Impulsivity and brain organization in childhood suicide: An Adolescent Brain and Cognitive Development (ABCD) Study

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Impulsivity and Brain Organization in Childhood Suicide: An Adolescent Brain and Cognitive Development (ABCD) Study

by

Katherine C. Lopez

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The Graduate School
of Washington University in
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requirements for the degree
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Katherine C Lopez

Washington University in St. Louis

August 2021
ABSTRACT OF THE DISSERTATION

Impulsivity and Brain Organization in Childhood Suicide: An Adolescent Brain and Cognitive Development (ABCD) Study

by
Katherine C. Lopez

Doctor of Philosophy in Brain and Psychological Sciences
Washington University in St. Louis, 2021
Professor Deanna Barch, Chair

Rates of suicide have steadily increased across all age cohorts, revealing a particularly concerning rise in suicide among much younger age groups (10-15 years old). Recent efforts aimed at understanding suicide in youth have leveraged work from the adult literature to more pointedly examine candidate risk factors associated with childhood suicide. A noteworthy body of work has begun to clarify the role that impulsivity plays in elevating suicide risk among adults and adolescents, a critical link warranting further research in childhood suicide given the vast and well-documented changes occurring in self-control and brain maturity throughout development. Here, we examined a large and representative sample of children endorsing lifetime suicide ideation \((N=849)\), suicide attempt \((N=186)\), and no history of suicide \((N=10,754)\) from the Adolescent Brain and Cognitive Development Study, with a particular interest in delineating group differences in 1) cognitive measures of impulsivity (i.e., set-shifting, working memory, inhibition); 2) personality measures of impulsivity (i.e., five trait impulsivity dimensions) and; 3) several properties of brain organization relevant to self-control (i.e., whole-brain topology, network topology of control networks, and connector hubs). Using multilevel modeling to account for the tiered nature of our dataset (Level 1: Child; Level 2: Family; Level 3: Site), our findings revealed that suicide ideation was marked by broad elevations in trait impulsivity while suicide attempt was better characterized by a dual profile of set-shifting deficits and elevations in urgency measures in girls (only elevated urgency measures in boys).
Behavioral profiles in attempters were accompanied by disruptions in several connector hubs, with greatest evidence for altered hubness in the dorsolateral prefrontal cortex (DLPFC) of the frontoparietal network (FPN) relative to ideators. These hub profiles, however, did not emerge as a mechanism by which impulsivity distinguished ideators from attempters, underscoring a dominant view that the shift from ideation to attempt is likely characterized by a complex and interacting profile of emotional, cognitive, environmental, and neural variables. Together, these findings provide supporting evidence for the roles that impulsivity and frontoparietal regions play in suicide ideation and attempt during childhood, overall extending adolescent- and adult-like profiles of suicide into much younger periods of development.
Introduction

Rates of suicide have increased worldwide, with the United States having seen a 25% rise in deaths by suicide in the past decade (Curtin, Warner, Hedegaard, Warner, & Curtin, 2016; Stone et al., 2018). While death by suicide is highest among adults, a disproportionate increase in ideation and attempts have been reported in youth. Indeed, death by suicide represents the second leading cause of death among children and adolescents, with approximately 12% of youth endorsing suicidal thoughts while 4% have attempted suicide (Nock et al., 2013; Patton et al., 2009). Critically, rates of ideation, attempt, and completed suicide are projected to climb in forthcoming years, underscoring the need to better understand the emotional, cognitive, and neurobiological risk factors that place youth at increased risk for the emergence of suicidal thoughts and transition from thoughts to attempts.

Current models of suicide— informed predominantly by evidence in adults— have identified a number of risk factors associated with suicidal behaviors, including the presence of mental disorders (e.g., mood disorders), negative life events, hopelessness, and impulsivity (Bertolote & Fleischmann, 2005; Brown, Beck, Steer, & Grisham, 2000; Rihmer, 2007). The recent implementation of the ideation-to-action framework, which studies the development of suicidal thoughts and the transition from thoughts to attempt as separate processes, has begun to disentangle how these previously identified risk factors differentially predict suicide ideation and suicide attempt. For example, severity of depressive symptoms, hopelessness, perceived burdensomeness, social disconnection, and bullying among children and adolescents appear to better predict suicide ideation, whereas acquired capability and mental imagery of death (i.e.,
ability to visualize one’s own death) are more strongly linked to attempt (Klonsky & May, 2010; Massing-Schaffer et al., 2018; Valderrama, Miranda, & Jeglic, 2016; Van Orden et al., 2010; Yen et al., 2009). Within this growing picture of suicide risk factors, there has been accumulating evidence suggesting that different aspects of impulsivity may play separate roles in the emergence of suicidal thoughts and the shift from thoughts to attempts, a particularly important profile to better delineate in early development, given well documented changes in self-control occurring throughout childhood and adolescence.

Impulsivity is considered a multidimensional construct, composed of cognitive processes (e.g., executive abilities, personality traits (e.g., trait impulsivity), and behavioral and emotional tendencies (e.g., externalizing tendencies) found to underpin impulsive behaviors. Early theories of suicide have posited that impulsivity might act to precipitate the transition from ideation to attempt (e.g., Baumeister, 1990), such that individuals endorsing suicidal thoughts, who were additionally more impulsive, had greater likelihood of attempting suicide. Evidence for this theory, however, has been mixed, with no clear consensus on which components of impulsivity best predict ideation versus attempt, an issue that has been partly hampered by the various ways impulsivity has been operationalized (discussed below and also in Bagge et al., 2013; Sharma, Markon, & Clark, 2014). As a result, only a minority of suicide models have formally incorporated impulsivity into their theoretical frameworks, with even fewer working theories having considered how impulsivity might interplay with a host of age-related changes (i.e., cognitive, emotional, and neural modifications) to elevate suicide risk in much younger stages of development. Importantly, given that impulsivity and self-control are among several factors considered in determining the imminence of suicide in clinical settings (e.g., Bryan & Rudd, 2006) and an increasing number of suicide risk assessments being conducted in younger samples,
it remains an ongoing priority for researchers and clinicians to more precisely understand how impulsivity might confer differential risk for suicide ideation and attempt during childhood.

**Conceptualizing Impulsivity: Cognitive and Personality Constructs**

Prominent models have examined impulsivity in two primary ways: as a state-based cognitive construct and as a trait-based personality construct (Evenden, 1999; Nigg, 2000, 2017; Swann, Bjork, Moeller, & Dougherty, 2002; Whiteside & Lynam, 2001). This has generated separate patterns of findings in the suicide literature: 1) impairment in executive abilities, a collection of top-down control processes that enable goal-directed behavior, including set-shifting abilities (mental flexibility), working memory (updating), and inhibition, as well as more complex process such as planning and decision-making and; 2) elevations in trait impulsivity, enduring dispositions for rash behavior, including elevated urgency, lack of perseverance, lack of planning, and sensation seeking.

