Brain and Cognition 140 (2020) 105548

Contents lists available at ScienceDirect

Brain and Cognition

journal homepage: www.elsevier.com/locate/b&c

Belief formation – A driving force for brain evolution

Rüdiger J. Seitz[a,b,*], Hans-Ferdinand Angel[c]

[a] Department of Neurology, Centre of Neurology and Neuropsychiatry, LVR-Klinikum Düsseldorf, Medical Faculty, Heinrich-Heine-University Düsseldorf, Düsseldorf, Germany

[b] Florey Neuroscience Institutes, Melbourne, Australia

[c] Karl Franzens University Graz, Institute of Catechetic and Pedagogic of Religion, Graz, Austria

ARTICLE INFO

Keywords:
Believing
Brain
Meaning
Neural processes
Phylogenesis

ABSTRACT

The topic of belief has been neglected in the natural sciences for a long period of time. Recent neuroscience research in non-human primates and humans, however, has shown that beliefs are the neuropsychic product of fundamental brain processes that attribute affective meaning to concrete objects and events, enabling individual goal setting, decision making and maneuvering in the environment. With regard to the involved neural processes they can be categorized as empirical, relational, and conceptual beliefs. Empirical beliefs are about objects and relational beliefs are about events as in tool use and in interactions between subjects that develop below the level of awareness and are up-dated dynamically. Conceptual beliefs are more complex being based on narratives and participation in ritual acts. As neural processes are known to require computational space in the brain, the formation of inceasingly complex beliefs demands extra neural resources. Here, we argue that the evolution of human beliefs is related to the phylogenetic enlargement of the brain including the parietal and medial frontal cortex in humans.

1. Introduction

The topic of belief has been of central interest in philosophy, and especially in the philosophical field of epistemology since Antiquity. Here, beliefs are predominantly understood as states of the mind (Churchland & Churchland, 2013,1). The most widely held concept understands belief as attitude formally expressed by "*S A that P*". In this canonical expression, S indicates the individual possessing of a mental state, A indicates the attitude, and P is a sentence expressing a proposition. Accordingly, a person can have different attitudes like fear, hope, or desire towards the same proposition (Schwitzgebel, 2015). Based on this philosophical tradition, beliefs are considered as mental states or attitudes which occur upon the appraisal of a proposition as true or probably true (Leicester, 2008). More recently beliefs have been considered as dispositions, representations, interpretations, or been described according to their functions (Schwitzgebel, 2015). In other approaches beliefs have been differentiated according to their content such as factual, autobiographical, semantic, ethical, political and religious (Harris, Sheth, & Cohen, 2007; Howlett & Paulus, 2015). In the natural sciences the topic of belief has long been neglected. In contrast, in the neurosciences there was a substantial lack of empirical efforts to understand "normal" beliefs theoretically which was described as a "neglect of belief" (Connors & Halligan, 2015). However, an increasing interest in beliefs can be observed also in the recent neuroscientific literature.

Commenting on the seminal neuroimaging study on beliefs by Harris et al. (2007), Sachs and Hirsch (2008) suggested that human beings tend to accept appearances as reality until they prove otherwise. Following this argument, four important implications can be put forward:

1. humans tend to believe their perceptions to be true,
2. humans develop a positive stance towards such a belief,
3. beliefs can be updated by confirming or disproving new evidence,
4. the processes underlying believing result from brain function.

Thus, Sachs and Hirsch (2008) pioneered the view that belief formation results from perceptive and affective information processing that takes place in the brain of individual subjects. Moreover, this neuropsychological approach departed from the ordinary usage of belief as the assignment of truth to a proposition about the state of the world.

Recently, we have taken Sachs's and Hirsch's notion further by arguing that beliefs are the product of neural processes that can be

* Corresponding author at: Department of Neurology, Centre of Neurology and Neuropsychiatry, LVR-Klinikum Düsseldorf, Bergische Landstrasse 2, 40629 Düsseldorf, Germany.

E-mail address: seitz@neurologie.uni-duesseldorf.de (R.J. Seitz).

https://doi.org/10.1016/j.bandc.2020.105548
Received 2 September 2019; Received in revised form 6 February 2020; Accepted 6 February 2020
Available online 12 February 2020

expressed by B = f(b) (Seitz, Paloutzian, & Angel, 2018). Here, B indicates a belief state expressed as noun, b indicates the processes of believing expressed as verb. Thus, the equation signifies that B is a function (f) of and thus dependent on a processual b. The processes while someone is believing have been labelled as credition to highlight the difference to noun-related conceptions of beliefs (Angel & Seitz, 2016). The believing processes were shown to correspond to perception and valuation which are fundamental neural processes (Seitz, Paloutzian, & Angel, 2016). They afford meaning making of signals in the environment and attribute personal relevance to them (Seitz & Angel, 2015). Consequently, the appearances in the environment represent reality and relevance for a given subject. But this may not be shared by other subjects. Accordingly, belief formation can be regarded without referring to the notions of truth, knowledge and rationality (Angel & Seitz, 2016). A further aspect of beliefs is that they typically become manifest below the level of awareness, as their processing in the nervous system occurs in the range of milliseconds (Bar, Neta, & Linz, 2006; Smith, 2011). Also, due to the limited detectability of objects and events in the environment, beliefs are probabilistic concerning both the subject's event knowledge (Taves & Asprem, 2016) as well as predictions of future events (Friston, 2010). Nevertheless, the processes of believing are based on re-iterative neural processes linking past to future events as depicted schematically in Fig. 1. Without going into the details regarding the theoretical and philosophical implications of the term representation (Huber, 2016) the resulting neural representations in the brain are flexible, as they are subject to modification by new information according to the principles of brain plasticity involved in learning (Angel & Seitz, 2017; Merzenich & Sameshima, 1993). As belief formation seems to reflect to the individual subject the meaning of his/her past and future interactions with the environment, beliefs are closely linked to guidance of spontaneous and contextualized behavior as well as decision making. In accordance with this assumption, Markl (2005) has argued that even animals typically dichotomize signals in the environment according to nurture versus threat and to react accordingly. Thus, we hypothesize that believing is a physiological brain function that stabilizes a perception in the light of its value to a given subject.

It is well-known that the evolution of higher cognitive abilities is interrelated with brain evolution. The evolution of special types of higher cognitive abilities, namely believing processes is probably highly influential on brain evolution. Neural processes, most likely including those underlying cognitive functions such as belief formation, are known to consume energy for synaptic transmission between neurons. Neurons have a complex organization in the cerebral cortex and in distributed neural networks. Both have been studied extensively with functional and structural brain imaging (e.g. Toga & Mazziotta, 2000). Apart from the sensory systems and the motor system, cognitive functions as in language, memory, empathy, social interaction etc. have been mapped to different, but nevertheless partially overlapping circuits of the human brain. It was shown that the cerebral representations of these neural systems and brain functions recruit neural resources in extensive neural circuits involving the overlapping and non-overlapping parts of the cerebral cortex and subcortical structures (e.g. Bullmore & Sporns, 2012). Importantly, more complex functions were found to require more neural resources in the cerebral cortex than more basic functions (e.g. Seitz, Stephan, & Binkofski, 2000, Toga & Mazziotta, 2000). Therefore, it is a reasonable presumption that the neural processes enabling belief formation about multifaceted events require more neural resources than those about simple objects. Furthermore, it is also reasonable to hypothesize that the evolution of complex conceptual beliefs in *Homo sapiens* was related to the phylogenetic enlargement of supramodal cortical areas as part of large-scale neural circuits.

