The Default Mode Network in Autism

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ABSTRACT
Autism spectrum disorder (ASD) is characterized by deficits in social communication and interaction. Since its discovery as a major functional brain system, the default mode network (DMN) has been implicated in a number of psychiatric disorders, including ASD. We review converging multimodal evidence for DMN dysfunction in the context of specific components of social cognitive dysfunction in ASD—self-referential processing, which is the ability to process social information relative to oneself; and theory of mind or mentalizing, which is the ability to infer the mental states, such as beliefs, intentions, and emotions, of others. We show that altered functional and structural organization of the DMN and its atypical developmental trajectory are prominent neurobiological features of ASD. We integrate findings on atypical cytoarchitectonic organization and imbalance in excitatory-inhibitory circuits, which alter local and global brain signaling, to scrutinize putative mechanisms underlying DMN dysfunction in ASD. Our synthesis of the extant literature suggests that aberrancies in key nodes of the DMN and their dynamic functional interactions contribute to atypical integration of information about the self in relation to “other” as well as to impairments in the ability to flexibly attend to socially relevant stimuli. We conclude by highlighting open questions for future research.

Keywords: Autism, Default mode network, Mentalizing, Self-referential processing, Social, Theory of mind

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AUTISM SPECTRUM DISORDER, SOCIAL DEFICITS, AND DEFAULT MODE NETWORK
Autism, derived from the Greek word “auto” meaning “self,” describes a lack of interest in social interactions with the “other.” The term autism was first used by Eugen Bleuler to describe adolescents and adults with schizophrenia (1), and it became the cornerstone for Leo Kanner’s characterization of infants and young children who showed a lack of interest in communicating with others and appeared to be “lost in their own narrow worlds” (2). Although these early descriptions have been influential in describing the cluster of social impairments now known to characterize autism spectrum disorder (ASD), it has become increasingly evident that self-related cognitive processing is also atypical in affected individuals (3). Understanding of “self” in the context of “other” is integral to successful social interactions (4), and it is theorized that individuals with ASD struggle with reciprocal social interaction largely owing to difficulties in both self-referential cognitive processing and inferring the mental states of others (5). Perhaps it is not surprising then that the default mode network (DMN), a core brain system for processing information about the self and other (6,7), has emerged as a key system underlying social dysfunction in ASD (3,6–9).

Despite the unique functional properties of the DMN and its links to the ASD phenotype (10), few attempts have been made to synthesize the extant multimodal literature and provide a unified framework of DMN dysfunction in ASD. We review converging evidence from multiple scales of brain organization that DMN dysfunction is a significant component of social impairments in ASD. We first describe the functional architecture of the DMN, focusing on aspects of social function that are known to be affected in ASD. These include self-referential processing, which is the ability to process social information relative to oneself, and mentalizing or theory of mind, which is the ability to infer the mental states, such as beliefs, intentions, and emotions, of others. We provide evidence for aberrant function of the DMN in ASD as it relates to deficits in these domains of social cognition. We then review functional, structural, cytoarchitectural, and neurophysiological evidence for neuronal disorganization in key nodes of the DMN in ASD. Our synthesis of the extant literature suggests that an altered developmental trajectory of structural and functional organization of the DMN is a prominent neurobiological feature of ASD. We discuss putative neuronal mechanisms underlying DMN dysfunction and highlight questions for future research.