From a cognitive framework, impulsivity has been defined as a state-based construct (i.e., low inhibitory control), measured via laboratory-based tasks assessing proponent response inhibition, interference control, proactive interference during working memory, and delay gratification (M. A. Cyders & Coskunpinar, 2011). Along with other aspects of executive impairments thought to overlap with cognitive impulsivity (e.g., poor set shifting, planning, decision-making; Evenden, 1999; Rochat et al., 2013; Sharma et al., 2014; Sweitzer, Allen, & Kaut, 2008), an emerging body of neuropsychological literature has provided some evidence to suggest that suicide ideation may be characterized by global executive dysfunction, including impairments in attention, inhibition, and set shifting, (Burton, Vella, Weller, & Twamley, 2011; S. J. Kim et al., 2015; Marzuk, Hartwell, Leon, & Portera, 2005; Pu, Setoyama, & Noda, 2017;
Saffer & Klonsky, 2018). By contrast, suicide attempt appears to be marked by even greater impairments in decision-making abilities, inhibition (Burton et al., 2011; Clark et al., 2011; Alexandre Y. Dombrovski et al., 2010; Dougherty et al., 2004; Saffer & Klonsky, 2018; Szanto et al., 2015), and possibly set-shifting (also referred to as mental flexibility McGirr, Dombrovski, Butters, Clark, & Szanto, 2012; Miranda, Valderrama, Tsypes, Gadol, & Gallagher, 2013; Valderrama et al., 2016). Similar profiles of executive impairments have emerged in adolescents (mean age= 17 years old). For example, adolescent female ideators have been reported to display greater impairments in attention and executive abilities as ideation severity increases (S. J. Kim et al., 2015), while adolescent attempters appear to show greater difficulties with inhibitory control and decision-making (Ackerman et al., 2015; Bridge et al., 2012; Horesh, 2001; Stewart et al., 2017). Although no known study has yet to examine the neuropsychological profiles of suicide in much younger children, preschoolers endorsing ideation appear to display a fixation with death (Tishler, Reiss, & Rhodes, 2007), raising the possibility that cognitive underpinnings of perseverative thinking (i.e., set-shifting) may be at play as young as 5-6 years old.

Overall, these findings suggest that several executive abilities might be important for understanding suicide in youth. Specifically, global executive dysfunction may play a role in the development of suicidal thoughts while deficits in inhibitory control and decision-making may contribute to the transition from ideation to attempts. Notably, because many of these abilities are in flux over the course of development, it remains to be determined the extent to which executive dysfunction in suicidal youth deviates from normative trajectories of executive maturity.

Impulsivity has also been conceptualized as a personality construct, also referred to as trait impulsivity, which is thought to represent more enduring dispositions for rash behavior. Though
several scales have been used to study trait impulsivity in suicide, multidimensional measures appear to best distinguish traits predicting ideation from traits predicting attempt (Klonsky & May, 2010). Multidimensional measures, such as the UPPS-P, distills impulsivity into five dimensions: negative urgency (the tendency to act rashly in the face of extreme negative mood), positive urgency (acting rashly in the face of extreme positive mood), lack of premeditation (tendency to behave without planning), lack of perseverance (tendency for boredom), and sensation seeking (tendency to seek novel or exciting experiences; Whiteside & Lynam, 2001). Elevations in negative urgency and lack of premeditation have been most frequently reported in suicide ideation (Klonsky & May, 2010; Millner et al., 2020), though higher levels of lack of perseverance and sensation seeking in adolescents have also been described (Lynam, Miller, Miller, Bornovalova, & Lejuez, 2011; Ortin, Lake, Kleinman, & Gould, 2012). Suicide attempt, on the other hand, appears to be marked by additional elevations in lack of premeditation and, in some cases, negative urgency (Klonsky & May, 2010; Lynam et al., 2011; Millner et al., 2020). Given these trends, it is possible that childhood ideation may be characterized by broad elevations in trait impulsivity, while attempters may display additional elevations in lack of premeditation.

Based on these separate lines of findings, it is feasible to reason that global executive dysfunction evident in the neuropsychological literature might be related to broad elevations in trait impulsivity, while additional impairments in decision-making and inhibitory control may be related to (or capturing significant overlapping variance in) lack of premeditation and urgency measures apparent among attempters. Existing work examining the overlap between these two conceptualizations of impulsivity have, at best, shown modest associations in healthy controls (e.g., high urgency with deficits in inhibitory control, lack of premeditation with decision making
impairments (Gay, Rochat, Billieux, d’Acremont, & Van der Linden, 2008; Rochat et al., 2013). Most studies, however, have been unsuccessful in reproducing such relationships in either healthy samples (Bagge et al., 2013; M. A. Cyders & Coskunpınar, 2011; Reynolds, Penfold, & Patak, 2008) or in individuals endorsing suicide (Bridge et al., 2012; Jollant et al., 2005; Keilp, Gorlyn, Oquendo, Burke, & Mann, 2008; Swann et al., 2005). Thus, although executive dysfunction and trait impulsivity dimensions might be capturing some overlapping variance, they likely represent two dissociable mechanisms of impulsivity, both of which may be contributing to the development of suicidal thoughts and the transition from thoughts to action in different ways. More specifically, global executive dysfunction and broad elevations in trait impulsivity may play separate roles in the development of suicidal thoughts, while additional impairments in select executive abilities (i.e., decision-making, inhibition) and elevation in certain dimensions of trait impulsivity (i.e., lack of preméditation, negative urgency) may better characterize attempters. The majority of this work, however, has been studied in adult and adolescent populations; thus, it remains to be determined whether such dissociable profiles of impulsivity can be replicated in much younger populations endorsing ideation and attempt. Such work has the potential to shed light on the continuity that executive impairments and trait impulsivity may have on suicide over the course of development, with implications for further investigating how more proximal, time-varying risk factors might interact with these impulsivity predictors to heighten suicide risk.

Notably, these two conceptualizations of impulsivity, especially the potential involvement of executive dysfunction, offer several theoretical leads that can better inform neuroimaging work aimed at characterizing neural markers of suicide ideation and those distinguishing ideation and attempt.
Neural Correlates of Suicide

Currently, the neuroimaging research in suicide is small, with too few studies within a given modality to adequately conduct meta-analyses. Despite this, several qualitative reviews—based on findings of primarily suicide attempt—have implicated structural, functional, and connectivity disruptions in the dorsolateral prefrontal cortex (DLPFC; BA 9/46), ventrolateral prefrontal cortex (VLPFC; BA 44/45) dorsal anterior cingulate cortex (dACC), insula, inferior and superior parietal cortices (BA 40/7) and subcortical structures (e.g., basal ganglia; Bani-Fatemi et al., 2018; Cox Lippard, Johnston, & Blumberg, 2014; Schmaal et al., 2020). These findings have been largely discussed as frontostriatal dysfunction, with a focus on how such circuit-level disruptions may underpin cognitive impairments in suicide (A. Y. Dombrovski et al., 2012; Ho et al., 2018; Jia et al., 2014; Myung et al., 2016). Recent work conducted on larger sample sizes, however, have yielded mixed evidence for striatal dysfunction (Rentería et al., 2017; van Heeringen, Bijttebier, Desmyter, Vervaet, & Baeken, 2014) and, in conjunction with evidence of dysfunction in other brain regions falling outside typical frontostriatal circuitry (e.g., parietal cortices; Johnston et al., 2017; Monkul et al., 2007; Schreiner, Klimes-Dougan, & Cullen, 2019), neuroimaging work in suicide has progressively shifted from a more focal examination of frontostriatal dysfunction to broader network-level dysfunction via resting state fMRI (J. Hwang et al., 2018; Jung et al., 2020; Kang et al., 2017; Ordaz, Goyer, Ho, Singh, & Gotlib, 2018; Schwartz, Ordaz, Ho, & Gotlib, 2019).

