BP, Aron EN, Aron A, Sangster MD, Collins N, Brown LL. 2014 The highly sensitive brain: an fMRI study of sensory processing sensitivity and response to others' emotions. *Brain Behav.* **4**, 580–594. (doi:10.1002/brb3.242)
- Wolf M, Van Doorn GS, Weissing FJ. 2008 Evolutionary emergence of responsive and unresponsive personalities. *Proc. Natl Acad. Sci. USA* **105**, 15 825–15 830. (doi:10.1073/pnas.0805473105)
- Homberg JR, Schubert D, Asan E, Aron EN. 2016 Sensory processing sensitivity and serotonin gene variance: insights into mechanisms shaping environmental sensitivity. *Neurosci. Biobehav. Rev.* **71**, 472–483. (doi:10.1016/j.neubiorev.2016.09.029)
- Uher R. 2014 Gene–environment interactions in common mental disorders: an update and strategy for a genome-wide search. *Soc. Psychiatry Psychiatr. Epidemiol.* **49**, 3–14. (doi:10.1007/s00127-013-0801-0)
- Boyce WT, Ellis BJ. 2005 Biological sensitivity to context: I. An evolutionary–developmental theory of the origins and functions of stress reactivity. *Dev. Psychopathol.* **17**, 271–301. (doi:10.1017/S0954579405050145)
- Belsky J. 2005 Differential susceptibility to rearing influence. In *Origins of the social mind: evolutionary psychology and child development* (eds BJ Ellis, DF Bjorklund), pp. 139–163. New York, NY: Guilford Press.
- Aron EN, Aron A, Jagiellowicz J. 2012 Sensory processing sensitivity: a review in the light of the evolution of biological responsiveness. *Pers. Soc. Psychol. Rev.* **16**, 262–282. (doi:10.1177/1088868311434213)
- Aron A, Melinat E, Aron EN, Vallone RD, Bator RJ. 1997 The experimental generation of interpersonal closeness: a procedure and some preliminary findings. *Pers. Soc. Psychol. Bull.* **23**, 363–377. (doi:10.1177/0146167297234003)
- Suomi SJ. 2006 Risk, resilience, and gene x environment interactions in rhesus monkeys. *Ann. N Y Acad. Sci.* **1094**, 52–62. (doi:10.1196/annals.1376.006)
- Belsky J, Pluess M. 2009 Beyond diathesis stress: differential susceptibility to environmental influences. *Psychol. Bull.* **135**, 885. (doi:10.1037/a0017376)
- Acevedo B, Jagiellowicz J, Aron E, Marhenke R, Aron A. 2017 Sensory processing sensitivity and childhood quality's effects on the human brain's emotional response. *J. Clin. Neuropsychiatry.* **14**, 359–373.
- Jagiellowicz J, Aron A, Aron EN. 2016 Relationship between the temperament trait of sensory processing sensitivity and emotional reactivity. *J. Soc. Behav. Pers.* **44**, 185–199. (doi:10.2224/sbp.2016.44.2.185)
- Masataka N. 2017 Implications of the idea of neurodiversity for understanding the origins of developmental disorders. *Phys. Life Rev.* **20**, 85–108. (doi:10.1016/j.plrev.2016.11.002)
- Schauder KB, Bennetto L. 2016 Toward an Interdisciplinary understanding of sensory dysfunction in autism spectrum disorder: an integration of the neural and symptom literatures. *Front. Neurosci.* **10**, 268. (doi:10.3389/fnins.2016.00268)