FUNCTIONAL NEUROANATOMY OF DMN AND ITS ROLE IN SOCIAL COGNITION
Over the past 3 decades, a number of influential studies have consistently demonstrated that a strongly intrinsically interconnected network of brain structures (11,12), including the posterior cingulate cortex (PCC), precuneus, medial prefrontal cortex (mPFC), temporoparietal junction (TPJ), and hippocampus (13,14) (Figure 1), is attenuated during a wide range of cognitive tasks (13,15). In parallel, several investigations have also uncovered that these structures, collectively named the default mode network, are significantly engaged during tasks involving social cognitive mental processes that are evaluative (16,17), including self-referential and autobiographical processing (13,15,16,18) and mentalizing and theory of mind.
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Figure 1. Functional and structural architecture of the default mode network (DMN) identified using multiple imaging modalities and methods. (A) Architecture of the DMN, identified as regions of “task-induced deactivation” in the seminal meta-analysis by Shulman et al. (135). Data derived from nine studies using [15O]H2O positron emission tomography and reconstructed as a surface rendering, as in Buckner et al. (136). (B) DMN topology is readily identifiable using resting-state functional magnetic resonance imaging data and use of an independent component analysis. (C) Core midline DMN nodes, the medial prefrontal cortex (mPFC) and posterior cingulate cortex (PCC), are structurally connected via a major white matter pathway, the cingulum bundle. Fibers reconstructed using diffusion tensor imaging tractography. (D) The strength of structural connections among DMN nodes can be quantified using diffusion imaging. Edge thickness and node size represent connection strength and node degree, respectively. PCC is the most strongly connected node within the DMN. (E) Spring graph illustrates the differing functional connectivity weights between DMN nodes, such that more strongly connected nodes are closer together in space, and these midline hubs are embedded centrally within the network. aMPFC, anterioromedial prefrontal cortex; dMPFC, dorsomedial prefrontal cortex; HF+, hippocampal formation; HIP, hippocampus; LTC, lateral temporal cortex; pIPL, posterior inferior parietal lobule; PHC, parahippocampal cortex; Rsp, retrosplenial cortex; supF, superior frontal gyrus; TempP, temporal pole; TP, temporal pole; TPJ, temporoparietal junction; vMPFC, ventromedial prefrontal cortex. (A, Adapted with permission from Buckner et al. (13); B, adapted with permission from Shirer et al. (137); C, adapted with permission from van den Heuvel et al. (138); D, adapted with permission from Tao et al. (139); E, adapted with permission from Andrews-Hanna et al. (140).)

Beyond socially relevant functions, the DMN is also associated with mind wandering and initiation of spontaneous thought processes (13) and subjective value judgments (19), but how these functions contribute to social cognition is not known. Given its central importance to the phenomenology of ASD, we focus on processes that are more directly relevant to social function. Analysis of the extent literature in neurotypical individuals reveals considerable overlap between core DMN nodes and brain regions involved in social cognition (6,17,20–22), most notably the PCC, mPFC, and TPJ (Figure 2).

We next summarize some of the known functional roles of these three brain regions as relevant for the present review.

As one of the most highly connected regions in the brain (23), with a high baseline metabolic rate (14), the PCC is considered to be a core functional “hub.” The PCC, which is situated between the marginal ramus of the cingulate sulcus and the parieto-occipital sulcus, has been implicated in both self-relevant and other-relevant processing, including tasks requiring autobiographical memory and imagining oneself in the future (20), and evaluating and processing mental states of others (16,24,25). The mPFC encompasses a collection of strongly interconnected, contiguous regions in the prefrontal cortex, including the medial superior frontal, orbital, and frontopolar cortices, and anterior portions of the cingulate cortex. The mPFC is associated with monitoring of both one’s own mental states and the mental states of others (16,17), which are thought to engage the ventral and dorsal subregions, respectively (13,26). The TPJ is situated between the inferior parietal cortex and posterior superior temporal cortex, with prominent overlap with the angular gyrus node of the DMN (27). The TPJ preferentially encodes other-relevant information, including the mental states and beliefs of others. For example, transcranial magnetic stimulation to the right TPJ has been shown to disrupt a participant’s ability to attribute intentions to others (28) and the ability to distinguish other-relevant from self-relevant information (29). The TPJ has also been linked with predicting behaviors of others during social interactions (30). Thus, the PCC, dorsal and ventral mPFC, and TPJ, core DMN nodes, play distinct and interacting roles in monitoring of both the psychological state of self and evaluation of others.

TASK-BASED FUNCTIONAL MAGNETIC RESONANCE IMAGING STUDIES OF ATYPICAL DMN FUNCTION

A prominent cognitive deficit of ASD is impairment in the ability to decode the mental states of self and others, and DMN dysfunction may be a critical neural signature of these deficits (31–33). The majority of task-based functional magnetic resonance imaging (fMRI) studies of ASD have been conducted with adults, or mixed groups of adolescents and adults, with ASD relative to age-matched neurotypical individuals. Task-related fMRI studies also focus primarily on activation in specific nodes of the social brain, including the DMN regions described above.