By correlating spontaneous low-frequency brain activity between remote regions of the brain during rest, studies using resting state fMRI have revealed a number of robust and dissociable functional networks (Biswal, Zerrin Yetkin, Haughton, & Hyde, 1995; Fox & Raichle, 2007; Greicius, Krasnow, Reiss, & Menon, 2003; Snyder & Raichle, 2012). Functional networks
emerging from the suicide literature implicate alterations in the frontoparietal network (FPN—involved in initiating and flexibly adjusting control); the cingulo-opercular (also known as the salience network; CON—involved in the maintenance of tasks); and, to a lesser extent, ventral attention network (VAN—implicated in bottom-up attention processing; Corbetta, 1998; Dosenbach et al., 2007; Ptak, Schnider, & Fellrath, 2017; Vossel, Geng, & Fink, 2014) The emergence of these networks, often referred to as control networks, is particularly noteworthy given that regions of dysfunction commonly reported in suicide (e.g., DLPFC, dACC and insula, VLPFC) represent key anchors of these control networks (e.g., FPN, CON, VAN, respectively)

Characterizing the ways in which control networks are differentially altered in suicide ideation and attempt—and their relation to executive abilities and trait impulsivity—may begin to refine our understanding of the mechanisms by which impulsivity may heighten risk for suicide-related thoughts and how such thoughts might go about actualizing into suicidal behaviors. An area of particular interest is the study of brain organization, which has accumulated considerable evidence for its role in supporting various cognitive abilities. One prominent finding emerging from this line of work is that the brain is marked by a mostly modular organization, with greater connections among brain regions belonging to the same network (i.e., segregation) and simultaneously fewer connections between brain regions of distinct networks (i.e., integration). Whereas segregation is thought to facilitate the processing of specialized network functions, integration is theorized to facilitate coordinated and effective cross talk between networks. By virtue of this segregation-to-integration balance, the brain has the ability to maintain local network specialization while fostering selective global processing in a way that minimizes metabolic cost and preserves neural homeostasis (Cohen & D’Esposito, 2016; De Pasquale et al., 2013; Rubinov & Sporns, 2010; Shine, Aburn, Breakspear, & Poldrack,
Recent developmental studies have expanded on this work by demonstrating that most networks—including several control networks implicated in suicide (e.g., FPN, DAN, VAN)—display patterns of increasing modularity from childhood into adolescence, with only certain networks showing clear signs of age-related integration (e.g., CON). Of importance, both segregation and integration bear meaningful relationships to evolving capacities for self-control (J. R. Cohen & D’Esposito, 2016; Grayson & Fair, 2017; Grayson et al., 2014; Gu et al., 2015; Lopez, Kandala, Marek, & Barch, 2020; Machida & Johnson, 2019; Marek, Hwang, Foran, Hallquist, & Luna, 2015a; Tononi, Edelman, & Sporns, 1998), and thus may have important implications for understanding cognitive dysfunction in suicide.

Segregation and integration have traditionally been inferred through connectivity profiles and, more recently, quantified through graph theory measures that assess network organization. Using connectivity profiles, in which patterns of within-network connectivity are typically used to infer segregation and between-network connectivity as integration, studies provide some evidence for potential segregation disruptions of control networks in suicide. Specifically, Ordaz and colleagues (2018) found that increasing ideation severity in adolescents was associated with reduced connectivity within a functionally equivalent network to the FPN (i.e., ‘executive control network’) and, moreover, that acute longitudinal improvements in ideation severity were linked to increased connectivity within a functionally equivalent network to the CON (i.e., ‘salience network,’ Ordaz et al., 2018; Schwartz et al., 2019). Additionally, adolescent suicide attempters display profiles of reduced connectivity within the FPN and CON, as well as elevated increased connectivity between these two networks (Jung et al., 2020). Together, these findings provide initial evidence of potential segregation disruptions in at least two control networks.
known to play dissociable roles in supporting higher-order cognition (Dosenbach et al., 2007), like executive abilities (Wallis, Stokes, Cousijn, Woolrich, & Nobre, 2015).

More recently, the application of graph theory techniques on resting state data has provided an instrumental way to quantify properties of segregation and integration. By conceptualizing the brain as a graph, composed of brain regions (nodes) and connections between regions (edges), graph theory quantifies the physical arrangement of nodes and edges within a given network and between networks. Such a framework has the benefit of providing a finer-grained measurement of segregation and integration at both the whole-brain level (global topology) and network-level (network topology; Bullmore & Sporns, 2009; Mohr et al., 2016; Rubinov & Sporns, 2010a, 2010b; Sporns, 2013). As such, if suicide ideation is indeed associated with reduced FPN and CON within-network connectivity (suggestive of segregation), graph theory measures would be able to replicate network-level disruptions in segregation and determine whether such segregation alterations are also observed at the whole-brain scale. Additionally, graph theory has the benefit of interrogating organizational properties at the region/hub-level, with the ability to examine a hub’s importance in supporting segregation and integration properties. For example, the DLPFC of the FPN, VLPFC of VAN and dACC of CON all represent connector hubs, showing a relatively greater number of between-network connections (higher hubness; K. Hwang, Hallquist, & Luna, 2013; Powers, 2010; van den Heuvel & Sporns, 2013), and thus considered to be more central players in network organization than non-hub regions. Indeed, a number of connector hubs have been shown to regulate connectivity of other nodes to enhance greater overall network segregation while fostering selective integration between networks (Bertolero, Yeo, Bassett, & D’Esposito, 2018). By contrast, disruptions to connector hubs have been associated with widespread alterations in segregation (Gratton, Nomura, Pérez, &
D’Esposito, 2012). If suicide ideation and attempt are in fact characterized by alterations in segregation, graph theory measures have the potential to determine whether such disruptions are due to hub alterations.

Taken together, suicide ideation in childhood may be characterized by global executive dysfunction and broad elevations in trait impulsivity, while suicide attempt may be marked by added impairments in only certain areas of executive functions and trait impulsivity. Such behavioral differences may be paralleled by separate neural profiles distinguishing children ideators and attempters, particularly in brain properties commonly implicated in executive control, including segregation, integration, and connector hubs.

**Current Study**

To test these lines of inquiry, the present study sought to (1) replicate profiles of executive and personality (trait) measures of impulsivity in much younger samples of children endorsing suicide ideation, attempt, and no suicide history; (2) examine organizational properties of control networks across suicide cohorts and; (3) assess whether such network properties serve as mechanisms by which impulsivity relates to suicide status. Given trends in the adolescent and adult literatures, we expect to find graded patterns of impulsivity, such that children with a history of attempt show greatest impairments in inhibitory control, lack of premeditation, and negative urgency relative to children endorsing ideation, whom in turn would show greater global executive impairments and broad elevations in trait impulsivity relative to those with no suicide history. To examine group differences in organizational properties of control networks, we examined whole-brain and network-level (i.e., FPN, CON, DAN, VAN) measures of segregation and integration, as well as connector hubs of each control network (i.e., DLPFC,
dACC, posterior DLPFC and VLPFC, respectively). Guided by our cognitive hypotheses, we expect to find tiered patterns of network disruptions, such that child attempters show greatest alterations relative to child ideators, whom in turn would show greater disruptions relative to children with no suicide history. Based on existing work, we expect to find disruptions primarily in segregation and hubness metrics. We anticipate such brain alterations to (1) show differential relationships to executive abilities and trait impulsivity and (2) mediate the relationship between impulsivity and suicide status (e.g., ideation and attempt). Ultimately, the overarching goal of this work is to build onto a growing profile of diverse risk factors that enable a more holistic understanding of how variables at different levels of analyses (i.e., neural to behavioral) are associated with the occurrence of suicidal thoughts and actions in much earlier periods of development.