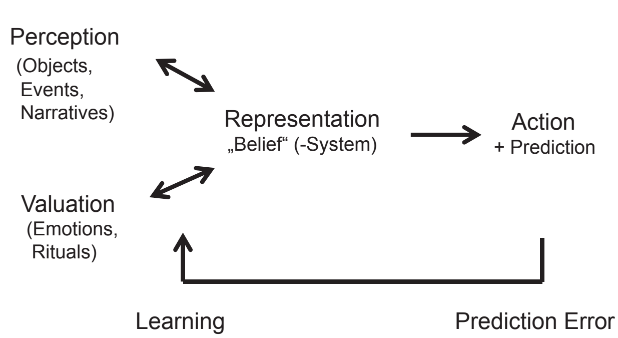

Fig. 1. Neuropsychic model of dynamic belief formation. Perception and subjective valuation of signals in the environment are re-interative, bottom-up and top-down processes constituting probabilistic neural representations, e.g. "beliefs". Coding of appropriate actions and of potential outcomes provide the basis for belief reinforcement and updating by learning.

From the perspective of the processes of believing described above we propose three catergories of beliefs that we characterize as empirical, relational, and conceptual. This differentiation is likely to have a linguistic counterpart in the European languages in the triple verbal expressions of beliefs involving "believe that", "believe someone" or "believe in". Also, we hypothesize that neural processing of increasingly complex beliefs contributed to brain evolution.

2. Three categories of beliefs

According to their processual properties we differentiate three different categories of beliefs as summarized in Table 1. Importantly, this categorization differs from field-related and content-based categorizations like political beliefs (Moretti, Cristofori, Zamboni, & Sirigu, 2013) or religious beliefs (Bulbulia & Schoedt, 2013; van Leeuwen, 2014).

Empirical beliefs develop upon first exposure to concrete objects outside of conscious awareness and do not rely on language (Fig. 1). For example, in tactile exploration subjects develop a probabilistic perceptual representation of the object comprising geometry, heaviness, surface properties, and pragmatic use (Binkofski et al., 1999; Bodegård, Geyer, Grefkes, Zilles, & Roland, 2001). Note, that sensory encoding differs from reality filtering which are partially independent processes involving different neural structures (Thézé, Manuel, Nahum, Guggisberg, & Schnider, 2017). In addition, the perceived object is valuated in terms of what its meaning is to the exploring subject, such that an emotional loading becomes assigned to the object including aesthetic value, desirability or averseness and threat (Ishizu & Zeki, 2013; Rolls, 2006; Thiruchselvam, Harper, & Homer, 2016). As the strength of the perceived value (positivity or negativity) was shown to be related to the perceived arousal, it decreases steadily as valence perception becomes more ambiguous (Brainerd, 2018). These processes occur instantaneously, e.g. already early, in sensation and become stabilized by re-inforcement learning or modified upon subsequent exposures (Seitz, Angel, & Paloutzian, 2019). Conversely, when the visibility of a potential reward is degraded, the ability to learn from outcomes is decreased leading the subjects to tend to repeat previous choices (Correa et al., 2018). This was found to be related to a significant modulation of neural activity with a strong relation to feelings of pleasure and desire (Correa et al., 2018). Moreover, positive emotional values or predicted outcomes have been shown to be linked to the self and used for self-enhancement promoting action, whereas negative outcomes are more often attributed to others with little effect on

Table 1
Properties of beliefs.

Category	Mode	Content	Linguistic Expression
Empirical Beliefs	instantaneous	objects	to believe that
Relational Beliefs	instantaneous	events	to believe someone
Conceptual Beliefs	language-bound	narratives	to believe in

behavior (Gentsch, Weiss, Spengler, Synofzik, & Schütz-Bosbach, 2015). Although empirical beliefs become established outside of conscious awareness, people can become aware of them and estimate their personal relevance and confidence in them (Sugiura, Seitz, & Angel, 2015). They consider an empirical belief as probably true - inspite of incomplete knowledge - with increasing confidence in proportion to the number of observations (Meyniel, Schlunegger, & Dehaene, 2015). Subjects can express their uncertainty through bodily expressions. But, verbally they may express their subjective confidence in the actual meaning made by "I believe that …". Similarly, it was shown that monkeys can acquire differentiated coo-call sounds for different items (Hihara, Yamada, Iriki, & Okanoya, 2003). This proto-language function most likely requires additional neural resources close to the perceptive and/or pragmatic representation of the items in the brain (Iriki & Taoka, 2012).

As the second category of beliefs we introduce relational beliefs (Table 1). Recently it was shown that humans and non-human primates have the capacity to assess relations in their environment. For example, ordinarily grouped items are processed with greater efficiency than the same number of isolated objects, a process known as "clumping" (Kaiser & Peelen, 2018). Moreover, when a subject realizes that an object can be used as a tool, e.g. to retrieve a reward, this is an event which reflects motivating relevance for the subject. In other words, the subject generates the belief that the object is a beneficial tool for him/her. Similarly, there is experimental evidence that non-human primates can make the step to include tools into their "body schema" as if they were effectors of their own body (Maravita & Iriki, 2004). In fact, the subject appears to appreciate the relation of the object or tool to the body as workable or trustable similarly to a part of him/herself. This can be extended also to social interactions. It was found that the brain gets more engaged when subjects are observed as interacting compared to similarly placed but non-interacting subjects (Isik, Koldewyn, Beeler, & Kanwisher, 2017; Papeo & Abassi, 2019; Walbrin, Downing, & Koldewyn, 2018). Similarly to tools that become integrated into the "body schema" (Maravita & Iriki, 2004) the counterpart is likely to become a part in the "personal schema" of the persons involved. They develop a belief of interpersonal trust (de Visser & Krueger, 2013) the deepest of which is usually called love. It should be highlighted that these processes occur almost instantaneously within a few milliseconds below the level of awareness (Potthoff & Seitz, 2015). Moreover, beliefs about reciprocity in personal interactions have been described to be related to an expected reward signal in the ventral striatum (Fairley, Vyrastekova, Weitzel, & Sanfey, 2019). This kind of experience can be signalled to others by bodily and/or proto-language expressions. At least, in the modern languages that follow the linguistic tradition prefigurated by Ancient Greek and Latin this may be expressed by "I trust him/her" or "I believe him/her".

