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Dynamic network organization of the self: implications for affective experience

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People form a variety of beliefs about themselves that often carry positive or negative valence (e.g. being confident versus awkward). We suggest that, like other complex systems, the self can be modeled as a network composed of nodes (self-beliefs) and connections between them. We describe how self-network organization may vary between individuals and within individuals over time, and highlight the implications of this variation for affective experience. We further articulate how the self-network emerges from dynamic interactions between large-scale brain networks including the default mode network, valuation network, and frontoparietal control network. Finally, we discuss how a network perspective on the self may provide new insights into the mechanisms that underlie cognitive behavioral therapy and mindfulness-based approaches to affective disorders.

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Introduction

A hallmark of human experience is a sense of 'self'. While the sense of self is multifaceted, a key aspect is the 'me' – a collection of *beliefs* about one's attributes, abilities, and social roles, that form a temporally extended autobiographical identity [1,2]. Affective experience is deeply intertwined with the beliefs that constitute the autobiographical self [3•,4,5]. The extent to which a person feels positive or negative in any given moment is shaped by what is currently salient about themselves, for example, whether they have thoughts about being successful or a failure; lovable or unlovable; generous or stingy; confident or insecure. There are differences between people (trait-like variation) and within people (state-like variation) in the content of self-beliefs, the strength of belief activation, and how those beliefs are linked together. This variation has important implications for understanding normal range variation in personality, and for treating disorders involving negative and positive affect.

Neuroimaging studies have begun to shed light on brain activity patterns that are relevant to understanding self-referential processing and affective experience. This work has highlighted the role of the default mode network (DMN) in self-referential processing and affective meaning [6–10], the role of the limbic and salience (valuation) networks in tagging aspects of the internal or external world with positive or negative valence [11–15,16•], and the role of the frontoparietal control network (FPCN) in regulating thoughts and emotions [17,18]. These separate lines of research have yielded important insights, but have yet to be tied together into a coherent picture related to the influence of self-beliefs on affective experience.

Here, we synthesize recent research on the self and affective experience, and suggest that further progress can be made by adopting a network science approach [19]. We suggest that the self can be conceptualized as a network of interconnected beliefs and describe how variation in the self-network between people and variation across time within people may influence well-being. This proposal builds on recent work in network science [20••,21••,22••], as well as ideas regarding self-schemas [3•] and the associative network structure of memory and emotion [23]. We further describe how dynamic interactions across large-scale brain networks may underpin the self-network. Finally, we describe how cognitive behavioral therapy and mindfulness-based approaches may target the self in different ways in the process of treating affective disorders. Our proposal is highly simplified and meant only to jump-start new research on the self and affect.