**Methods and Materials**

**Study Design**

The three aims of the current study were examined in several steps, summarized in Figure 1. In an effort to reproduce dissociable profiles of impulsivity via cognitive and personality measurements (Aim 1), two measures of impulsivity—cognitive-based measures and personality-based measures—were compared between children with no suicide history and children endorsing ideation (i.e., Control v. Ideation), as well as between children with ideation and those with a history of attempt (i.e., Ideation v. Attempt). Notably, measures of impulsivity were modelled separately and then simultaneously to confirm whether these profiles were, in fact, independent from one another. Using a similar group difference design, three neural metrics were examined between suicide cohorts (Aim 2)—two whole brain topology measures, four
network topology measures (one for each control network: FPN, CON, DAN, VAN), and four connector hubs affiliated with each network (DLPFC, dACC, posterior DLPFC, and VLPFC).

We subsequently modeled the extent to which brain organization mediated the relationship between impulsivity measures and suicide status (Aim 3), examining indirect effects for impulsivity and neural variables that were significantly predicted by suicide status (i.e., those emerging as significant in Aims 1 and 2). Finally, to confirm that impulsivity measures demonstrate expected relationships to brain organization we examined brain-behavior relationships between all measures of impulsivity and brain metrics. Such relationships served to verify whether normative trajectories of brain organization relate to impulsivity measures in ways consistent with the literature. Better executive abilities, for example, should be associated primarily with evidence of increasing segregation (J. R. Cohen & D’Esposito, 2016; Dwyer et al., 2014; Wang, Hu, Weng, Chen, & Liu, 2020), whereas elevated trait impulsivity might be associated with increasing levels of integration.

**Participants**

Participants were 11,782 children aged 9-10 years old from the Adolescent Brain and Cognitive Development (ABCD) study, a large-scale, multisite, longitudinal study examining cognitive, emotional, and neural development in adolescents across 21 sites in the United States (Barch et al., 2018). Data from the first wave of the ABCD data (Release 2.01) were examined and included twin pairs and siblings across sites. Participants included in the present analyses completed: (1) the Kiddie Schedule for Affective Disorders and Schizophrenia for DSM-5 (KSADS-5); (2) ABCD Youth NIH Toolbox, with a focus on measures classified under the domain of executive functions; (3) UPPS-P- Impulsive Behavior Scale, Youth Version (UPPS-P-Y) and; (4) at least one resting-state fMRI scan.
Measures

Clinical Diagnostic Assessment
The KSADS-5 (Kaufman et al., 1997), a reliable and valid measure of psychopathology in youth, was used to identify children endorsing current or past suicidal thoughts, attempt, and those with no suicide history using both child and parent report. The KSADS-5 defines suicidal thoughts as a dichotomous measure (present/absent) of current or lifetime thoughts of self-injury with the intent of dying, thoughts of methods, or thoughts related to a specific plan but with no behavioral effort put forth to carry out such thoughts. Suicidal attempt, also a dichotomous metric, was considered to be any current or lifetime attempts that were interrupted, aborted, and/or behaviors made in preparation of suicide attempt. Children were placed into the lifetime ideation or lifetime attempt groups if suicide was endorsed either by the child themselves or their parent reported that their children endorsed suicidal tendencies. A total of 848 children were placed in lifetime ideation group (7%), 186 children in the lifetime attempt group (2%) , while the majority of children (10, 748) were placed in the control group (i.e., no reported history of suicide; 91%), figures that are generally consistent with rates of youth suicide in the general population (Cash & Bridge, 2009). To control for the effects of psychopathology, parent reported depressive symptoms from the Child Behavioral Checklist (CBCL; dimensional measure; Achenbach, 2009) and hopelessness from the KSADS-5 (dichotomous measure, both child and parent report) were used as covariates. Finally, to adjust for the effects of SES, we used parent responses from seven questions on the ABCD Longitudinal Parent Demographics Survey related to financial adversity (e.g., ‘needed food but couldn't afford to buy it or couldn't afford to go out to get it?’). These questions were yes/no responses; as such, overall cumulative scores were used as a measure of SES (range from 0-7).
Cognitive, state-based impulsivity: Executive Functions.

All participants completed the ABCD Youth NIH Toolbox, a well-validated comprehensive battery of cognitive, emotional, and motor assessments designed for children and adolescents (Bauer & Zelazo, 2013). Given that several lab-based measurements designed to assess impulsivity overlap with several components of executive functions (Bickel, Jarmolowicz, Mueller, Gatchalian, & McClure, 2012; Nigg, 2017; Sharma et al., 2014), we examined performance on three subtests classified under the domain of executive functions: the Flanker Inhibitory Control and Attention task, providing a measure of inhibitory control of prepotent responses; List Sorting Working Memory Test, tapping into updating and working memory abilities; and the Dimensional Change Card Sort Test, providing a measure of set-shifting. See Table 1 for a full description of these measures. Notably, these three domains of executive functioning have been implicated in at least suicide ideation (inhibitory in suicide attempt) and are consistent with Miyake’s (2001) conceptualization of executive functioning, which distills executive abilities into three dissociable components (i.e., inhibition, updating, and set-shifting Miyake et al., 2000). Notably, these domains of have been found to contribute to impulsivity to varying degrees (Bickel et al., 2012), and were therefore examined separately, rather than as an overall composite score of executive functioning. In addition to executive measures, we used performance on the NIH Toolbox Picture Vocabulary Test to control for the effects of estimated verbal IQ. Raw score measures of each task were converted into uncorrected standardized score (mean= 100, SD=15; age and sex used as covariates), which converts raw scores into a standard scale across all cognitive measures. Lower standardized scores denote greater cognitive impairment.

Personality, trait-based impulsivity: Trait Impulsivity
Trait impulsivity was measured using the short UPPS-P (UPPS-P) youth version, an abbreviated form of the UPPS-P Impulsive Behavior Scale adult version, originally developed by Whiteside & Lynam, 2001 and subsequently modified by Cyders & Smith, 2007. The psychometric properties of the UPPS-P were recently examined in the ABCD dataset, overall yielding a five-factor structure similar to the adult version, as well as good reliability and validity (Watts, Smith, Barch, & Sher, 2019). More specifically, five dissociable factors of dispositional trait impulsivity emerged: Negative Urgency, measuring one’s tendency to act rashly in the face of intense negative mood; Positive Urgency, examining one’s tendency to act rashly to extreme positive mood; Lack of Premeditation (also referred to as Lack of Planning), measuring one’s tendency for poor planning and weighing the consequences of one’s actions; Lack of Perseverance, indexing one’s difficulty to remain focused on difficult and/or mundane tasks and; Sensation Seeking, a tendency for seeking novel and exciting experiences. Higher scores on these subscales denote greater trait impulsivity.

**fMRI scanning and preprocessing**

All participants underwent a full scanning session on 3T scanners—Siemens Prisma, General Electric 750, or Philips depending on site. A complete description of ABCD image acquisition parameters and procedures is detailed in Casey, Tottenham, Liston, & Durston, 2005 and Hagler et al., 2018. The present study focused on participants with a resting state fMRI scan (600 frames, 8 min) and T1- and T2-weighted structural images (0.7mm isotropic). fMRI parameters were identical across scanners for resting state scans (TR = 800 ms, TE = 30 ms, field of view = 216x216, flip angle = 52°, matrix 90x90, 60 slices, voxel size = 2.4 × 2.4 × 2.4 mm), with images acquired on the axial plane using an EPI sequence. Participants were instructed to watch a movie quietly or look at a fixation crosshair. Due to concerns of head motion in younger
populations, (Fair et al., 2013; J. D. Power, Barnes, Snyder, Schlaggar, & Petersen, 2012; J. D. Power et al., 2014; Satterthwaite et al., 2012) a real-time head motion system was implemented in select sites with Siemens scanners to correct for movement based on a participant’s degree of head motion. (Dosenbach et al., 2017) Further, T1- and T2-weighted structural images were examined for cortical segmentation of the brain, parameters which varied across scanners (See https://abcdstudy.org/images/Protocol_Imaging_Sequences.pdf).