Beliefs of the third category refer to abstract processing and are labeled conceptual beliefs (Table 1). They pertain to human-unique events including the sequences of sensory signals such as music and language-based information (Hauser, Chomsky, & Fitch, 2002). Humans are used to telling stories about their own and other people's past, their origins, and their goals, and their future after physical death (Belzen, 2010). These narratives are repeatedly presented to children by their grandparents, parents, siblings and other family members and depicted in books or in other media eventually building the repertoire of the subject's concepts concerning the broad spectrum of cultural life (Belzen, 2010). It is well known that fairytales and stories get emotional loading by the way, e.g. rhythm, prosody and tune, as well as the situation and environment in which they are told. Moreover, it was argued that ritual practices provide non-language bound emotional loadings for narratives facilitating belief acquisition and maintenance affecting goal states and social connection (Hobson, Schroeder, Risen, Xygualatas, & Inzlicht, 2018; Schnell, 2012). Such advanced conceptual beliefs about ecological, social, cultural, religious and political identities and norms evolve gradually over years from infancy onwards into adult life and owing to their language-based contents are consciously present to the individuals. Given the involved neural processes of meaning making and affective loading, conceptual beliefs appear similar to empircal and relational beliefs but are far more abstract (Fig. 1). In consequence, the believing person comes to see a given message as relevant for him/her self and therefore generalizable, but with the option of constant recalibration (Sperber, 1996; Tomasello, 2003, 2008). Although beliefs may become ideosyncratic in individual subjects, they ultimately may include transcendent meanings about a deity, people's fate or the world (Paloutzian & Park, 2014). Advanced beliefs of this sort provide insight into a concept. This appears to be reflected linguistically, as conceptual beliefs may be expressed by "I trust in …" as an emotional statement or "I believe in…" as a statement conveying also subjective confidence.

3. What are the representations of beliefs in the brain?

As described above, belief formation should be seen as processes of supramodal integrative neural computations. These computations were hypothesized to involve Bayesian model averaging of processed information and prediction-outcome comparisons as implemented in parallel and subsequently arranged thalamocortical loops (Friston, Parr, & de Vries, 2017). Thereby, discrete neural states related to concrete events become linked to continuous neural states that reflect guidance of behavior. Here, we discuss both aspects, the role of the cerebral cortex and that of cortico-subcortical neural loops. Also, we describe the evidence suggesting that more complex forms of neural computations in the cortex are accompanied by phylogenetic enlargemedICnt of that cortical area.

The neural representations affording beliefs are likely to be stored in the cerebral cortex. A candidate area is the parietal cortex which accommodates in close vicinity the neural representations of executive, perceptual, and higher order conceptual functions. By virtue of its reciprocal cortico-cortical and cortico-subcortical connectivity the parietal cortex is a supramodal integration area (Caspers & Zilles, 2018; Freedman & Ibos, 2018). For example, the highly tuned exploratory finger movements have been shown to be co-localized with the sensory properties of the objects as so-called motor images in humans (Binkofski et al., 1999; Bodegård et al., 2001; Faillenot, Decety, & Jeannerod, 1999; Jeannerod & Decety, 1995). By electrophysiological recordings in primates the parietal cortex has been shown to accommodate in close vicinity neurons with perceptual, temporal, social and conceptual properties in close interleaving proximity to each other (Iriki & Taoka, 2012, Fig. 2). This close neighborhood of nerve cells indicates supraordinate information processing. For example, neurons in this parietal area of non-human primates have been found by electrophysiological recordings to code dissimilarity and similarity

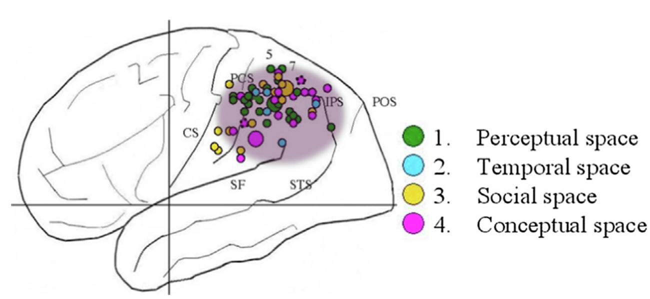

Fig. 2. Mapping of neural responses reflecting perceptive, temporal, social and conceptual information in left parietal cortex. Note the considerable spatial overlap in an area which has expanded profoundly during phylogenetic development from non-human primates to humans (pink area). Lateral view of the brain including stereotatic coordinates through the anterior and posterior commissure according to Talairach and Tournoux (1988). Further details in Iriki and Taoka (2012).

depending on the experimental context (Yamazaki, Yokochi, Tanaka, Okanoya, & Iriki, 2010). In addition, by means of functional neuroimaging the parietal cortex of humans was found to code tool use and action goals (Orban & Caruana, 2014; Vingerhoets, Vandekerckhove, Honoré, Vandemaele, & Achten, 2011). Therefore, it is likely that the cortical node representing the subject's concept of what the given stimulus is and the cortical node representing the subject's valuation of what the object is good for are likely to be in close spatial neighborhood and underlie coding of the action repertoire and possibly conceptual generalizations (Yamazaki et al., 2010). Importantly, this portion of the parietal lobe has undergone a dramatic enlargement during phylogeny from primates to humans reflecting most likely the increasingly complex information underlying beliefs about concrete objects and events as well as their supramodal abstract representations (Iriki & Taoka, 2012). In addition, an area in the medial parietal cortex (right precuneus) was found to carry semantic conceptual representations (Leshinskaya, Contreras, Caramazza, & Mitchell, 2017).

Another higher order brain area most likely to have important implications for belief formation and belief-associated behavior is the dorsal medial frontal cortex including the pre-supplementary motor area (pre-SMA). From the parietal cortex there are highly differentiated and strong anatomical connections to the medial and lateral frontal cortex (Rizzolatti, Luppino, & Matelli, 1998; Ruan et al., 2018). The pre-SMA has been reported to be a critical area for valuation of sensory information (Seitz, Franz, & Azari, 2009). Moreover, the anterior medial prefrontal cortex in superior frontal gyrus exhibits schematic event patterns that generalize across different stories, subjects, and modalities as found by fMRI during perception of real-world narratives (Baldassamo, Hasson, & Norman, 2018). After listening to narratives discrediting the notion of free will the readiness potential over the medial frontal cortex related to button pressing was signficantly decreased as compared to subjects not exposed to this intervention (Rigoni, Kühn, Sartori, & Brass, 2015). This difference started as early as several hundreds of milliseconds before the action. These changes in higher order motor areas influence the motor output system in motor cortex. For example, motor cortex excitability is enhanced by subjective values of reward motivating behaviour but is insensitive to prospective loss as found by transcranial magnetic stimulation in an incentive motivation task (Galaro, Celnik, & Chib, 2019). Conversely, religious conviction has been reported to be inversely correlated to activity in the adjacent anterior cingulate cortex, an area known to be involved in the experience of anxiety and in regulating behaviour (Inzlicht, McGregor, Hirsh, & Nash, 2009). Furthermore, conceptual beliefs have been shown to influence behavior by semantic rule processing in the left temporoparietal junction and in ventrolateral prefrontal cortex (Berns et al., 2012).

In addition to the perceptive aspects of belief formation discussed above there is also the predictive nature of beliefs. In fact, evidence accumulation in terms of active inference allows for error prediction on outcomes (Friston et al., 2017). It was shown recently that storage of new representations engages cortico-subcortical loops that are under dopaminergic control with the magnitude of belief updating being encoded in midbrain and ventral striatum (Babayan, Uchida, & Gershman, 2018; Nour et al., 2018). Specifically, PET imaging revealed that neural encoding of meaningful information was negatively related to dopamine 2/3 receptor availability in the midbrain and dexamphetamine-induced dopamine release capacity in the striatum (Nour et al., 2018). This was extended by deep brain stimulation in patients with Parkinsons disease showing that conflict processing involves cortico-subcortical loops that are modulated in the basal ganglia by the subthalamic nucleus (Ghahremani et al., 2018).