Self-beliefs and affective experience

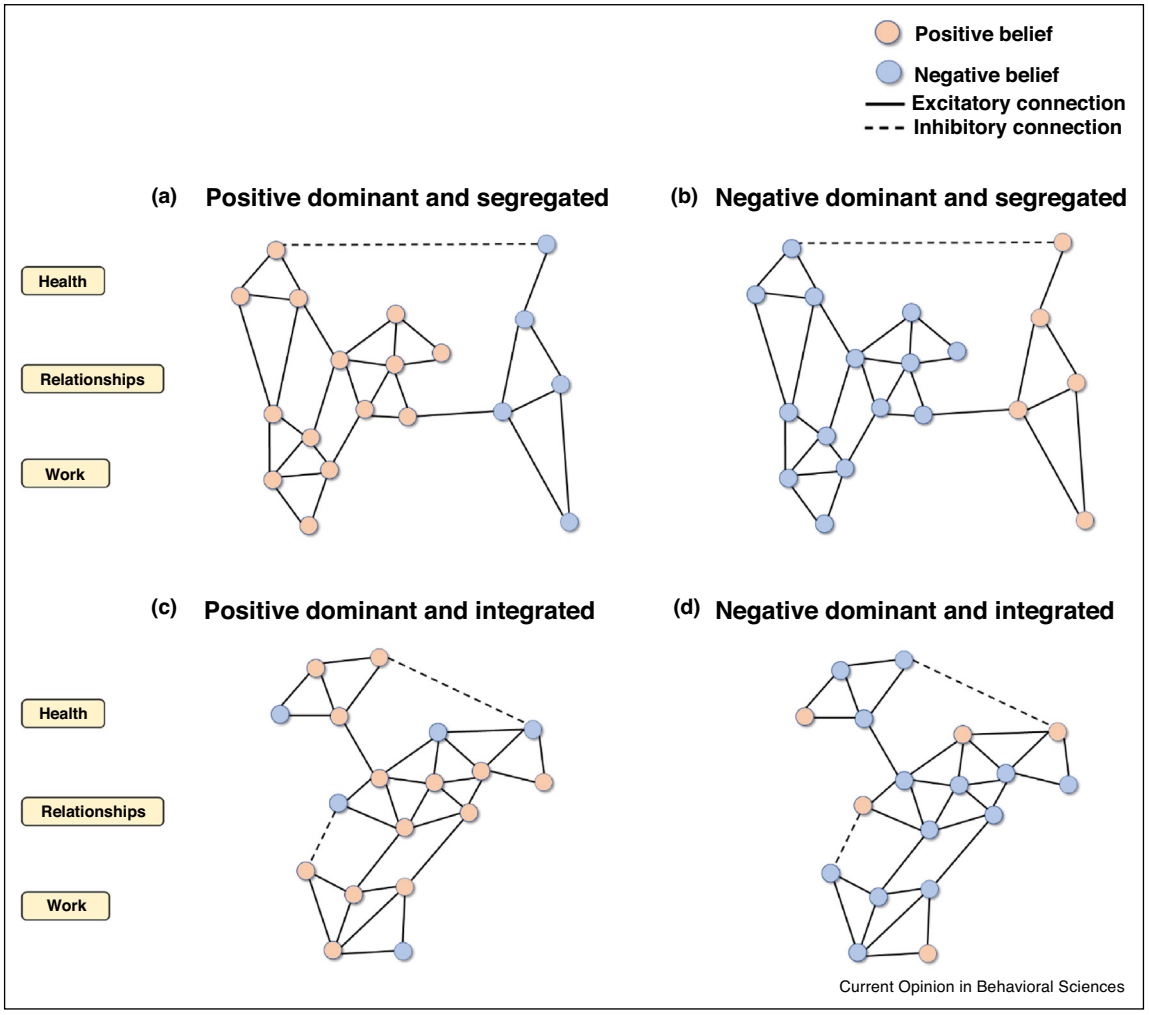
People generally hold many beliefs about themselves related to a variety of life domains including work, relationships, and health. These self-beliefs often carry a positive or negative charge and can be assessed with the self-referential encoding task (SRET), which involves asking participants whether they identify with various positive and negative trait words. The key metrics are usually the percentage of positive and negative traits that are endorsed by participants.

Healthy individuals generally endorse more positive than negative traits, whereas individuals with affective disorders (e.g. social anxiety or depression) generally endorse more negative than positive traits [3•,24–26]. Self-beliefs may have their origin in in childhood experiences and become solidified through experience across the lifespan [3•]. In line with this idea, individuals with social anxiety disorder who endorse a greater number of negative self-beliefs also report more childhood emotional maltreatment [27••]. Self-beliefs may influence affective experience directly through their valence, and also indirectly by influencing how events are interpreted and evaluated – that is, they act as a filter that makes the proverbial glass seem half empty or half full [3•].

The network organization of self-beliefs

Because self-beliefs are generally captured with one or two summary statistics, little attention has been paid to the way in which self-beliefs may be organized in structured associative networks. We suggest that it may be useful to adopt a network science approach and explicitly model the self as a network of nodes (self-beliefs) and edges (connections between nodes) [3•]. Specific patterns of structural connections in this 'self-network' can vary across individuals and influences the way in which activation spreads between nodes and creates a trajectory through various states [20••,21••,28•]. These elements can be conceptualized as trait-like and state-like features of the network, respectively, and can be illuminated using