24. American Psychiatric Association. 2013 Diagnostic and statistical manual of mental disorders (DSM-5®).
25. Werner E, Dawson G, Osterling J, Dinno N. 2000 Brief report: recognition of autism spectrum disorder before one year of age: a retrospective study based on home videotapes. *J. Autism Dev. Disord.* **30**, 157–162. (doi:10.1023/A:1005463707029)
26. Osterling J, Dawson G. 1994 Early recognition of children with autism: a study of first birthday home videotapes. *J. Autism Dev. Disord.* **24**, 247–257. (doi:10.1007/BF02172225)
27. Maestro S, Muratori F, Cavallaro MC, Pei F, Stern D, Golse B, Palacio-Espasa F. 2002 Attentional skills during the first 6 months of age in autism spectrum disorder. *J. Am. Acad. Child Adolesc. Psychiatry.* **41**, 1239–1245. (doi:10.1097/00004583-200210000-00014)
28. Cox A, Klein K, Charman T, Baird G, Baron-Cohen S, Swettenham J, Drew A, Wheelwright S. 1999 Autism spectrum disorders at 20 and 42 months of age: stability of clinical and ADI-R diagnosis. *J. Child Psychol. Psychiatry.* **40**, 719–732. (doi:10.1111/1469-7610.00488)
29. Schultz RT. 2005 Developmental deficits in social perception in autism: the role of the amygdala and fusiform face area. *Int. J. Dev. Neurosci.* **23**, 125–141. (doi:10.1016/j.ijdevneu.2004.12.012)
30. Sigman MD, Kasari C, Kwon JH, Yirmiya N. 1992 Responses to the negative emotions of others by autistic, mentally retarded, and normal children. *Child Dev.* **63**, 796–807. (doi:10.1111/j.1467-8624.1992.tb01662.x)
31. Sigman M, Mundy P, Sherman T, Ungerer J. 1986 Social interactions of autistic, mentally retarded and normal children and their caregivers. *J. Child Psychol. Psychiatry.* **27**, 647–655. (doi:10.1111/j.1469-7610.1986.tb00189.x)
32. Baron-Cohen S, Belmonte MK. 2005 AUTISM: a window onto the development of the social and the analytic brain. *Annu. Rev.* **28**, 109–126. (doi:10.1146/annurev.neuro.27.070203.144137)
33. Sugranyes G, Kyriakopoulos M, Corrigan R, Taylor E, Frangou S. 2011 Autism spectrum disorders and schizophrenia: meta-analysis of the neural correlates of social cognition. *PLoS ONE* **6**, e25322. (doi:10.1371/journal.pone.0025322)
34. Rosenblau G, Kliemann D, Dziobek I, Heekeren HR. 2017 Emotional prosody processing in autism spectrum disorder. *Soc. Cogn. Affect. Neurosci.* **12**, 224–239. (doi:10.1093/scan/nsw118)
35. Kleinhans NM, Johnson LC, Richards T, Mahurin R, Greenson J, Dawson G, Alyward E. 2009 Reduced neural habituation in the amygdala and social impairments in autism spectrum disorders. *Am. J. Psychiatry.* **166**, 467–475. (doi:10.1176/appi.ajp.2008.07101681)
36. Kim S-Y *et al.* 2015 Abnormal activation of the social brain network in children with autism spectrum disorder: an fMRI study. *Psychiatry Investig.* **12**, 37–45. (doi:10.4306/pi.2015.12.1.37)
37. Di Martino A, Ross K, Uddin LQ, Sklar AB, Castellanos FX, Milham MP. 2009 Functional brain correlates of social and nonsocial processes in autism spectrum disorders: an activation likelihood estimation meta-analysis. *Biol. Psychiatry* **65**, 63–74. (doi:10.1016/j.biopsych.2008.09.022)
38. Lanius RA, Bluhm R, Lanius U, Pain C. 2006 A review of neuroimaging studies in PTSD: heterogeneity of response to symptom provocation. *J. Psychiatr. Res.* **40**, 709–729. (doi:10.1016/j.jpsychires.2005.07.007)
39. van der Kolk BA, Roth S, Pelcovitz D, Sunday S, Spinazzola J. 2005 Disorders of extreme stress: the empirical foundation of a complex adaptation to trauma. *J. Trauma Stress.* **18**, 389–399. (doi:10.1002/jts.20047)