Given the fact that empirical and relational beliefs are formed primarily below the level of awareness, one would like to know which brain areas become involved in causal interference processing. It was shown by neuroimaging that estimating a common source for different signals engaged multisensory neurons in the posterior intraparietal sulcus (Rohe & Noppeney, 2015, 2016). By contrast, neurons in the anterior intraparietal sulcus were reported to be concerned with the uncertainty about the putatively combined source of different signals (Rohe & Noppeney, 2015, 2016). Moreover, perceiving social interactions between two agents has been shown by functional imaging in humans to lead to greater activation in the posterior superior temporal sulcus closely adjacent to the theory of mind and face perception regions (Isik et al., 2017). Conversely, by transcranial brain stimulation of the right inferior parietal lobe it was shown that implicit religiousness and spirituality could be decreased as assessed with an implicit association test (Crescentini, Di Bucchianico, Fabbro, & Urgesi, 2015). These parietal areas are located within the pink area in Fig. 2 which signifies a spatial enlargement in humans as compared with non-human primates. Although, there is good evidence for the correspondence of functional units in the parietal cortex as evident from combined fMRI studies in healthy subjects and lesion studies in stroke patients (Binkofski et al., 1998), it should be emphasized that cognitive processes are mediated by functional brain circuits rather than single brain areas. Functional brain circuits can be identified by multivariate image analysis approaches and multiple path modeling. For example, beliefs about testable and non-testable propositions as well as religious and political contents are maintained by large-scale circuits involving higher order brain areas in both cerebral hemispheres as observed in different ethnic groups (Han, Zhang, Wang, & Han, 2017; Howlett & Paulus, 2015; Kapogiannis et al., 2009; Zamboni et al., 2009). Although the anatomical resolution of magnetic resonance imaging is crude when compared to the microscopical dimension of local neural networks in cortical columns of neurons, the functionally more complex neural architecture is likely to go along with more complex connectivity patterns among different cortical areas and subcortical structures. Thus, in accordance with a hypothetical framework proposed by van Elk and Aleman (2017) we suggest that the neural processes underlying formation and maintenance of beliefs in an increasingly complex social environment demanded augmented processing resources in the brain. It is possible that this enhanced processing demand was the force driving the phylogenetic enlargement of the parietal and frontal cortex which are key cortical areas in the cerebral circuits affording integrative supramodal information processing.

4. Discussion

Here, we have proposed that beliefs are the neuropsychic product of neural processes allowing individuals to develop a personal affective stance concerning the signals in their environment. Our presentation focused on the processes underlying belief formation. Therefore, we distinguish between beliefs as the result of believing processes, formation of beliefs as an expression for modifiable beliefs and the believing processes (creditions) which underpin belief formation. According to the believing processes result we propose three categories of beliefs which we call empirical, relational, and conceptional beliefs.

Empirical and relational beliefs appear to evolve in the sensory domains involving reinforcement learning, but are not dependent on language which may qualify them as primal or "proto-beliefs". In addition, humans can acquire language-based, conceptual beliefs which include imaginative accounts of narratives as found in the ecological background of individuals, religious contents, and political views. They build upon the manifold repetitions and/or differentiated and frequently repeated ritual interactions within the environment at the physical, interpersonal and social levels of belief formation (Sugiura et al., 2015). Thus, advanced conceptual beliefs are ubiquitous in our cultural life and probably build the fundament for our self-understanding in our social environment conveying imaginative abstractions as well as transcendent connotations. Importantly, human beliefs may become object of introspection and verbal expression accounting for a hierarchical, but not mutually exclusive interdependence of empirical, relational and conceptual beliefs. We have argued that the increasingly complex neural processes underlying language-based beliefs as compared to primal beliefs demanded a more complex brain organisation in terms of neuron populations and neural connectivity patterns. Along a similar line of argument, an enhanced capacity and resilience of the human brain have been proposed to result from the combined effect of physical exercise and cognitive challenge on neuroplasticity (Raichlen & Alexander, 2017).

4.1. Functions of beliefs

Our hypothesis is in line with a similar view suggesting that the function of beliefs can be understood as a means for increasing the efficiency of brain mechanisms involved in problem solving, decision making, goals setting as well as in maneuvering in the environment (Garcés & Finkel, 2019). According to McKay and Dennett (2009), beliefs that best approximate reality are those that maximise the survival of the believer. The predictive information conveyed in such beliefs is suited to allow for causal judgements about objects and events (Leshinskaya & Thompson-Schill, 2019) and, thereby, to guide the subjects' behavior. In accordance with other interpretations one of the herein involved sensory driven neural processes is concerned with prompt intuitive associations of a stimulus in a subject's environment, whilst the other aims at generating an adequate response (Morewedge & Kahneman, 2010; Risen, 2015). The first process is fast taking place out of conscious awareness, while the second is a slow process that subjects may become aware of. Accordingly, beliefs may serve as essential tools that allow an individual to trust his/her incomplete or possibly unreliable knowledge at a given point in time enabling the individual to act or react as fast and adequately in his/her physical and social environment as possible for the benefit of his/her survival.

Acting in the social environment depends heavily on decisions that are typically based on beliefs about the environment. By computational modelling and electrophysiology it was shown that decisional cues influence supramodal confidence estimates (Faivre, Filevich, Solovey, Kühn, & Blanke, 2018). Although in decision making preferences have been shown to be dynamically adjusted over time, behaviorally relevant choices were based on preferences that were remembered and, thus, related to hippocampal activity (Voigt, Murawski, Speer, & Bode, 2019). It is, therefore, possible that motivational aspects (Izard, 2009) inherent in beliefs play a key role for subjects to establish and employ stable preferences in hard decisions. Furthermore, evidence was provided showing that beliefs shared by groups of subjects provide benefits such as group identity and group cohesion (Gelpi, Cunningham, & Buchsbaum, 2019; Han & Ma, 2015) which most likely also influence decision preferences. Although supernatural beliefs have been argued to be a side-effect of a suite of cognitive mechanisms adapted for other purposes (Boyer, 2003; McKay & Dennett, 2009), they most likely also have a strong influence on decision making. On this background it is mandatory to become aware that a breakdown in the neural processes underlying belief formation may lead to delusions and social malfunctioning (Langdon & Coltheart, 2000; Pechey & Halligan, 2012).