Figure 1



Examples of self-network community structures. These hypothetical community structures emerge from a combination of two factors: the relative number of positive versus negative self-belief nodes; and the extent to which positive and negative self-belief nodes exist in segregated versus integrated communities. For simplicity, we illustrate undirected graphs (all connections are bidirectional), though, in future work it could be useful to consider the directionality of connections. We suggest that these organizations may be somewhat trait-like, though we acknowledge that the truth is likely more complex, with some contextual dependency in the content and organizations of nodes and connections. Connections between self-belief nodes can be excitatory (positively weighted) in the sense that activity in one node leads to activity in the connected node, or connections can inhibitory (negatively weighted) in the sense that activity in one node leads to a suppression of activity in the connected node.

network science concepts such as 'community structure' [19,22••], and 'activity flow mapping' [21••] and 'network controllability' [20••,28•]. We suggest that valenced beliefs can be at various levels of 'activation' and that it is primarily when they are active that they contribute to one's overall affective experience. Trait variation is relevant to affect because it makes certain patterns of activation of valenced self-beliefs more or less likely. State variation emerges from the interaction between trait-like features of the self-network and input from the world. This input may be bottom-up input (e.g. a disparaging comment from someone) or top-down input (e.g. a retrieved memory).

Trait-like aspects of the self-network

Self-beliefs can be thought of as the nodes that serve as the building blocks of the self-network. As noted above, people vary in the content of their beliefs (e.g. some people believe that they are lovable, while others believe that they are unlovable). People also differ in how these beliefs are linked together. Community structure refers to the idea that networks are usually composed of several distinct communities of nodes that show strong connections to members of the same community and weak connections to members of different communities [22••]. If the pairwise connections between nodes are known, community structure can be estimated in a data-driven manner using algorithms that seek to optimize a modularity score (the relative strength of within-community connections versus between-community connections). Community structure can take many different forms, but for simplicity, we will describe two dimensions of variation that may be particularly relevant to self-network organization (Figure 1). Specifically, we will consider: (i) the relative number of positive versus negative self-belief nodes; and (ii) the extent to which positive and negative self-belief nodes form integrated or segregated communities. There may also be other relevant dimensions that are beyond the scope of the present manuscript, including the centrality of particular nodes (e.g. the self-beliefs that serve as hub nodes within the network); the strength of local clustering (the strength of interconnection between related beliefs); and node flexibility (i.e. the extent to which nodes remain in stable configurations or shift allegiance between communities over time). In describing these hypothetical network organizations, we consider their impact on the frequency, flexibility, and intensity of positive and negative affect, as well as an individual's ability to cope with challenges and their vulnerability to affective disorders (Figure 2).