40. Etkin A, Wager TD. 2007 Functional neuroimaging of anxiety: a meta-analysis of emotional processing in PTSD, social anxiety disorder, and specific phobia. *Am. J. Psychiatry.* **164**, 1476–1488. (doi:10.1176/appi.ajp.2007.07030504)
41. Hayes JP, Hayes SM, Mikedis AM. 2012 Quantitative meta-analysis of neural activity in posttraumatic stress disorder. *Biol. Mood Anxiety Disord.* **2**, 9. (doi:10.1186/2045-5380-2-9)
42. Patel R, Spreng RN, Shin LM, Girard TA. 2012 Neurocircuitry models of posttraumatic stress disorder and beyond: a meta-analysis of functional neuroimaging studies. *Neurosci. Biobehav. Rev.* **36**, 2130–2142. (doi:10.1016/j.neubiorev.2012.06.003)
43. Rougemont-Bücking A, Linnman C, Zeffiro TA, Zeidan MA, Lebron-Milad K, Rodriguez-Romaguera J, Rauch SL, Pitman RK, Milad MR. 2011 Altered processing of contextual information during fear extinction in PTSD: an fMRI study. *CNS Neurosci. Ther.* **17**, 227–236. (doi:10.1111/j.1755-5949.2010.00152.x)
44. Thomas K, Dorrepaal E, Draijer N, Jansma EP, Veltman DJ, van Balkom AJ. 2014 Can pharmacological and psychological treatment change brain structure and function in PTSD? A systematic review. *J. Psychiatr. Res.* **50**, 1–15. (doi:10.1016/j.jpsychires.2013.11.002)
45. Koenigs M, Grafman J. 2009 Posttraumatic stress disorder: the role of medial prefrontal cortex and amygdala. *Neuroscientist* **15**, 540–548. (doi:10.1177/1073858409333072)
46. Sartory G, Cwik J, Knuppertz H, Schürholt B, Lebens M, Seitz RJ, Schulze R. 2013 In search of the trauma memory: a meta-analysis of functional neuroimaging studies of symptom provocation in posttraumatic stress disorder (PTSD). *PLoS ONE* **8**, e58150. (doi:10.1371/journal.pone.0058150)
47. Jardri R, Pouchet A, Pins D, Thomas P. 2011 Cortical activations during auditory verbal hallucinations in schizophrenia: a coordinate-based meta-analysis. *Am. J. Psychiatry* **168**, 73–81. (doi:10.1176/appi.ajp.2010.09101522)
48. Aleman A, Kahn RS. 2005 Strange feelings: do amygdala abnormalities dysregulate the emotional brain in schizophrenia? *Prog. Neurobiol.* **77**, 283–298. (doi:10.1016/j.pneurobio.2005.11.005)
49. Goghari VM, Sanford N, Spilka MJ, Woodward TS. 2017 Task-related functional connectivity analysis of emotion discrimination in a family study of schizophrenia. *Schizophr. Bull.* **43**, 1348–1362. (doi:10.1093/schbul/sbx004)
50. Gur RC *et al.* 2002 A method for obtaining 3-dimensional facial expressions and its standardization for use in neurocognitive studies. *J. Neurosci. Methods.* **115**, 137–143. (doi:10.1016/S0165-0270(02)00006-7)
51. Taylor SF, Kang J, Brege IS, Tso IF, Hosanagar A, Johnson TD. 2012 Meta-analysis of functional neuroimaging studies of emotion perception and experience in schizophrenia. *Biol. Psychiatry* **71**, 136–145. (doi:10.1016/j.biopsych.2011.09.007)
52. Wylie KP, Tregellas JR. 2010 The role of the insula in schizophrenia. *Schizophr. Res.* **123**, 93–104. (doi:10.1016/j.schres.2010.08.027)
53. Green MF, Horan WP, Lee J. 2015 Social cognition in schizophrenia. *Nat. Rev. Neurosci.* **16**, 620. (doi:10.1038/nrn4005)
54. Ackerman S. 1992 Major structures and functions of the brain. In *Discovering the brain* (ed. S Ackerman). Washington, DC: National Academies Press (US).
55. Marshall GN, Miles JN, Stewart SH. 2010 Anxiety sensitivity and PTSD symptom severity are reciprocally related: evidence from a longitudinal study of physical trauma survivors. *J. Abnorm. Psychol.* **119**, 143–150. (doi:10.1037/a0018009)
56. Shenton ME, Dickey CC, Frumin M, McCarley RW. 2001 A review of MRI findings in schizophrenia. *Schizophr. Res.* **49**, 1–52. (doi:10.1016/s0920-9964(01)00163-3)