Studies of self-referential processing, requiring self-related versus other-related judgments, demonstrate reduced activation in the PCC (34) and mPFC (33). One study comparing the neural response in the ventral mPFC to self-related versus other-related judgments, showed preferential activation of this region for self-related judgments in neurotypical control adults, but not in adults with ASD (33). Analysis of multivariate voxel patterns further suggests that in adults with ASD, these midline structures and the PCC in particular are insensitive to semantic processing of words that connote social interactions. Moreover, machine learning algorithms classified individuals as autistic or control with 97% accuracy from their fMRI neurocognitive markers in these regions (35). Together, results suggest that the PCC and mPFC exhibit aberrant patterns of self-representation in ASD.

Theory of mind and mentalizing tasks typically involve viewing images, animation, or stories and test participants’ understanding of others’ intentions or mental states. Overall, these studies report decreased recruitment of the TPJ and dorsal mPFC in adults with ASD (36–41). However, other studies report decreases only in relation to sexual dimorphism in ASD, with one study showing that male, but not female,
adults with ASD demonstrate decreased activity in mPFC and TPJ relative to neurotypical adults (42), while a different study suggested the opposite pattern, showing that female, but not male, subjects in the ASD group demonstrate decreased activation in the mPFC (43). Few studies have examined functional connectivity during such tasks and report decreased interhemispheric connectivity of the TPJ with the left lateral temporal cortex (44) and between TPJ and mPFC (45) in adults with ASD.

There have been far fewer task-based fMRI investigations in children with ASD, likely owing to difficulties with task compliance and excessive head movement. When asked to either infer the emotional state of another individual (other-task) or judge their own emotional response (self-task), individuals with ASD (12–31 years of age) showed increased dorsal mPFC activation with age, whereas neurotypical control subjects showed age-related decreases (46). Further evidence that group differences may be age dependent comes from a study that used a similar task and found no significant differences when children and adolescents with ASD were pooled together (47). Lastly, studies using theory of mind tasks report reduced activation of dorsal mPFC, TPJ, and PCC in children (48), while other studies report increased activation in adolescents with ASD (49) relative to age-matched control subjects. More studies are needed to clarify the developmental profile of functional deficits in ASD.

The extant literature suggests that social impairments in ASD are linked to atypical function of the DMN. Despite considerable heterogeneity with respect to age and sex of participants and type of task, findings generally point to hypoactivation of DMN nodes in ASD, with decreased recruitment of ventral mPFC during processing of self-relevant information and dorsal mPFC and TPJ during processing of other-relevant information. A significant limitation is the lack of developmental studies and connectivity-based approaches. Despite the strong interconnectivity of the DMN and a large body of evidence that ASD is a disorder of network-level brain organization, it is surprising that very little is known regarding functional connectivity of the DMN during social tasks. As reviewed below, there is more consistent evidence from intrinsic connectivity studies that the overall functional organization of the DMN is aberrant in ASD.

**INTRINSIC FUNCTIONAL CONNECTIVITY EVIDENCE FOR ABERRANT DMN**

Intrinsic functional connectivity as measured by resting-state fMRI has been widely used to investigate the functional architecture of the DMN (16). Resting-state fMRI has been used more extensively in studies of ASD than task-related fMRI owing to the relative ease of acquiring the data, especially in developmental cohorts (50). There is strong evidence that the DMN is among the most disrupted functional networks in ASD (10,51). Importantly, a number of studies report that disrupted intrinsic DMN organization is associated with social deficits in children and adults with ASD (52–56).

Most intrinsic functional connectivity studies in children with ASD report increased within-network connectivity between core DMN nodes, while studies in adolescents and adults report decreased connectivity, and studies in mixed age groups report both increases and decreases (57–71). These “inconsistencies” likely reflect developmental changes and heterogeneity in connectivity profiles across different nodes of the DMN (9). For example, we previously showed that children with ASD demonstrate strong hyperconnectivity between the PCC and lateral and medial temporal lobe but hypoconnectivity within DMN subregions (65) (Figure 3A). Furthermore, PCC hyperconnectivity also predicted social communication deficits in children with ASD (Figure 3B) (65).
Over the course of typical development, intrinsic functional connectivity between DMN nodes increases between childhood and adulthood (Figure 4A, B) (72,73). In ASD, there appears to be no consistent evidence of such developmental increases in DMN connectivity (63,74,75). This suggests that hyperconnected DMN links in childhood ASD may become underconnected in adulthood owing to failure to strengthen long-range pathways with age in ASD. Finally, cross-network connectivity also increases with age in neurotypical individuals (Figure 4C) (76), but not in individuals with ASD (61,63), suggesting that the development of critical intranetwork and internetwork connections is altered in ASD.