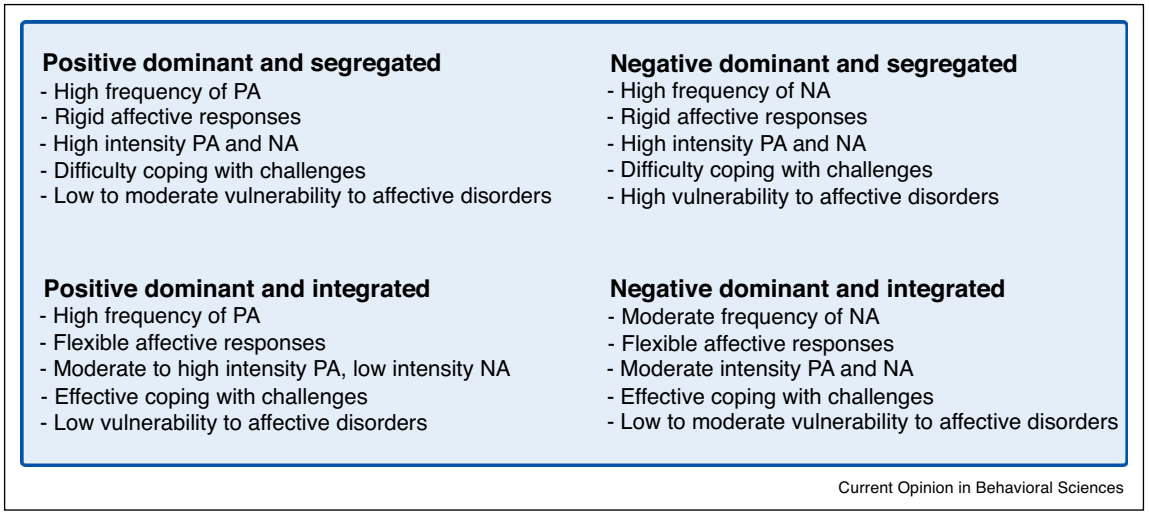
Positive dominant and segregated

Some individuals may have a network organization that is characterized by more positive than negative self-belief nodes, and communities defined by node valence (i.e. segregated communities of positive nodes and negative nodes, with dense within-community connections and few between-community connections) (Figure 1a). A segregated organization may occur if a person tends to emphasize positive self-beliefs and push negative self-beliefs out of awareness either as a strategy for enhancing positive affect, or because of difficulty accepting or coping with negative self-beliefs. In general, individuals with this network organization may frequently experience positive affect, because there is a higher probability that input from the world will activate a positive self-belief node and spread almost exclusively to other positive nodes. Because there are few connections between positive and negative node communities, activation of a positive or negative node is likely to reverberate around nodes of the same valence for considerable time, creating a rigid and high intensity affective state. In other words, these individuals may tend to get 'stuck' in either positive or negative affective states. Thus, while suppression of negative self-beliefs may be intended to enhance positive affect, it may paradoxically increase negative affect when input activates the negative self-belief community. These individuals may have difficulty coping with challenging situations due to the fact that positive self-beliefs and constructive interpretations are unlikely to become activated. These individuals may engage in maladaptive emotion regulation strategies such as rumination or suppression during challenging events. Rumination is the tendency to think about one's problems and negative feelings in endless cycles [5], while suppression is the tendency to inhibit internal emotional feelings and outward expressions of emotions [29]. These individuals would be unlikely to engage adaptive strategies [29–32] such as reappraisal (reinterpreting the meaning of a situation) or mindful acceptance (non-judgmentally experiencing uncomfortable emotions) because these strategies require some degree of positive self-belief activation (e.g. the belief that one has the capacity to effectively implement these strategies) [e.g. Ref. 33]. Because negative self-beliefs remain segregated from positive self-beliefs possibly due to a denial of their existence, these individuals may also resort to substance abuse as a way of coping with the negative self-beliefs that will be inevitably triggered from time to time. Altogether, these considerations suggest that although these individuals may exhibit frequent bouts of positive affect, they may still have a moderate vulnerability to affective or substance abuse disorders.

Negative dominant and segregated

Some individuals may have a network organization that is characterized by more negative than positive self-belief nodes, and communities defined by node valence (i.e. segregated communities of positive nodes and negative nodes) (Figure 1b). In this case, the segregated organization may occur if a person tends to focus on negative self-beliefs and push positive self-beliefs out of awareness either as a strategy for maintaining self-consistency [5], or due to heightened expectations that future events will be

Figure 2



Properties of different self-network organizations. *Abbreviations*: PA, positive affect; NA, negative affect.

negative [34]. In general, these individuals may frequently experience negative affect due to the higher probability of negative self-belief activation. Furthermore, the segregated organization is likely to create rigid and high intensity affective states due to the tendency of activation to reverberate around nodes of the same valence [3•]. These individuals may have difficulty coping with challenging situations due to the low probability of engaging positive self-belief nodes once the negative self-belief community is activated, and they may become highly vulnerable to depression or anxiety. This again may relate to a tendency to engage maladaptive emotion regulation strategies that involve repetitive thinking about one's problems and flaws and attempts to avoid the actual experience of uncomfortable emotions elicited by challenging events.