4.2. Theoretical background of beliefs

Our cognitive neuroscience hypothesis about the formation and maintenance of beliefs touches upon a long-held Western tradition of discourse that has existed since Antiquity. It has focused on concepts of "belief" and their epistemic relevance in regard with concepts of knowledge (Dierse, 1974; Schwitzgebel, 2015). The topic has been vividly discussed in Christian theology since the Middle Ages (Gössmann, 1984; Slenczka, 1984). It has especially flourished in epistemology after the Enlightenment period (Vorster, 1974) and is a central topic in the philosophy of religion (Plantinga & Wolterstorff, 1983). In Anglosaxon debates the topic has been enriched as the English language provides a differentiation between faith and belief (Smith, 1987; Swinburne, 1983). Influenced by cognitive science which tends to ascribe the notion of belief to a so-called "folk psychology" in contemporary philosophy a strong support can be found for the eliminativism paradigm which proposes the elimination of folk psychology terms from scientific approaches to understand cognitive processes (Churchland, 1979; Fodor, 1980; Stich, 1996). Nevertheless, there will be the need to translate findings obtained in cognitive neuroscientific research into common language. Probably, this gap cannot easily be bridged in a satisfying manner. One of the communicative challenges is to be aware that many philosophical terms cannot be a field of empirical research unless they can be operationalized sufficiently. And, likewise, neurocognitive findings should be translated carefully into common language (Bennett & Hacker, 2003). Therefore, we favour a translational approach that differentiates between certain philosophical terms and empirical findings. Specifically, we argue that a belief is the subjective probabilistic assumption concerning environmental information to which a subject becomes exposed. Note, that rapidly formed empirical and relational beliefs do not rely on language and, thus, do not necessarily represent consciously held propositions. Furthermore, similarly to primal beliefs advanced conceptual beliefs also pertain to neural processes. This corroborated by the finding that language-bound conceptual beliefs were affected subconsciously by contradictory statements which was paralleled by attenuated signals of neural processing (Rigoni et al., 2015). In our opinion these data substantiate our processual concept of belief formation but should also be reflected against a philosophical background according to which a so-called doxastic agent gets to decide voluntarily what to believe (Huber, 2016). As a discussion of whether "voluntary" generation of an action is an illusion (Wegner, 2003) would go far beyond the scope of this article, we limit the discussion on our neuroscientifically-based hypothesis that beliefs are probabilistic meaningful accounts with subjective credibility.

It should be emphasized that the three categories of beliefs presented here are the result of neural processes while a subject is believing. Thus, we have both, a close linguistic relation and a theoretical tension between, the term belief and the verb "to believe". The term belief belongs to the category of nouns which are typically associated with concepts of substantiality and stability which enables comparing the semantic contents of different beliefs with regard to similarity and dissimilarity. In contrast, the use of the verb "to believe" focusses on the processes ongoing during belief formation and while someone is believing. This provides a principally fluid understanding of belief (Visala & Angel, 2017). It is important to point out, however, that the distinction between the noun "belief" and the verb "believe" rests upon the Western linguistic tradition. The so-called "universal" or "generative" grammar (Hauser et al., 2002; Yang, Crain, Berwick, Chombsky, & Bolhuis, 2017) differentiates grammatical elements such as "noun", "subject", or "verb". But such common subject-object patterns are not present in languages from other traditions and the Western approach has been criticized for reductionism supported by recent data about language acquisition in children (Goldberg, 2008; Tomasello, 2003, 2008). We do not want to immerse further into the ongoing discussion that scientific research on belief mainly focusses on "WEIRD" (Western, educated, industrialized, rich, and democratic) people and societies (Henrich, Heine, & Norenzayan, 2010). Rather, we argue that empirical, relational and conceptual beliefs are reflected by slightly different expressions in Western languages (Table 1). In Western and other languages verbal expressions often employ metaphors some of which have been drawn from descriptions of space helping people to construct time (Boroditsky, 2018).

4.3. Social role of beliefs

Finally, an intriguing question that follows is how beliefs become accepted and supported by a group of people or even by an entire population of a geographical area or nation. In a large series of cross-cultural studies comprising 67.000 people it was found that cultural learning is an important factor for acquiring supernatural beliefs (Maij et al., 2017). Thus, narratives and rituals practiced similarly in a group of subjects or in a society can be expected to establish similar conceptual beliefs in their members. Furthermore, recent modelling approaches provided some insight. For example, statistical models and network modelling have described community formation in actual societies (Galesic & Stein, 2019; Weir, Walker, Zdeborova, & Mucha, 2019). The results showed that it is important to understand belief formation at the individual level and to model individual differences in social interaction terms. Moreover, in the voter model people adopt their neighbour's state; in the majority model conformism was the driving force; in the expert rule model people rely on someone considered to be an expert. Further, by the model of interconnected nodes it became apparent that the existence of logical constraints on beliefs affected the collective convergence to a shared belief (Friedkin, Prokurnikov, Tempo, & Parsegov, 2015). Moreover, in an empirical study it was found that affective attachments are more important than actual political positions for tying political belief systems of different people together and motivating behaviour (Brandt, Sibley, & Osborne, 2019). The perspective of these social neuroscience approaches is to understand how beliefs of individuals as analyzed in neuroscientific terms can affect groups of people and their behaviors.

5. Conclusion

We have shown that beliefs are the product of fundamental brain processes. We hypothesize that beliefs often and in certain contexts attribute personal affective meaning to concrete objects and events in the physical and social environment. We tentatively have called them empirical, relational and conceptual beliefs. This categorization is derived from a process-related approach which highlights putative processes of believing. We describe that humans can give verbal accounts of these functionally different belief domains in a differentiated manner through belief-word-prefaced propositions used in discourse. We have argued that the herein inherent neural computations were most likely the driving force for the phylogenetic expansion of the human brain. It is thrilling to speculate if computer-based technology including artificial intelligence and internet-based communication might introduce a novel belief domain and if this is accommodated possibly by a further expansion of brain areas.

CRediT authorship contribution statement

Rüdiger J. Seitz: Conceptualization, Writing - original draft, Visualization. **Hans-Ferdinand Angel:** Conceptualization, Writing - review & editing.

Acknowledgements

The authors thank Prof. Jay Feierman and two anonymous reviewers for their constructive comments on this paper.

The authors have nothing to declare.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

Angel, H.-F., & Seitz, R. J. (2016). Process of believing as fundamental brain function: The concept of credition. *SFU Research Bulletin, 3*, 1–20. https://doi.org/10.15135/2016.4.1.1-20.

Angel, H.-F., & Seitz, R. J. (2017). Violation of expectation as matter for the believing process. *Frontiers in Psychology, 8*, 772. https://doi.org/10.3389/fpsyg.2017.00772.

Babayan, B. M., Uchida, N., & Gershman, S. J. (2018). Belief state representation in the dopamine system. *Nature Communications, 9*, 1891.

Baldassamo, C., Hasson, U., & Norman, K. A. (2018). Representation of real-world event schemas during narrative perception. *Journal of Neuroscience, 38*, 9689–9699.

Bar, M., Neta, M., & Linz, H. (2006). Very first impressions. *Emotion, 6*, 269–278.

Belzen, J. A. (2010). Religion and Self: Notions from a cultural psychological perspective. *Pastoral Psychology, 59*, 199–409.

Bennett, M. R., & Hacker, P. M. S. (2003). *Philosophical foundations of neuroscience.* Oxford, UK: Blackwell.

Berns, G. S., Bell, E., Capra, C. M., Prietula, M. J., Moore, S., Anderson, B., ... Atran, S. (2012). The price of your soul: Neural evidence for the non-utilitarian representation of sacred values. *Philosophical Transactions of the Royal Society B: Biological Sciences, 367*, 754–762.

Binkofski, F., Dohle, C., Posse, S., Stephan, K. M., Hefter, H., Seitz, R. J., & Freund, H.-J. (1998). Human anterior intraparietal area subserves prehension. A combined lesion and functional MRI activation study. *Neurology, 50*, 1253–1259.

Binkofski, F., Buccino, G., Posse, S., Seitz, R. J., Rizzolatti, G., & Freund, H.-J. (1999). A fronto-parietal circuit for object manipulation in man: Evidence from an fMRI study. *European Journal of Neuroscience, 11*, 3276–3286.