All resting-state scans for each participant underwent several preprocessing steps using the Multi-Model Pressing Stress software package. These steps included the (1) removal of initial frames; (2) normalization and detrending of voxel time series using mean time for each voxel; (3) regression of signals of non-interest, including quadratic trends, signals correlated with motion time courses, as well as, the mean time courses of white matter, ventricles, and whole brain measurements derived from Freesurfer (Fischl et al., 2002). As a final step, temporal band-pass filtering (0.009 and 0.08 Hz) was applied to remove respiratory artifact. Adolescents with resting state scans containing at least 600 frames with framewise displacement of <0.2 mm (i.e., low movement data) were included in the present analyses.

**Resting State Functional Connectivity Analyses**

Functional networks were defined by Gordon et al. (2016) parcellation scheme, in which boundary-map derived parcels were affiliated with one of 14 brain networks (Gordon et al., 2016). In the present study, we focused on control networks (See Figure 1B ‘Network Topology’) — the frontoparietal (FPN; yellow), cinguloopercular (CON; purple), dorsal attention (DAN; green), and ventral attention (VAN; cyan) networks. We used graph theory metrics to evaluate measures of whole brain segregation and integration (Figure 1B: ‘Whole Brain
Topology’), network-level topology measures for each control network (Figure 1B: ‘Network Topology’), and connector hubs affiliated with each control network (Figure 1B: ‘Hubs’).

First, Pearson’s r values were computed from the average BOLD time-series in each parcel, converting these r values to Fisher’s Z transforms. From these, 333x333 unthresholded whole-brain connectivity matrices were constructed for each participant. These matrices were rank ordered from strongest to weakest, then thresholded to retain the top 2-10% highest correlation coefficients, in 1% increments, for a total of 9 graphs for each participant. Such thresholding had the three-fold purpose of (1) facilitating graph comparison across ages given that graphs may exhibit differences in network density (i.e., distributions of correlation magnitude); (2) retaining the strongest correlations by eliminating connections that fall below the threshold (i.e., setting to r=0), thereby eliminating small correlations that may reflect noise and; (3) removing negative correlations (Powers, 2010). Additionally, the 2-10% density range was chosen so as to be most consistent with previous literature that has identified and reproduced canonical large-scale brain networks at the strongest 10% densities ((J. D. Power, Schlaggar, & Petersen, 2015; Yeo et al., 2011)

Next, graph theory algorithms were applied to each correlation matrix using the brain connectivity toolbox (http://www.brain-connectivity-toolbox.net). By conceptualizing the brain as a graph, composed of nodes (brain regions) and edges (connections between brain regions), graph theory allows the quantification of organizational properties at a whole-brain scale, network scale, and node scale (Bullmore & Sporns, 2009; Mohr et al., 2016; Rubinov & Sporns, 2010a, 2010b; Sporns, 2013). Here, we examine segregation and integration at a whole-brain level and network level while we hubs are examined at the node. Specifically, we examined whole-brain measures of segregation and integration via modularity and global efficiency,
respectively (Bullmore & Sporns, 2009). Modularity (Q) quantifies the overall number of connections within modules (intra-module edges) relative to the overall connections between modules (inter-module edges) across the brain. As such, modularity is thought to represent the extent to which the brain can be divided into segregated modules, such that higher modularity is characterized by a relatively greater number of within-network connections and concurrently fewer number of between-network connections. In contrast, global efficiency quantifies the average shortest path length across all connections in the brain, such that shorter average path length between brain regions across networks represents more efficient whole-brain information transfer (F. De Pasquale, Della Penna, Sporns, Romani, & Corbetta, 2016). Notably, both metrics provide a single global value of segregation and integration and, therefore, do not specify which networks, more specifically, are contributing to patterns of segregation and/or integration. To evaluate network-level topology, participation coefficient at the network scale was calculated for each control network of interest. For a given network (e.g., FPN), the total number of connections a particular node has with nodes belonging to other networks is calculated (nodal participation coefficient), then collapsed across all nodes for a given module, yielding an overall network estimate of intra-module connection density (Satterthwaite et al., 2015). Higher values (closer to 1) represent a network that is more diversely connected whereas lower values (closer to 0) represent a network more cohesively segregated. Finally, level of hubness of four connector hubs were assessed via node-level participation coefficient. Canonical connector hubs of each network were examined (See Figure 1B ‘Hubs): the DLPFC of the FPN (BA 46; yellow); dorsal ACC of the CON (BA 32; purple); posterior DLPFC of the DAN (BA 9; green) and; the VLPFC of the VAN (BA 45; cyan). Higher nodal participation coefficient represents greater between-network connections (or hubness).
**Statistical analysis**

Due to the nested structure of the current dataset, in which a subset of children are nested within families (e.g., siblings) and all children clustered within one of 21 different sites, we employed hierarchical linear models to account for dependencies in family units (level 2) and acquisition sites (level 3). In particular, each model specified family units and acquisition sites as random intercepts while predictors were specified as fixed effects.

**Aim 1:** The first set of models examined the relationships of suicide status to three measures of executive functioning (i.e., set shifting, working memory, inhibition) and five dimensions of trait impulsivity (i.e., negative urgency, positive urgency, lack of perseverance, lack of planning, sensation seeking). Suicide status was defined as a three-level categorical variable, yielding two primary contrast variables: Control v. Ideation and Ideation v. Attempt. Each model controlled for the effects of age (in months), sex, IQ, SES, depressive symptoms, and hopelessness symptoms. Additionally, a subsequent ‘suicide status by gender’ interaction was performed to examine sex differences in cognitive- and personality-based impulsivity. False Discovery Rates (p<0.05) was applied within each behavioral domain to correct for multiple comparisons (e.g., across executive functions, separately for children in the control, ideation, and attempt groups). Finally, for all significant models showing differences between Ideators and Attempters, post-hoc analyses modeling Attempt v. Controls were conducted to confirm that attempters showed executive impairments (or elevated trait measures) relative to both ideators and controls.

**Aim 2:** The second set of models examined the relationships of suicide status to two measures of whole brain topology (i.e., modularity, global efficiency), four measures of network topology (i.e., average participation coefficient for FPN, CON, DAN, and VAN), and four connector hubs (i.e., DLPFC of FPN, dACC of CON, posterior DLPFC of DAN, and VLPFC of
VAN). These models included all previously mentioned covariates, in addition to framewise displacement and numbers of frames retained to further adjust for motion confounds. Sex differences were examined, FDR correction was applied within network organization property (e.g., across whole-brain metrics, separately for controls, ideation, and attempt), and post-hoc analyses comparing metrics between attempters and controls were examined, again to confirm that attempters displayed impairments relative to both controls and ideators.