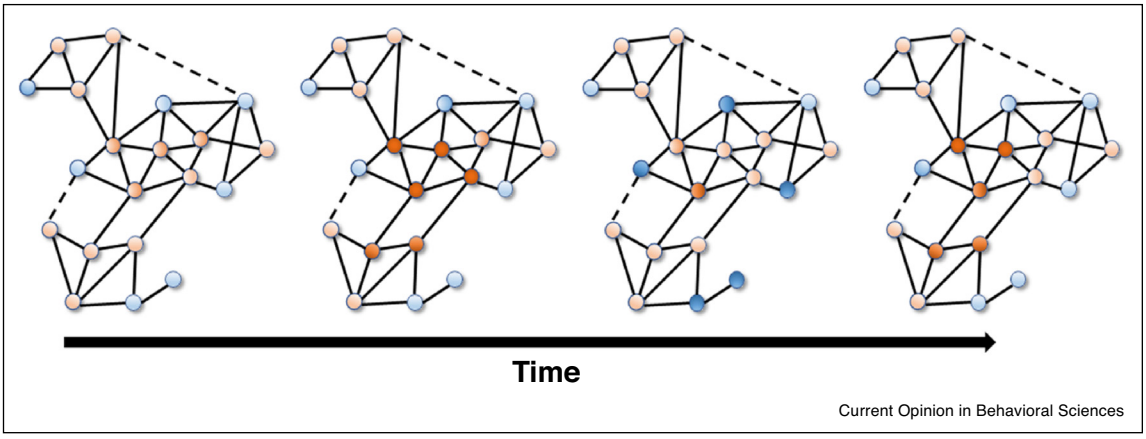
Positive dominant and integrated

Some individuals may have a network organization characterized by more positive than negative self-belief nodes, and communities defined by life domain rather than valence. In this case, there may be communities related to work, relationships, health, and so on, with each community containing a mix of positive and negative self-belief nodes (Figure 1c). These individuals are likely to experience frequent episodes of positive affect given the higher probability of life events activating positive self-belief nodes. Moreover, the utility of an integrated community organization is that when activation occurs in a negative self-belief node, it is likely to spread to at least a few positive self-belief nodes. As positive beliefs are brought online, negative affect may only reach moderate intensity levels and may more easily switch back to positive affective states. This type of integrated community structure may occur when individuals accept the 'negative' aspects of themselves and allow positive and negative self-beliefs to co-exist and inform one another (e.g. a person may acknowledge that they are not as naturally gifted as others in academics, but may believe that they can succeed by working hard and focusing on incremental growth). This may encourage a sense of affective flexibility and authentic well-being that enables individuals to cope with challenging situations and protects them against affective disorders. In particular, these individuals may frequently use reappraisal and mindful acceptance as emotion regulation strategies due to the tendency to activate some positive self-belief nodes during challenging events, such as the belief that seemingly negative events can be reconstrued in a positive light (e.g. believing that there is something useful to learn from uncomfortable events and feelings).

Negative dominant and integrated

This network organization is again characterized by communities defined by life domain, with each community including a mix of positive and negative self-belief nodes. However, in this case, the overall network contains more negative than positive self-belief nodes (Figure 1d). This network organization may be associated with a moderate frequency and intensity negative affective states, given that activation is likely to spread to at least some positive nodes. Moreover, it may facilitate affective flexibility and the ability to effectively cope with stressful circumstances, given that network activity is unlikely to get stuck in the negative self-belief community. Thus, despite seeing the world through less than rosy glasses, these individuals may still bring some positive self-beliefs to bear on their interpretations and evaluations of the world, and therefore use adaptive regulation strategies (reappraisal and mindful acceptance) more than

Figure 3



The strength of activation of various self-belief nodes may change across time and context. In this example, self-belief nodes related to the 'relationship community' become more activated over time (darker shades of color) in response to input from the world (walking into a restaurant). Over time the relative activity in positive versus negative nodes shifts as a function of the focus of attention – a conversation with a friend, or the presence of a disliked co-worker.

maladaptive strategies (rumination and suppression), thereby producing only a low to moderate vulnerability to affective disorders.

State-like aspects of the self-network

While the community structure of the self-network may be trait-like and slow to adapt through experience, the relative activation of any particular node (and the overall network activity pattern) may be more state-like, continuously evolving with moment-to-moment changes in input from the world (Figure 3). For example, certain positive self-belief nodes related to relationships may gradually increase in activity as a person makes their way to meet a friend at a restaurant. If the person then happens to see a disliked co-worker at the restaurant, the activity may shift from positive to negative valence nodes within the relationship domain. Activity may shift back again towards the positive nodes as the person chooses to focus on the conversation with their friend and ignore the co-worker. Simply put, the 'volume' of various positive and negative self-belief nodes may be turned up or down depending on the nature of current input.