The extant literature provides converging evidence for aberrant intrinsic DMN organization and development in ASD. Overall, the most commonly observed profile in childhood ASD has three features: 1) increased within-network connectivity in the default mode network; 2) increased connectivity between the default mode network and other systems of the brain; and 3) increased connectivity with the posterior cingulate cortex (PCC) in children with autism spectrum disorder (ASD).

Figure 3. Hyperconnectivity with the posterior cingulate cortex (PCC) predicts social communication deficits in children with autism spectrum disorder (ASD). (A) Children with ASD demonstrate whole-brain hyperconnectivity with PCC and retrosplenial cortex (RSC) and hypoconnectivity with precuneus (PreC). *p < .01, **p < .005, ***p < .001. (B) Hyperconnectivity between the PCC and target regions, including the right parahippocampal gyrus, left temporal pole, and right lingual gyrus, predicted social impairments as measured by the Autism Diagnostic Observation Schedule (ADOS) social subscale in children with ASD. No such significant relationships were demonstrated by the RSC and PreC. *Significant. aLTC, anterolateral temporal cortex; DMPFC, dorsomedial prefrontal cortex; EFC, entorhinal cortex; L, left; LG, lingual gyrus; n.s., not significant; PHG, parahippocampal gyrus; pSTS, posterior superior temporal sulcus; R, right; ROI, region of interest; TD, typical development; TempP, temporal pole. [Adapted with permission from Lynch et al. (65).]

Figure 4. The default mode network transitions from an immature state in childhood to a cohesive network in adulthood. (A) Independent component analysis applied to resting-state functional magnetic resonance imaging data reveals stronger medial prefrontal cortex functional connectivity in a group of adults relative to a group of children 7–9 years of age. (B) Comparison of medial prefrontal cortex functional connectivity strength in children (left) and adults (middle) confirms greater connectivity, especially with posterior cingulate cortex, later in development (right). (C) Connectivity between the default mode network and other systems of the brain change over development. Spring graph representation of brain network development using resting-state functional magnetic resonance imaging during three periods of development: 9 years (left), 13 years (middle), and 25 years (right). Note that some default mode network nodes (filled red) are isolated from one another in childhood but are more strongly integrated in adulthood. [A, Adapted with permission from Superek et al. (72); B, adapted with permission from Fair et al. (73); C, adapted with permission from Power et al. (76).]
the DMN, most notably between the PCC and mPFC; 2) reduced connectivity of DMN nodes with other functional systems outside the DMN; and 3) increased local connectivity within DMN nodes. These patterns appear to take on a more complex profile with age involving an overall developmental shift from hyperconnectivity in childhood to hypoconnectivity in adolescence and adulthood. Such altered connectivity between DMN nodes likely underlies disturbances in self-referential and mentalizing processes, whereas reduced intrinsic connectivity between DMN and other functional systems may reflect a difficulty in adaptively switching between the DMN and networks involved in monitoring and attending to salient stimuli (57).

As reviewed above, there is now considerable evidence for aberrant functional organization of the DMN in ASD, with the strongest and most consistent findings to date emerging from analysis of intrinsic functional connectivity. Importantly, the converging evidence points to a complex and dynamic neurobiological phenotype of ASD, with both hyper-connectivity and hypoconnectivity profiles that shift with development.