**Aim 3:** The final set of models examined the indirect (mediating) effects of brain metrics on the association between cognition/trait impulsivity and suicide status. Notably, these were only for findings that survived FDR correction. Mediation models were fit within a Structural Equation Modeling (SEM) framework using Lavaan to simultaneously model three distinct paths (See Figure 1C; Rosseel, 2012): (a) direct relationships between impulsivity measures and Suicide Status; (b) direct relationships between impulsivity measures and organization brain metrics and; (c) direct associations between organization brain metrics and Suicide Status as, well as an inferred relationship (d) the indirect effects of organization brain metrics in the relationship between impulsivity measure and Suicide Status. Additionally, because of the three-tiered nature of the dataset, we took a multi-group mediation approach, in which mediation models were conducted separately for singleton children (unclustered data) and siblings (clustered data), controlling for the effects of data acquisition site and all prior covariates. Children were collapsed into a single mediation analysis only if models were to show significant mediations effects.

**Confirmatory Analyses:** Finally, to ensure that impulsivity demonstrated expected relationships to brain organization—e.g., low impulsivity was is associated with mostly segregated networks—confirmatory brain-behavior relationships between impulsivity and *all*
brain organization metrics were examined. Here, we include all measure of brain organization, not just metrics predicted by suicide status, to corroborate the relationship between low impulsivity and mostly segregated networks suggested by the literature. For each brain metric (e.g., segregation), FDR was applied within behavioral variable (e.g., across all segregation measures within set-shifting). Findings that survived multiple comparisons are reported below and all data are summarized in Supplement Tables 1 and 2.

Results

Demographic and behavioral associations

Table 2 summarizes demographic information, as well as motion parameters across suicide cohorts. Briefly, there was a larger percentage of male children across ideators and attempters, with comparable distribution of genders between ideators and controls. As expected, attempters showed greatest cumulative depressive symptoms, followed by ideators, then control children. Although SES levels did not differ across groups, estimated verbal IQ was significantly lower in attempters relative to ideators. With respect to motion parameters, the total numbers of frames retained was significantly lower in attempters relative to ideators, although average framewise displacement did not differ. Overall, demographic and motion artifact differences were primarily observed between ideators and attempters; as such, these variables were statistically controlled for in all analyses.
Relationships between measures of executive functioning, trait impulsivity, and age are depicted in Figure 2A. Generally, executive abilities were modest-to-moderately associated with one another, with set-shifting and inhibitory control showing the strongest associations. Consistent with normative trajectories of cognition, all components of executive functioning demonstrated significant age-related improvements. Similarly, most trait impulsivity measures displayed significant associations with one another, also ranging from modest to moderate. Sensation Seeking, however, was an exception, showing low associations with Lack of Planning and a negative relationship to Lack of Perseverance. Of all trait impulsivity measures, only Positive Urgency and Lack of Perseverance displayed age-related elevations during late childhood. Notably, executive abilities and trait impulsivity measures generally demonstrated expected negative correlations, such that poor executive performance was modestly-to-moderately related to elevated trait impulsivity. Overall, these findings provide confirmatory evidence that poorer executive abilities are generally, though somewhat modestly, associated with higher trait impulsivity.

**Suicide status relationships to executive functioning and trait impulsivity**

As shown in Figure 2B, while the Control v. Ideation group did not predict performance on any measure of executive functioning, the Ideation v. Attempt group contrast significantly predicted set-shifting performance, such that children with a history of suicide attempt displayed poorer set-shifting performance than children endorsing ideation (b= -3.75, T= -3.02, p=0.002, R²(fixed)= 0.11; Figure 2). A follow up analysis using an Attempt v. Control contrast variable confirmed that attempters also displayed poorer performance than Controls b= 4.06, T= 3.60, p<0.001, R²(fixed)= 0.11). Models testing for gender interactions indicated that only females displayed set shifting differences between ideators and attempters (b= 4.44, T= 2.69, p=0.007,
Overall, these findings indicate that female attempters displayed greater set shifting impairment than both female ideators and controls (depicted in Figure 2B).

Models predicting trait impulsivity measures revealed a two-fold profile (Summarized in Figure 2C). First, the Control v. Ideation group significantly predicted negative urgency ($b = -1.17$, $T = -10.48$, $p = 0.000$, $R^2_{\text{fixed}} = 0.05$), positive urgency ($b = -0.93$, $T = -7.44$, $p = 0.000$, $R^2_{\text{fixed}} = 0.05$), lack of perseverance ($b = -0.67$, $T = -6.98$, $p = 0.000$, $R^2_{\text{fixed}} = 0.04$), and lack of planning ($b = -0.86$, $T = -8.52$, $p = 0.000$, $R^2_{\text{fixed}} = 0.11$). For each of these effects, ideators displayed significantly elevated trait impulsivity scores than controls. Second, the Ideation v. Attempt group predicted negative urgency ($b = 0.85$, $T = 3.51$, $p = 0.000$, $R^2_{\text{fixed}} = 0.05$) and positive urgency ($b = 0.79$, $T = 2.91$, $p = 0.003$, $R^2_{\text{fixed}} = 0.05$), such that attempters displayed significantly elevated urgency scores than ideators (See Figure 3A). Follow up analyses indicated that attempters’ elevations of negative and positive urgency were also significantly different from controls ($b = -2.02$, $T = -9.02$, $p = 0.000$, $R^2_{\text{fixed}} = 0.05$) Notably, no sex differences were observed for any trait impulsivity measure. Overall, these findings indicate that ideators displayed broad elevations in four trait impulsivity measures, with attempters displaying additional elevations in negative and positive urgency. Given this pattern of findings, it appears that only negative and positive urgency displayed the graded pattern of impulsivity elevations we had hypothesized, such that attempters displayed greatest elevations, followed by ideators, then controls.

Finally, to determine whether reductions in set shifting performance and concurrent elevations trait impulsivity scores observed among attempters were dissociable from one another, three follow-up models were conducted; one model predicting set-shifting with negative and positive urgency as additional covariates and two models predicting negative urgency and
positive urgency, separately, with scores on the Dimensional Card Sort Task as an added covariate. All models—set shifting (b= -3.72, T= -3.01, p=0.002; including gender effects), negative urgency (b= 0.85, T= 3.49, p=0.000), and positive urgency (b= 0.77, T= 2.84, p=0.004)— held significance, suggesting that set-shifting impairments and urgency elevations represent dissociable profiles of impulsivity in attempters.

**Suicide status relationships to segregation, integration, and hubness.**

Both the Control v. Ideation and Ideation v. Attempt groups failed to predict differences in whole brain topology (i.e., modularity and global efficiency), network-level topology of control networks, and hubs. However, the Ideation v. Attempt group did significantly predict hubness of the DLPFC of FPN (b= 0.03, T= 2.37, p=0.02, R\textsuperscript{(fixed)}= 0.09), VLPFC of VAN (b= 0.03, T= 2.18, p=0.03, R\textsuperscript{(fixed)}= 0.10), and dACC of the CON (b= -0.04, T= -2.36, p=0.02, R\textsuperscript{(fixed)}= 0.15). Specifically, child attempters displayed higher levels of hubness in the DLPFC of FPN and VLPFC of the VAN relative to ideators, suggesting that these connector hubs display greater number of between-network connections among attempters. Interestingly, child attempters displayed lower average levels of hubness in the dACC of the CON relative to ideators, suggesting that dACC show reductions in the number of between-network connections among attempters.

Secondary analyses modeling Attempt v. Control revealed group differences only in the DLPFC of FPN (b= -0.045.02, T= -1.99, p=0.04, R\textsuperscript{(fixed)}= 0.03) but not the VLPFC of the VAN (b= -0.017, T= -1.01, p=0.04, R\textsuperscript{(fixed)}= 0.31) or dACC of the CON (b= -0.00, T= -0.039, p=0.69, R\textsuperscript{(fixed)}= 0.00). Thus, despite hubness differences between ideators and attempters across most connectors, clear evidence of hubness alteration in attempters is observed for the DLPFC of the FPN (Figure 3)
Mediation suicide status effects on executive functioning and trait impulsivity through brain organization.