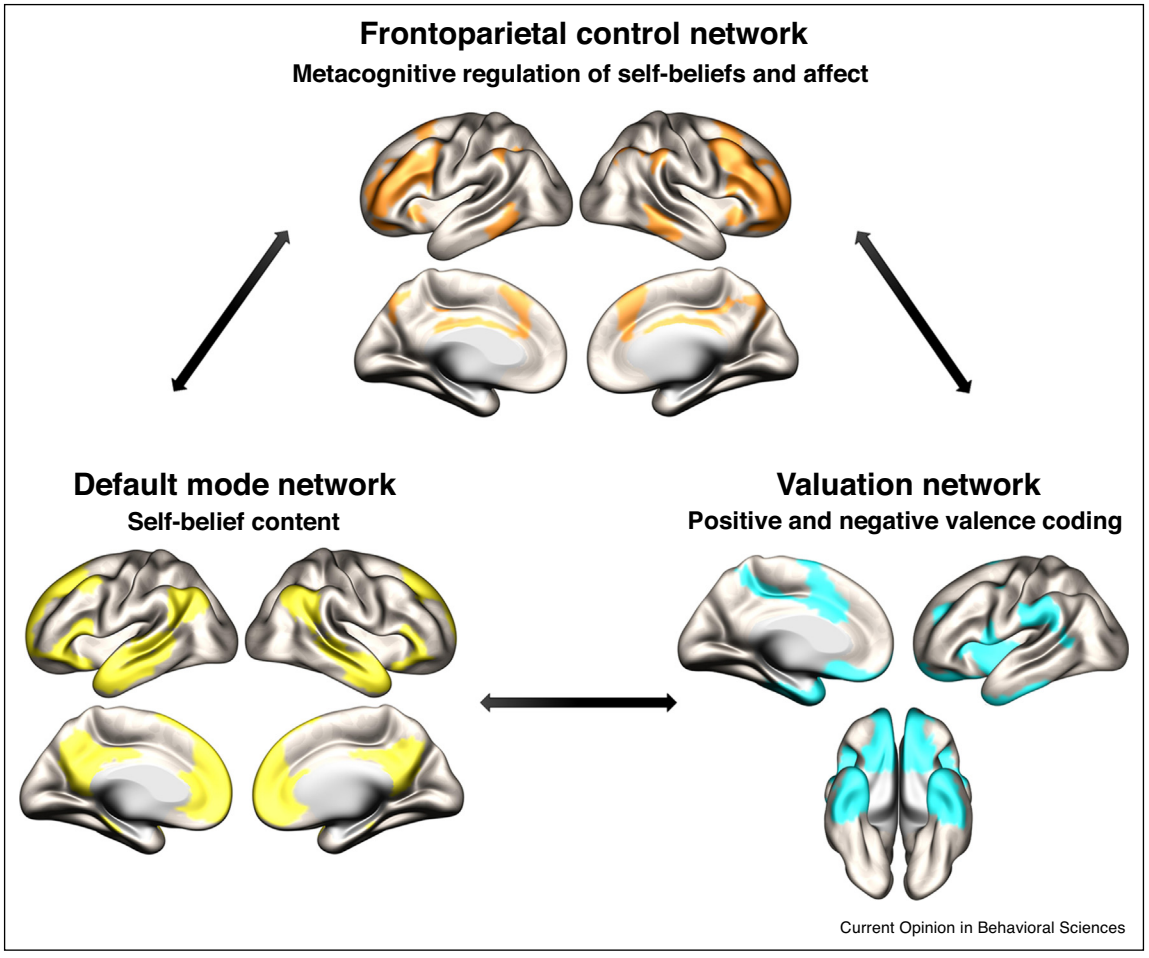
Network science offers several concepts that can illuminate the state-dependent trajectory of network activity patterns. For example, the concept of activity flow mapping [21••,35] suggests that the strength of activation in a given node can be predicted by the sum of activity in all other nodes of the network multiplied by their connection strength to that target node. Another useful concept is network controllability, which provides insight about which nodes of a network are most influential in pushing activity in other nodes toward new states [20••,28•]. This work may eventually provide a mechanistic understanding of state-like variation in self-network activity in response to triggering events and how that variation impacts affect and behavior.