**STRUCTURAL MRI EVIDENCE FOR ATYPICAL DMN IN ASD**

Prominent structural aberrations in the DMN across several morphological metrics have been reported in ASD, including cortical thickness and volume and gray matter density. One study using voxel-based morphometry reported altered PCC gray matter organization in children and adolescents with ASD, which was associated with symptom severity (77). Furthermore, there is also evidence of increased cortical thickness in the PCC (78) and ventral mPFC (79) (Figure 5C) in children, adolescents, and adults. Using a metric of cortical folding, or gyri-}

![Image](https://www.sobp.org/BPCNNI)

**Figure 5.** Structural, neurochemical, and cytoarchitectonic disorganization of key default mode network nodes in autism spectrum disorder (ASD). (A) Right temporoparietal junction (TPJ) sulcus is shallower in children with ASD (red line) compared with neurotypical children (blue line). (B) Relationship between TPJ gray matter volume and ability to assess interactions between two objects in a social motion experiment in adults with ASD (red line) relative to neurotypical adults (blue line). Note that the relationship between gray matter volume in ASD is significant, such that greater gray matter volume is associated with better performance. (C) Increased cortical thickness of the bilateral medial prefrontal cortex (mPFC) in children with ASD relative to adults and neurotypical children is replicable across sites of the ABIDE data set. (D) Sex differences in gyri-}

ization that is with a few notable exceptions (77,86), most studies do not show direct links with behavioral deficits, which
future studies should incorporate. Nevertheless, together, MRI studies point to structural abnormalities of the DMN in ASD that appear to persist throughout development.

**ATYPICAL WHITE MATTER PATHWAYS-associated with DMN in ASD**

A number of diffusion tensor imaging studies report atypical white matter connectivity in ASD (88). White matter tracts along the cingulum bundle connect the mPFC and PCC (Figure 1C), and the majority of studies report decreased fractional anisotropy, a metric of white matter integrity, in the cingulum in children and adolescents with ASD (89–93), although some studies report increases (94,95). Tracts connecting the PCC and TPJ have been challenging to measure with conventional diffusion tensor imaging owing to crossing fibers in this region (96); however, some studies have identified reduced fractional anisotropy in tracts adjacent to the TPJ in children and adolescents with ASD (91,97). Over the course of typical development, there is evidence of increases in fractional anisotropy within the cingulum from childhood to adulthood (98,99), reflecting a strengthening of white matter tracts between the PCC and mPFC over development. Evidence from cross-sectional developmental studies suggest that decreased fractional anisotropy in the cingulum (67,114), leading to difficulties in local neural circuits that subserve sensory, social, and affective processes (109–113). E/I imbalance in ASD is thought to alter local and global brain signaling and contribute to atypical fluctuations in regional fMRI signals (67,114), leading to difficulties with modulating flexible and goal-directed behaviors. Thus, the DMN has emerged as a key target for E/I investigations using optogenetic studies in rodents, and there is evidence that elevated E/I balance in the rodent mPFC is associated with impaired social function, an effect that was improved by increasing inhibitory function (115).

One mechanism for E/I imbalance is atypical expression of inhibitory interneurons, modulated by the neurotransmitter gamma-aminobutyric acid (GABA). During early embryonic development, GABAergic interneurons are involved with regulating cell migration, differentiation, and synapse formation (116). Rodent models suggest that decreasing GABA transmission in the mPFC decreases sociability (117), consistent with our view that E/I imbalance in the DMN can contribute to impaired social function in autism. There is evidence of altered signaling in inhibitory pathways that are modulated by GABAergic interneurons in ASD (118–120). Significant reductions in GABA expression have been found using magnetic resonance spectroscopy (121) as well as in postmortem brain tissue of individuals with ASD (Figure 5F) (122). The colocalized pattern of deficits in cell migration and GABA signaling in the cortex of individuals with ASD suggests that these deficits occur early in cortical development, potentially leading to persistent E/I imbalances throughout development (123–125) and altered brain connectivity (9,126,127). Crucially, these types of developmental aberrancies in local brain circuits are likely to influence global circuit function, especially if they occur in widely connected hubs such as the PCC (67,112). Studies using magnetic resonance spectroscopy in combination with resting-state and task-based fMRI are needed to probe GABA-related and E/I imbalance–related DMN dysfunction in ASD.

Research on the effects of GABA on social function have led to the development of specific drugs that potentiate GABA transmission as treatment for ASD symptoms (128). For example, the GABAa agonist arbaclofen has been used to improve social function in patients with fragile X syndrome, a genetic condition that often manifests with ASD symptoms (129). In a mouse model of autism, administration of benzodiazepines, which enhances GABAergic signaling, improved social and cognitive deficits (130). Whether altering DMN function using locally delivered GABAa agonists such as arbaclofen can improve social function is an important topic for future research.