Having found group differences between ideators and attempters in set-shifting, negative urgency, positive urgency, as well as concurrent alterations in DLPFC, VLPFC, and dACC hubness, we sought to determine whether these hubness disruptions might be a plausible mechanism by which impulsivity might elevates risk for transitioning from ideation to attempt. To this end, we examined whether variations in impulsivity (cognitive and personality measures) predicted individual differences in hubness of each connector hub and, subsequently, whether these connector hubs mediated the relationship between impulsivity and suicide status (i.e., Ideation v. Attempt). Thus, three sets of mediation models were fit for each connector hub, using a multi-group mediation approach to address the three-tiered nature of the dataset. This approach modeled singleton children (unclustered data) separately from siblings (clustered data), controlling for the effects of data acquisition site. Children were collapsed into a single overall meditation model only if groups showed significant effects that were statistically equivalent (i.e., significant mediation effects in both singletons and siblings).

**DLPFC of FPN** (Figure 4A): For set-shifting, models for siblings (clustered) and singletons (unclustered) demonstrated generally adequate fit ($\chi^2$(overall)$=19.974$, $\chi^2$(Singleton)$=5.175$, $\chi^2$(Siblings)$=14.799$, $df=17$, $p=0.009$, RMSEA=0.024 (0.000–0.059), CFI=0.595, SRMR=0.003); however, neither model showed significant mediating effects ($p_{\text{singleton}}=0.824$; $p_{\text{sibling}}=0.254$). Clustered and unclustered models demonstrated better fits for negative urgency ($\chi^2$(overall)$=18.106$, $\chi^2$(Singleton)$=4.751$, $\chi^2$(Siblings)$=13.355$, $df=17$, $p=0.031$, RMSEA=0.014 (0.000–0.054), CFI=0.775, SRMR=0.001) and positive urgency ($\chi^2$(overall)$=19.445$, $\chi^2$(Singleton)$=4.993$, $\chi^2$(Siblings)$=14.452$, $df=17$ $p=0.015$, RMSEA=0.022 (0.000–0.058),
CFI=0.617, SRMR=0.001). However, neither displayed significant mediating effects (Negative Urgency: \( p_{\text{singleton}}=0.205; p_{\text{sibling}}=0.323 \); Positive Urgency: \( p_{\text{singleton}}=0.845; p_{\text{sibling}}=0.130 \)).

**VLPFC of VAN** (Figure 4B): Models for siblings (clustered) and singletons (unclustered) also demonstrated adequate fit for set shifting \( (\chi(\text{overall})^2=27.082, \chi(\text{Singleton})^2=9.084, \chi(\text{Siblings})^2=17.999, \text{df}=17, p=0.033, \text{RMSEA}=0.044 (0.000–0.073), \text{CFI}=0, \text{SRMR}=0.001) \), which did not show significant mediating effects \( (p_{\text{singleton}}=0.641; p_{\text{sibling}}=0.193) \). Models demonstrated a poor fit for negative urgency \( (\chi(\text{overall})^2=26.148, \chi(\text{Singleton})^2=8.3889, \chi(\text{Siblings})^2=17.259, \text{df}=17, p=0.027, \text{RMSEA}=0.042 (0.000–0.072), \text{CFI}=0, \text{SRMR}=0.000) \) but better fit for positive urgency \( (\chi(\text{overall})^2=28.164, \chi(\text{Singleton})^2=9.654, \chi(\text{Siblings})^2=18.511, \text{df}=17, p=0.019, \text{RMSEA}=0.046 (0.008–0.075), \text{CFI}=0, \text{SRMR}=0.000) \). However, neither displayed significant mediating effects (Negative Urgency: \( p_{\text{singleton}}=0.638; p_{\text{sibling}}=0.531 \); Positive Urgency: \( p_{\text{singleton}}=0.764; p_{\text{sibling}}=0.521 \)).

**dACC on CON** (Figure 4C): Finally, models demonstrated adequate fit for set-shifting \( (\chi(\text{overall})^2=19.974, \chi(\text{Singleton})^2=5.175, \chi(\text{Siblings})^2=14.799, \text{df}=17, p=0.276, \text{RMSEA}=0.024 (0.000–0.059), \text{CFI}=0.595, \text{SRMR}=0.003) \); however, neither model showed significant mediating effects \( (p_{\text{singleton}}=0.824; p_{\text{sibling}}=0.254) \). Models demonstrated good fit for negative urgency \( (\chi(\text{overall})^2=18.106, \chi(\text{Singleton})^2=4.751, \chi(\text{Siblings})^2=13.355, \text{df}=17, p=0.382, \text{RMSEA}=0.014 (0.000–0.054), \text{CFI}=0.775, \text{SRMR}=0.001) \); and positive urgency \( (\chi(\text{overall})^2=19.445, \chi(\text{Singleton})^2=4.993, \chi(\text{Siblings})^2=14.452, \text{df}=17, p=0.015, \text{RMSEA}=0.022 (0.000–0.058), \text{CFI}=0.617, \text{SRMR}=0.001) \). Neither model showed significant mediating effects (Negative Urgency: \( p_{\text{singleton}}=0.205; p_{\text{sibling}}=0.323 \); Positive Urgency: \( p_{\text{singleton}}=0.845; p_{\text{sibling}}=0.130 \)). All mediating effects are summarized in Figure 4.
Confirmatory brain-behavior associations

To examine whether segregation and integration properties displayed expected relationships to impulsivity measures—lower impulsivity with increasing segregation—we conducted confirmatory brain-behavior relationships between all behavioral variables (i.e., executive performance and trait impulsivity) and all brain metrics (i.e., whole brain metrics, network metrics, and hubs). Within each of these brain metrics, FDR correction was applied across each brain metric behavioral domain (e.g., FDR across set-shifting for all whole-brain metrics). All findings are summarized in Supplement Table 3 and only effects passing multiple comparisons are reported below (and depicted in Figure 5).

Across all participants, decreasing levels of average participation coefficient of the CON and DAN were associated with improvements in set shifting (CON: \( b = -10.32, T= -2.69, p=0.007, R^2(\text{fixed})= 0.07; \) DAN: \( b = -8.12, T= -2.16, p=0.020, R^2(\text{fixed})= 0.08 \)), overall suggesting that set-shifting is marked by patterns of segregation (i.e., decreased integration). Opposing patterns emerged in relation to trait impulsivity. Specifically, increasing levels of average participation coefficient of the VAN was associated with higher levels of Negative Urgency (\( b = 2.18, T= 2.28, p=0.020, R^2(\text{fixed})= 0.07 \)). Additionally, greater levels of participation coefficient in all control networks and decreasing levels of modularity were associated with higher Positive Urgency (FPN: \( b = 3.96, T= 3.56, p<0.000; \) CON: \( b = 3.27, T= 2.52, p=0.01; \) DAN: \( b = 3.04, T= 2.38, p=0.020; \) VAN: \( b = 3.36, T= 3.17, p=0.001, R^2(\text{fixed})= 0.04; \) Modularity: \( b = 4.99, T= -2.56, p=0.010, R^2(\text{fixed})= 0.04 \)). Together, this pattern suggests that elevated impulsivity—particularly in urgency measures—is characterized by patterns of reduced segregation, observed both at the whole-brain and network level. Hubness did not predict individual differences in either set shifting or trait impulsivity measures. Notably, effect sizes of our brain-behavior
associations are comparable to those revealed by behavioral wide associations studies (BWAS), which suggest that connectivity to behavior associations are modest ($r= 0.14-0.34$), at best (Marek et al., 2020)