Brain networks associated with self-referential processing and affect

Neuroimaging studies have provided key insights about several brain networks that contribute to self-referential processing and affective experience (Figure 4). The DMN is consistently activated when individuals reflect on their traits [7–10], retrieve autobiographical memories [36], process information within schema-based knowledge structures [37], and use memory to imbue events with meaning [6]. It may therefore contribute to the long-term storage of self-beliefs, organized in specific community structures.

Self-beliefs may acquire valence through interactions between the DMN and valuation regions within the limbic and salience networks (e.g., amygdala, orbitofrontal cortex, striatum, and insula) [15,38–40]. Valuation regions contain separate populations of positive valence-coding and negative valence-coding neurons [14,16•,41,42] that signal the relevance of internal or external events given one's current goals [43]. Interactions between the DMN and valuation network may play a role in the extent to which self-beliefs adapt or become increasingly rigid as a result of new input from the world. For example, individuals with social anxiety disorder exhibit disproportionate updating of self-beliefs based on negative feedback from others [44•]. This may reflect a strengthening over time of connections between negative valence-coding neurons in the valuation network and self-belief representations in distributed DMN activity patterns.

Figure 4



Brain networks involved in self-referential processing and affective experience. The default mode network is implicated in the capacity to represent the self as an object of awareness with particular attributes and may therefore contribute to the representation of self-belief content. The limbic and salience (valuation) networks contains populations of positive valence-coding and negative valence-coding neurons and may tag self-beliefs with valence. This may contribute to the extent to which positive versus negative self-beliefs are salient and tend to capture attention. The frontoparietal control network contributes to metacognitive awareness and the ability to reflect upon and restructure self-beliefs in service of reducing emotional reactivity. These brain networks may continuously interact and support dynamic changes in patterns of self-network activity as an individual engages with their environment.

Finally, the frontoparietal control network (FPCN) may contribute to metacognitive processes that enable people to become aware of their self-beliefs and potentially regulate the affective experience associated with those beliefs. For example, FPCN activity is greater when individuals attempt to regulate emotional reactivity evoked by negative self-beliefs by using a reappraisal strategy compared to a no regulation condition [45••,46]. However, rather than simply turn down the DMN, reappraisal is associated with co-activation of the FPCN and DMN, suggesting that synergistic interactions enable individuals to challenge and restructure negative self-beliefs [45••]. Thus, communication between these networks may facilitate the regulation of mental activity in a constructive manner [17] and contribute to state-dependant changes in the strength of particular self-belief nodes. In turn this may facilitate adaptive regulation of emotional reactivity, perhaps shifting valuation network activity away from negative valence-coding neurons and toward positive valence-coding neural neurons.

Implications for treating clinical disorders

Cognitive behavioral therapy (CBT) and mindfulness-based approaches are popular and effective options for treating affective disorders, and work in part, by increasing positive self-beliefs and reducing negative self-beliefs [25,26]. We can conceptualize these treatment modalities as targeting the self-network in different ways.

Mindfulness-based interventions encourage individuals to accept present moment experience and perceive self-beliefs as transient and insubstantial mental events, like

clouds passing through the sky. This may have the effect of turning down the activation of self-belief nodes and thereby reducing emotional reactivity in a global manner. If used repeatedly over time, mindfulness-based approaches may lead to enduring changes in network structure, such as less connection strength in general between valence coding neurons and neurons supporting self-belief representations, thus creating a more flexible and 'transparent' self-network that enables individuals to more effectively process events 'as they are'. This may limit habitual emotional reactivity and facilitate fluid affective responses that are situationally appropriate [47]. In line with this, a variety of studies suggest that mindfulness-based approaches reduce DMN activity related to cognitive elaborations and judgments and increase valuation network activity related to concrete present moment sensory experience [45••,48–50]. Furthermore, FPCN regions take on more 'hub-like' qualities when individuals accept rather than judge their experience [51], suggesting a role in regulating the flow of information throughout the global brain network such that present-moment sensory experience is emphasized.