**DMN Dysfunction in the Context of Salience Network Aberrations in ASD**

Complex social behaviors involve cognitive and perceptual processes that are supported by interactions between
large-scale brain systems, including the DMN (131). Notably, the DMN interfaces with two other major networks in the brain, the salience network (SN) and the central executive network (131). Thus, the consequences of DMN dysfunction likely manifest also in interactions of the DMN with other brain systems (10,131).

A triple network model of psychopathology (131) posits that atypical interactions with the SN might contribute to DMN dysfunction in ASD and contribute to a lack of engagement with socially relevant stimuli. The SN is a large-scale neurocognitive network anchored in the anterior insula and anterior cingulate cortex, and it plays a critical role in detecting salient stimuli and orienting attentional resources to them in an adaptive and goal-relevant manner (132). As such, reduced activation of the PCC and mPFC of the DMN may arise from weak mapping of salient socially relevant cues with self-relevance and subjective value necessary for effective social function. Consistent with this view, recent evidence suggests that children with ASD exhibit intrinsic functional hyperconnectivity within the SN, central executive network, and DMN (66) and other neural systems (67). This within-network intrinsic hyperconnectivity in ASD can result in “network isolation,” limiting dynamic interactions between brain networks that are necessary for complex social behaviors (57,133). Consistent with this view, a recent study demonstrated that intrinsic connectivity between the DMN, SN, and central executive network predicted longitudinal improvements in adaptive behaviors in ASD (134), highlighting the significance of internetwork interactions in the pathophysiology of ASD (131).

CONCLUSIONS
We have sought to provide a comprehensive review of evidence pointing to aberrant DMN function in the context of mental processes that contribute to social deficits in ASD. These processes most prominently include mentalizing, theory of mind, and self-referential processing, which have consistently been shown to activate the core nodes of the DMN in neurotypical individuals. We have linked neural models of DMN function with specific phenotypic features of social dysfunction in ASD. We used this framing to delineate how DMN function is disrupted in children, adolescents, and adults with ASD. As we have reviewed, there is now substantial evidence that structural and functional disruptions to key nodes of the DMN, their connectivity with each other, and atypical patterns of connectivity with other brain regions play an important role in the symptomatology of ASD. Our synthesis of extant findings suggests that atypical integration of information about self and other in the DMN underlies social deficits in ASD.

Research on how the DMN changes from childhood to adulthood is providing fundamental new insights not only into the ontogeny of complex social functions in typically developing individuals, but also into components of social cognition that can go awry in ASD. It is clear that research on the DMN and its dysfunctional organization have laid the groundwork for a more sophisticated and principled approach to investigations of the complex, but interrelated, social and behavioral problems that define autism. Despite an explosive amount of research on individual brain regions and their interconnectivity, progress in our understanding of how the brain interactively processes socially relevant stimuli remains a major challenge for the neuroscience of ASD. Analysis of brain circuit dynamics offers new possibilities in this regard. The ability to flexibly switch between different modes of thought and reference frames is a critical feature of adaptive social function, and impairments in complex social processes in ASD are likely dependent on interactions between multiple large-scale brain systems. Progress in the field will depend on better characterization of DMN dysfunction in ASD and aberrant dynamic context-specific interactions with other brain networks, such as the salience network. Box 1 lists some questions for future research.

The findings reviewed here highlight the necessity for studying heterogeneous patterns of functional and structural brain connectivity and their interrelationships at different stages of development. Longitudinal studies leveraging quantitative multimodal systems neuroscience approaches will play a crucial role moving forward. This includes novel computational tools, individualized atlases, wiring diagrams, and methodological developments that will propel systematic ways of thinking about atypical brain organization in ASD. Knowledge of how functional interactions between the DMN and other brain systems mature over time and how they change mental representations of socially relevant information will be fundamental to the study of the neurobiological basis of social interaction deficits in ASD.

Box 1. Questions for Future Research

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<td>When do structural aberrations of the DMN emerge during fetal development and infancy?</td>
<td>The emergence of structural aberrations in the DMN during fetal development and infancy is likely to impact early social cognitive development in ASD.</td>
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