Bodegård, A., Geyer, S., Grefkes, C., Zilles, K., & Roland, R. E. (2001). Hierarchical processing of tactile shape in the human brain. *Neuron, 31*, 1–20.

Boroditsky, L. (2018). Language and the construction of time through space. *Trends in Neurosciences, 41*, 651–653.

Boyer, P. (2003). Religious thought and behaviour as by-products of brain function. *Trends in Cognitive Sciences, 7*, 119–124.

Brainerd, C. J. (2018). The emotional-ambiguity hypothesis: A large-scale test. *Psychological Science, 29*, 1706–17015.

Brandt, M. J., Sibley, C. G., & Osborne, D. (2019). What is central to political belief system networks? *Personality and Social Psychology Bulletin,* 1–13. https://doi.org/10.1177/0146167218824354.

Bulbulia, J., & Schoedt, U. (2013). The neural basis of religion. In F. Krueger, & J. Grafman (Eds.). *The neural basis of human belief systems* (pp. 169–190). New York: Taylor and Fancis, Hove.

Bullmore, E., & Sporns, O. (2012). The economy of brain network organization. *Nature Reviews Neuroscience, 11*, 336–349.

Caspers, S., & Zilles, K. (2018). Microarchitecture and connectivity of the parietal lobe. *Handbook of Clinical Neurology, 151*, 53–72. https://doi.org/10.1016/B978-0-444-63622-5.00003-6.

Churchland, P. (1979). *Scientific realism and the plasticity of mind.* Cambridge: Cambridge University Press.

Churchland, P., & Churchland, P. M. (2013). What are beliefs? In F. Krueger, & J. Grafman (Eds.). *The neural basis of human belief systems* (pp. 1–17). Hove, New York: Taylor & Fancis.

Connors, M. H., & Halligan, P. W. (2015). A cognitive account of belief: A tentative roadmap. *Frontiers in Psychology, 5*, 1588. https://doi.org/10.3389/fpsyg.2014.01588.

Correa, C. M. C., Noorman, S., Jiang, J., Palminteri, S., Cohen, M. X., Lebreton, M., & van Gaal, S. (2018). How the level of reward awareness changes the computational and electrophysiological signatures of reinforcement learning. *Journal of Neuroscience, 38*, 10338–10348.

Crescentini, C., Di Bucchianico, M., Fabbro, F., & Urgesi, C. (2015). Excitatory stimulation of the right inferior parietal cortex lessens implicit religiousness/spirituality. *Neuropsychologia, 70*, 71–79.

de Visser, E., & Krueger, F. (2013). Interpersonal trust as a dynamic belief. In F. Krueger, & J. Grafman (Eds.). *The neural basis of human belief systems* (pp. 169–190). Hove, New York: Taylor & Fancis.

Dierse, U. (1974). Glaube und Wissen. In J. Ritter, & K. Gründer (Vol. Eds.), *Historisches Wörterbuch der Philosophie: Vol. 3*, (pp. 646–655). Basel-Stuttgart: Schwabe & Co.

Faillenot, I., Decety, J., & Jeannerod, M. (1999). Human brain activity related to the perception of spatial features of objects. *Neuroimage, 10*, 114–214.

Fairley, K., Vyrastekova, J., Weitzel, L., & Sanfey, A. G. (2019). Subjective beliefs about trust and reciprocity activate an expected reward signal in the ventral striatum. *Frontiers in Neuroscience, 13*, 660. https://doi.org/10.3389/fnins.2019.00660.

Faivre, N., Filevich, E., Solovey, G., Kühn, S., & Blanke, O. (2018). Behavioral, modeling, and electrophysiological evidence for supramodality in human metacognition. *Journal of Neuroscience, 38*, 263–277.

Fodor, J. (1980). *The language of thought.* Harvard.

Freedman, D. J., & Ibos, G. (2018). An integrative framework for sensory, motor, and cognitive functions of the posterior parietal cortex. *Neuron, 97*, 1219–1234.

Friedkin, N. E., Prokurnikov, A. V., Tempo, R., & Parsegov, S. E. (2015). Network science on belief system dynamics under logic constraints. *Science, 354*, 321–326.

Friston, K. (2010). The free-energy principle: A unified brain theory? *Nature Reviews Neuroscience, 11*, 127–138. https://doi.org/10.1038/nrn2787.

Friston, K. J., Parr, T., & de Vries, B. (2017). The graphical brain: Belief propagation and active inference. *Network Neuroscience, 1*, 381–414.

Galaro, J. K., Celnik, P., & Chib, V. S. (2019). Motor cortex excitability reflects the subjective value of reward and mediates its effects on incentive-motivated performance. *Journal of Neuroscience, 39*, 1236–1248.

Galesic, M., & Stein, D. L. (2019). Statistical physics models of belief dynamics: Theory and empirical tests. *Physica A, 519*, 275–294.

Garcés, M., & Finkel, L. (2019). Emotional theory of rationality. *Frontiers in Integrative Neuroscience, 13*, 11. https://doi.org/10.3389/fnint.2019.00011.

Gelpi, R., Cunningham, W. A., & Buchsbaum, D. (2019). Belief as a non-epistemic adaptive benefit. *PsyArXiv*. https://doi.org/10.31234/osf.io/6ythf.

Gentsch, A., Weiss, C., Spengler, S., Synofzik, M., & Schütz-Bosbach, S. (2015). Doing good or bad: How interactions between action and emotion expectation shape the sense of agency. *Social Neuroscience, 10*, 418–430.

Ghahremani, A., Aron, A. A., Udupa, K., Saha, U., Reddy, D., Hutchinson, W. D., ... Chen, R. (2018). Event-related deep brain stimulaton of the subthalamic nucleus affects conflict processing. *Annals of Neurology, 84*, 515–526.

Gössmann, E. (1984): Glaube V. Mittelalter. In G. Müller et al. (Eds.), Theologische Realenzyklopädie (TRE) (Vol. 13, pp. 308–318). Berlin-New York: De Gruyter.

Goldberg, A. (2008). *Constructions at work: The nature of generalization in language.* Oxford:

Oxford University Press.
Han, S., & Ma, Y. (2015). A culture–behavior–brain loop model of human development. *Trends in Cognitive Sciences, 19*(11), 666–676. https://doi.org/10.1016/j.tics.2015.08.010.
Han, X., Zhang, T., Wang, S., & Han, S. (2017). Neural correlates of believing. *Neuroimage, 156*, 155–165. https://doi.org/10.1016/j.neuroimage.2017.05.035.
Harris, S., Sheth, S. A., & Cohen, M. S. (2007). Functional neuroimaging of belief, disbelief, and uncertainty. *Annals of Neurology, 63*, 141–147.
Hauser, M. D., Chomsky, N., & Fitch, W. T. (2002). The faculty of language: What is it, who has it, and how did it evolve? *Science, 298*, 1569–1579.
Henrich, J., Heine, S. J., & Norenzayan, A. (2010). The weirdest people in the world? *Behavioral and Brain Sciences, 33*, 61–135. https://doi.org/10.1017/S0140525X0999152X Epub 2010 Jun 15.
Hihara, S., Yamada, H., Iriki, A., & Okanoya, K. (2003). Spontaneous vocal differentiation of coo-calls for tools and food in Japanese monkeys. *Neuroscience Research, 45*, 383–389.
Hobson, N. M., Schroeder, J., Risen, J. L., Xygualatas, D., & Inzlicht, M. (2018). The psychology of rituals: An integrative review and process-based framework. *Personality and Social Psychology Review, 22*, 260–284.
Howlett, J. R., & Paulus, M. P. (2015). The neural basis of testable and non-testable beliefs. *PLoS ONE, 10*, e0124596. https://doi.org/10.1371/journal.pone.0124596.
Huber, F. (2016) Formal representations of belief. In E. N. Zalta (Ed.), The Stanford encyclopedia of philosophy. Spring Edition, URL: https://plato.stanford.edu/archives/spr2016/entries/format-belief/.
Inzlicht, M., McGregor, I., Hirsh, J. B., & Nash, K. (2009). Neural markers of religious conviction. *Psychological Science, 20*, 385–392.
Iriki, A., & Taoka, M. (2012). Triadic (ecological, neural, cognitive) niche construction: A scenario of human brain evolution extrapolating tool use and language from the control of reaching actions. *Philosophical Transactions of the Royal Society B: Biological Sciences, 367*, 10–23.
Ishizu, T., & Zeki, S. (2013). The brain's specialized systems for aesthetic and perceptual judgment. *European Journal of Neuroscience, 37*, 1413–1420. https://doi.org/10.1111/ejn.12135.
Isik, L., Koldewyn, K., Beeler, D., & Kanwisher, N. (2017). Perceiving social interactions in the posterior superior temporal sulcus. *Proceedings of the National academy of Sciences of the United States of America, 114*, E9145–E9152.
Izard, C. E. (2009). Emotion theory and research: Highlights, unanswered questions, and emerging issues. *Annual Review of Psychology, 60*, 1–25.
Jeannerod, M., & Decety, J. (1995). Mental motor imagery: A window into the representational stages of action. *Current Opinion in Neurobiology, 5*, 727–732.
Kaiser, D., & Peelen, M. V. (2018). Transformation from independent to integrative coding of multi-object arrangements in human visual cortex. *Neuroimage, 169*, 334–341.
Kapogiannis, D., Barbey, A. K., Su, M., Zamboni, G., Krueger, F., & Grafman, J. (2009). Cognitive and neural foundations of religious belief. *Proceedings of the National academy of Sciences of the United States of America, 106*(4876–4881), 19273839. https://doi.org/10.1073/pnas.0811717106 2660736.
Langdon, R., & Coltheart, M. (2000). The cognitive neuropsychology of delusions. *Mind Language, 15*, 184–218. https://doi.org/10.1111/1468-0017.00129.
Leicester, J. (2008). The nature and purpose of belief. *The Journal of Mind and Behavior, 29*, 217–238.
Leshinskaya, A., Contreras, J. M., Caramazza, A., & Mitchell, J. P. (2017). Neural representations of belief concepts: A representational similarity approach to social semantics. *Cerebral Cortex, 27*, 344–357.
Leshinskaya, A., & Thompson-Schill, S. L. (2019). From the structure of experience to concepts of structure: How the concept "cause" is attributed to objects and events. *Journal of Experimental Psychology: General, 148*, 619–643.
Maij, D. L. Ft, von Harreveld, F., Gervais, W., Schrag, Y., Mohr, C., & van Elk, M. (2017). Mentalizing skills do not differentiate believers from non-believers, but credibility enhancing displays do. *PLoS ONE,* e0182764. https://doi.org/10.1371/journal.pone.0182764.
Maravita, A., & Iriki, A. (2004). Tools for the body (schema). *Trends in Cognitive Sciences, 8*. https://doi.org/10.1016/j.tics.2003.12.008.
Markl, H., 2005. Evolution der Wahrnehmung — was macht uns erkenntnisfähig? In M. Lessl & J. Mittelstra (Eds.), From perception to understanding (pp. 29–46). Workshop supplement 12. Berlin, Germany: Springer.
McKay, R. T., & Dennett, D. C. (2009). The evolution of misbelief. *Behavioral and Brain Sciences, 32*, 493–561.
Merzenich, M. M., & Sameshima, K. (1993). Cortical plasticity and memory. *Current Opinion in Neurobiology, 3*, 187–196.
Meyniel, F., Schlunegger, D., & Dehaene, S. (2015). The Sense of confidence during probabilistic learning: A normative account. *PLoS Computational Biology, 11*, e1004305. https://doi.org/10.1371/journal.pcbi.1004305.
Morewedge, C. K., & Kahneman, D. (2010). Associative processes in intuitive judgment. *Trends in Cognitive Sciences, 14*, 435–440.
Moretti, L., Cristofori, I., Zamboni, G., & Sirigu, A. (2013). The neural structure of political belief. In F. Krueger, & J. Grafman (Eds.). *The neural basis of human belief systems* (pp. 159–168). Hove & New York: Taylor & Fancis.
Nour, M. M., Dahoun, T., Schwartenbeck, P., Adams, R. A., FitzGerald, T. H. B., Coello, C., ... Howes, O. D. (2018). Dopaminergic basis for signaling belief updates, but not surprise, and the link to paranoia. *Proceedings of the National academy of Sciences of the United States of America, 15*, E10167–E10176. https://doi.org/10.1073/pnas.180929811.
Orban, G. A., & Caruana, F. (2014). The neural basis of human tool use. *Frontiers in Psychology, 5*, 310. https://doi.org/10.3389/fpsyg.2014.00310.
Paloutzian, R. F., & Park, C. L. (2014). Religiousness and spirituality: The psychology of multilevel meaning-making behavior. *Religion Brain Behavior, 5*, 166–178.
Papeo, L., & Abassi, E. (2019). Seeing social events: The visual specialization for dyadic human-human interactions. *Journal of Experimental Psychology: Human Perception and Performance*. https://doi.org/10.1037/xhp0000646.
Pechey, R., & Halligan, P. (2012). The prevalence of delusion-like beliefs relative to sociocultural beliefs in the general population. *Psychopathology, 44*, 106–115.
Plantinga, A., & Wolterstorff, N. (1983). *Faith and rationality: Reason and belief in god.* Notre Dame: University of Notre Dame Press.
Potthoff, D., & Seitz, R. J. (2015). Role of the first and second person perspective for control of behaviour: Understanding other people's facial expressions. *Journal of Physiology (Paris), 109*, 191–200.
Raichlen, D. A., & Alexander, G. E. (2017). Adaptive capacity: An evolutionary-neuroscience model linking exercise, cognition, and brain health. *Trends in Neurosciences, 40*, 408–421.
Rigoni, D., Kühn, S., Sartori, G., & Brass, M. (2015). Inducing disbelief in free will alters brain correlates of preconscious motor preparation: The brain minds whether we believe in free will or not. *Psychological Science, 22*, 613–618.
Risen, J. L. (2015). Believing what we do not believe: Acquiescence to superstitious beliefs and other powerful intuitions. *Psychological Review, 123*, 182–207.
Rizzolatti, G., Luppino, G., & Matelli, M. (1998). The organisation of the cortical motor system: New concepts. *Electroencephalography and Clinical Neurophysiology, 106*, 283–296.
Rohe, T., & Noppeney, U. (2016). Distinct computational principles govern multisensory integration in primary sensory and association cortices. *Current Biology, 26*, 509–514.
Rohe, T., & Noppeney, U. (2015). Cortical hierarchies perform Bayesian causal inference in multisensory perception. *PLoS Biology*. https://doi.org/10.1371/journal.pbio.1002073.
Rolls, E. T. (2006). Brain mechanisms underlying flavour and appetite. *Philosophical Transactions of the Royal Society B: Biological Sciences, 361*, 1123–1136.
Ruan, J., Bludau, S., Palomero-Gallagher, N., Caspers, S., Mohlberg, H., & Eickhoff, S. B. (2018). …Cytoarchitecture, probability maps, and functions of the human supplementary and pre-supplementary motor areas. *Brain Structure & Function, 223*, 4169–4186. https://doi.org/10.1007/s00429-018.1738-6.
Sachs, O., & Hirsch, J. (2008). A neurology of belief. *Annals of Neurology, 63*, 129–130.
Schnell, T. (2012). Spirituality with and without religion. *Archive for the Psychology of Religion, 34*, 33–62.
Schwitzgebel, E. (2015). Belief. In E. N. Zalta (Ed.), The Stanford Encyclopedia of Philosophy. http://plato.stanford.edu/archives/sum2015/entries/belief/.
Seitz, R. J., Stephan, K. M., & Binkofski, F. (2000). Control of action as mediated by the frontal lobe. *Experimental Brain Research, 133*, 71–80.
Seitz, R. J., Franz, M., & Azari, N. P. (2009). Value judgments and self-control of action: The role of the medial frontal cortex. *Brain Research Reviews, 60*, 368–378.
Seitz, R. J., & Angel, H.-F. (2015). Psychology of religion and spirituality: Meaning making and processes of believing. *Religion, Brain Behavior, 5*, 139–147. https://doi.org/10.1080/2153599X.2014.891249.
Seitz, R. J., Paloutzian, R. F., & Angel, H.-F. (2016). Processes of believing: Where do they come from? What are they good for? *F1000Res, 5*, 2573. https://doi.org/10.12688/f1000research.9773.2.
Seitz, R. J., Paloutzian, R. F., & Angel, H. F. (2018). From believing to belief: A general biomathematical model. *Journal of Cognitive Neuroscience, 30*, 1254–1264.
Seitz, R. J., Angel, H. F., & Paloutzian, R. F. (2019). Believing is representation mediated by the dopamine brain system. *European Journal of Neuroscience, 80*, 200–206.
Slenczka, R. (1984): Glaube VI. Reformation/Neuzeit/Systematisch-Theologisch. In G. Mülle, et al. (Eds.), Theologische Realenzyklopädie (TRE) (Vol. 13, pp. 318–365). Berlin-New York: De Gruyter.
Smith, W. C. (1987). *Faith and belief.* Princeton, New Jersey: Princeton University Press.
Smith, M. I. (2011). Rapid processing of emotional expressions without conscious awareness. *Cerebral Cortex, 22*, 1748–1760.
Sperber, D. (1996). *Explaining culture: A naturalistic approach.* Oxford: Blackwell Publishing.
Stich, S. (1996). From folk psychology to cognitive science. The case against belief. 2nd ed. Cambridge Massachusetts.
Sugiura, M., Seitz, R. J., & Angel, H.-F. (2015). Models and neural bases of the believing process. *Journal of Behavioral and Brain Science, 5*, 12–23.
Swinburne, R. (1983). *Faith and reason.* Oxford: Clarendon Press.
Talairach, J., & Tournoux, P. (1988). *Co-planar atlas of the human brain.* Stuttgart: Thieme.
Taves, A., & Asprem, E. (2016). Experience as event: Event cognition and the study of (religious) experiences. *Religion Brain and Behavior*. https://doi.org/10.1080/2153599X.2016.115037.
Thézé, R., Manuel, A. L., Nahum, L., Guggisberg, A. G., & Schnider, A. (2017). Simultaneous reality filtering and encoding of thoughts: The substrate for distinguishing between memories of real events and imaginations? *Frontiers in Behavioral Neuroscience, 11*, 216. https://doi.org/10.3389/fnheh.2017.00216.
Thiruchselvam, R., Harper, J., & Homer, A. L. (2016). Beauty is in the belief of the beholder: Cognitive influences on the neural response to facial attractiveness. *Social Cognitive and Affective Neuroscience,* 1999–2008. https://doi.org/10.1093/scan/nsw115.
Toga, A. W., & Mazziotta, J. C. (2000). *Brain mapping. The systems.* San Diego: Academic Press.
Tomasello, M. (2003). *Constructing a language: A usage-based theory of language acquisition.* Cambridge, Mass: Harvard University Press.
Tomasello, M. (2008). *Origins of human communication.* Cambridge, Mass: MIT Press.
van Elk, M., & Aleman, A. (2017). Brain mechanisms in religion and spirituality: An integrative predictive processing framework. *Neuroscience & Biobehavioral Reviews, 73*, 359–378.
van Leeuwen, N. (2014). Religious credence is not factual belief. *Cognition, 133*, 698–715.