CBT may play a complementary role as individuals are trained in challenging the validity of negative self-beliefs and are encouraged to engage in rewarding activities that may enhance positive self-beliefs. As this process is repeated, it may lead to enduring changes in the building blocks of the self-network. In particular, it may change the content of self-beliefs that are included within the self-network and it may alter the associative weights between self-beliefs, thereby changing community structure. For example, as a person learns to challenge a certain negative belief, perhaps by bringing counter (positive) evidence to bear on the interpretation of a particular situation, this may alter the potency of the negative self-belief node and encourage the growth of connections between that node and other positive self-belief nodes, creating a shift toward a more integrative community structure. If the negative self-belief node becomes activated on future occasions, it may now spread to those positive nodes, resulting in a rich context that may hold emotional reactivity in check. These changes to the self-network may be supported by a shift in the interactions between the valuation network and DMN, such that connections between negative-valence coding neurons in the valuation network and the DMN are gradually weakened, and connections between positive valence-coding neurons in the valuation network and the DMN are gradually strengthened. This restructuring of connections may be guided by the FPCN, through its role in reappraisal as noted above [45••,46]. Thus, mindfulness-based approaches and CBT may target the self-network in complementary ways via changes in large-scale brain network interactions. When combined, these approaches may provide a powerful means of modifying maladaptive self-beliefs that diminish positive affect.

Conclusions and future directions

We have considered the neurocognitive network structure of self-beliefs and speculated regarding their impact on affective experience. This is a highly simplified proposal, meant only to be a starting point, but may offer some hints about general principles of network organization and the dynamics of affective responses. There may be many types of self-network community structures beyond those explored here, and there are certainly many other network concepts that can provide additional information, such as the 'hubness' of nodes and the density of local and global connectivity. Progressing from simple to more complex network models of the self will be a key challenge for future research. Additionally, while our focus was the influence of self-belief structure on affective experience, future work could investigate the influence of affective states on activity propagation through the self-belief network, thereby illuminating how activation may cycle up from concrete viscerosomatic states to more abstract beliefs, complementing the 'top-down' perspective outlined here. It will also be important to make these ideas more concrete and testable. One possibility would be to have individuals rate not only the self-descriptiveness of trait words, but also rate the subjective relatedness of pairs of beliefs. This would allow for the construction of a self-network that could be submitted to further graph analyses. In terms of brain activity, it could be useful to employ multi-voxel pattern analysis to identify signatures of positive and negative self-beliefs, given that univariate analyses generally do not have the capacity to distinguish positively and negatively valenced content.

Our self-network perspective suggests a number of questions for future work. First, how can we measure the network-based attributes of the self? While measuring individual self-beliefs is easy, it is unclear how to assess the relationship (i.e. connections) between them. This will require new innovative task paradigms. Second, how does the psychological self-network map onto large-scale brain networks? While we discussed the functions of several brain networks that are relevant to self-referential processing and affect, it remains to be determined how these brain network interactions relate to different features of the self-network, such as different types of community structure. Our understanding of the mapping between cognitive representations and brain network models is still in its infancy, however, there are exciting proposals about how to make progress on this front [20••,21••]. Third, how can we probe the dynamic nature of the self and its impact on affective experience? Existing paradigms largely take snapshots of the self at a single point in time. A complete account will require the ability to track the state-like evolution of self-network activity patterns. Fourth, can we use this perspective to potentially inform individualized treatment using CBT, mindfulness, or other approaches? Probing the specific content and organization of a given individual's self-network may

shed light on problematic beliefs that interfere with positive and flexible affective responses. Fifth, future research would benefit from examining the relationship between self-network structure and self-esteem. One possibility is that self-esteem may roughly map onto the number of positive versus negative nodes in the network. Self-network organization may also relate to the extent to which self-esteem changes over time in response to feedback. For example, individuals with a negative dominant and integrated architecture versus those with a negative dominant and segregated architecture may show a lower learning rate (less tendency to update self-esteem) in response to negative feedback, because there is less tendency to get stuck in negative self-referential ruminative loops and therefore less tendency to generate a negative prediction error that lowers self-esteem further. Finally, at a longer time scale, assessing change in network structure may provide increased clarity regarding developmental changes in affect, including salient changes that occur from childhood to adolescence, and changes that occur in late adulthood, sometimes as the result of brain disease (e.g. frontotemporal dementia). Pursuing these questions promises valuable new insights regarding both normal range variation in personality, and new treatment approaches for helping prevent and ameliorate disorders of positive and negative affect.

Conflict of interest statement

Nothing declared.

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- •• of outstanding interest

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