Vingerhoets, G., Vandekerckhove, E., Honoré, P., Vandemaele, P., & Achten, E. (2011). Neural correlates of pantomiming familiar and unfamiliar tools: Action semantics versus mechanical problem solving? *Human Brain Mapping, 32*, 905–918.

Visala, A., & Angel, H.-F. (2017). The theory of credition and philosophical accounts of belief: Looking for common ground. In H.-. F. Angel, L. Oviedo, R. F. Paloutzian, A. L. C. Runehov, & R. J. Seitz (Eds.). *Processes of believing: The acquisition, maintenance, and change in creditions* (pp. 183–193). Dordrecht, Heidelberg: Springer.

Voigt, K., Murawski, C., Speer, S., & Bode, S. (2019). Hard decisions shape the neural coding of preferences. *Journal of Neuroscience, 39*, 718–725.

Vorster, H. (1974). Glaube. In J. Ritter, & K. Gründer (Vol. Eds.), *Historisches Wörterbuch der Philosophie: Vol. 3*, (pp. 627–644). Basel-Stuttgart: Schwabe & Co.

Walbrin, J., Downing, P., & Koldewyn, K. (2018). Neural responses to visually observed social interactions. *Neuropsychologia, 112*, 31–39.

Wegner, D. M. (2003). The mind's best trick: How we experience conscious will. *Trends in Cognitive Sciences, 7*, 65–69.

Weir, W. H., Walker, B., Zdeborova, L., & Mucha, P. J. (2019) Modularity belief propagation on multilayer networks to detect significant community structure (in press). arXiv preprint arXiv:1908.04653.

Yamazaki, Y., Yokochi, H., Tanaka, M., Okanoya, K., & Iriki, A. (2010). Potential role of monkey inferior parietal neurons coding action semantic equivalences as precursors of parts of speech. *Social Neuroscience, 5*, 105–117.

Yang, C., Crain, S., Berwick, R. C., Chombsky, N., & Bolhuis, J. J. (2017). The growth of language: Universal grammar, experienc3e, and principles of computation. *Neuroscience & Biobehavioral Reviews, 81*, 103–119. https://doi.org/10.1016/j.neurobiorev.2016.12.023.

Zamboni, G., Gozzi, M., Krueger, F., Duhamel, J. R., Sirigu, A., & Grafman, J. (2009). Individualism, conservatism, and radicalism as criteria for processing political beliefs: A parametric fMRI study. *Social Neuroscience, 4*, 367–383.