Discussion

In light of emerging developments in the suicide literature, the present study sought to (1) replicate profiles of cognitive and personality impulsivity in a large sample of children endorsing suicide ideation, attempt, and no suicide history; (2) examine group differences in organizational properties of control networks and; (3) assess whether these neural profiles could plausibly serve as mechanisms by which impulsivity confers suicide risk. Overall, our findings revealed that children endorsing ideation displayed global elevations in most trait impulsivity dimensions, whereas suicide attempt was better characterized by a dissociable impulsivity profile, marked by poorer set-shifting and elevated urgency in girls (only elevated urgency in boys). Behavioral profiles in attempters were accompanied by hubness alterations in the DLPFC (FPN), VLPFC (VAN), and dACC (CON) relative to child ideators. Of these, the DLPFC of the FPN demonstrated clearest evidence of alterations relative to both ideators and controls. These connector hubs, however, did not emerge as mechanistic links by which impulsivity elevated risk for transitioning from ideation to attempt, suggesting that the ideation-to-attempt shift is likely marked by a complex profile of interacting variables, not just neural markers. All together, these findings provide supporting evidence for the developmental continuity of impulsivity in suicide, with different cognitive and personality measurements of impulsivity showing differential importance to suicidal thoughts and behaviors.

Cognitive and personality measures of impulsivity
Examining two prominent conceptualizations of impulsivity, our findings reveal that certain components of executive abilities and most dimensions of trait impulsivity are differentially affected in children endorsing suicide ideation and attempt.

Children with a history of ideation, more specifically, were characterized by broad elevations in trait impulsivity dimensions (i.e., negative urgency, positive urgency, lack of perseverance, lack of planning), but showed no significant differences in executive abilities, relative to children with no history of suicide. Given the enduring nature of personality-based impulsivity dimensions, it is not surprising that our findings generally echoed evidence in the adult literature in suicide, implicating elevations in urgency measures, lack of planning, and lack of perseverance (Klonsky & May, 2010; Valderrama et al., 2016). Indeed, these impulsivity dimensions generally fit within existing conceptualizations of suicide ideation, with evidence linking trait impulsivity to a number of latent factors found to comprise the larger construct of suicide ideation. Specifically, suicide ideation is thought to be composed of 1) low affectivity, such as perceived burdensomeness and social disconnection and 2) externalizing tendencies (Rogers & Joiner, 2018; Rogers et al., 2018). Whereas elevations in urgency measures may contribute to suicidal thoughts via a heightened sensitivity to failures or a tendency for isolation/disconnection (both indices of low affectivity), elevations in lack of perseverance and planning may be related to externalizing tendencies associated with suicidal thought. Elevations in negative urgency, more specifically, has been shown to co-occur with higher levels of perceived burdensomeness, particularly in the presence of low distress tolerance (Anestis & Joiner, 2011; Christensen, Batterham, Mackinnon, Donker, & Soubelet, 2014; Joiner, Van Orden, Witte, & Rudd, 2009; May & Klonsky, 2016; Van Orden, Witte, Gordon, Bender, & Joiner, 2008). Given that childhood is marked by underdeveloped coping mechanisms (Power, T. G., 2004), it is
feasible that children with particularly elevated negative urgency might present with heightened sensitivity to social/peer rejection, a vulnerable state that may place children at heightened risk for considering suicidal thoughts. Interestingly, our findings indicate that positive urgency is also elevated in children endorsing ideation, suggesting that the emergence of suicidal thoughts during childhood may be prompted by a wider range of intense affective stimuli, not just negative affect. By contrast, elevations in lack of perseverance and planning may contribute to the emergence of suicidal thoughts by facilitating the expression of externalizing tendencies. For example, reduced perseverance and planning may help promote more hasty shifts from passive thoughts about death to more active thoughts of ideation, a hypothesis in line with evidence that externalizing characteristics are associated with varying levels of ideation (Miller, Bozzay, Ben-Porath, & Arbisi, 2019). In sum, elevations in a number of trait impulsivity dimensions among youth may have close ties to key latent variables (i.e., low affectivity, externalizing tendencies) that give rise to suicidal thoughts, representing one potential pathway for the emergence of suicidal thoughts in children.

By contrast, children with a history of past attempts displayed impairments in set shifting abilities, in addition to further elevations in negative and positive urgency. Girls, in particular, displayed lower levels of set shifting (i.e., cognitive inflexibility) and these deficits were found to be dissociable from elevations in urgency measures. Although this pattern of findings did not replicate deficits in inhibitory control and elevations in Lack of Planning most frequently reported in adults (and initially hypothesized in the present study), they are consistent with evidence suggesting that perseverative thinking styles and heightened sensitivity to failures/rejection may facilitate the transition from suicidal thoughts to behaviors by increasing one’s acquired capability (Anestis, Bagge, Tull, & Joiner, 2011; Rajappa, Gallagher, & Miranda,
2012; Rogers & Joiner, 2018), a predictor receiving accumulating support for activating the transition from ideation to attempt (Joiner & Silva, 2012; May & Victor, 2018; Smith & Cukrowicz, 2010; Van Orden et al., 2010).

Cognitive inflexibility, reflected by poor set-shifting abilities, has been identified as a causal predictor of future suicide ideation among adult attempters (Miranda et al., 2013), suggesting that greater perseveration is closely tied to the enaction of thoughts into behaviors. Based on cognitive models of suicidal behavior, cognitive inflexibility is theorized to disrupt the ease with which individuals effectively switch from one coping mechanism to another, particularly in the face of stressful changes in one’s environment (Wenzel & Beck, 2008). It is, therefore, possible that once children have formulated thoughts of suicide, perseveration on these suicide-related thoughts may hinder one’s ability to generate alternative coping strategies that may be more adaptive. This interpretation is consistent with work linking attempts to suicide-specific ruminations, including longitudinal evidence that cognitive inflexibility predicts future suicide attempts by way of increasing rumination (McGirr, Dombrovski, Butters, Clark, & Szanto, 2012). Interestingly, only female attempters in the current dataset displayed cognitive inflexibility, a finding that parallels ruminative tendencies predominantly observed in female children and adolescents (See Johnson & Whisman, 2013 for a meta-analytic review). One hypothesis for these findings is that cognitive inflexibility may heighten risk for suicide attempt during periods of puberty, which typically occurs earlier in development for girls (8-12 years old). Indeed, an emerging model has outlined the probable role that the onset of the menstrual cycle and fluctuations in ovarian hormones may play in exacerbating risk for attempt among preteen and teenage girls (Owens et al., 2020). In conjunction with some suggestions that attentional and executive abilities vary by different phases of the menstrual cycle (Reed, Levin,
& Evans, 2008; Wright & Badia, 1999), it is conceivable that hormonal changes observed at the onset of puberty might exacerbate the effects that cognitive rigidity (and ruminative tendencies) may have on the risk for attempting suicide. Notably, it remains to be determined whether reduced set-shifting abilities during peak periods of male puberty (~13.5 years old) increases risk for suicide attempts in boys, or whether the link between cognitive rigidity and suicide attempt is unique to girls.

In addition to cognitive impairments, both girls and boys with a history of suicide attempt were also characterized by even further elevations in negative and positive urgency (i.e., beyond elevations seen in ideators). As previously noted, urgency elevations have been tied to heightened sensitivity to evocative and painful experiences, and also with greater reactivity, inciting quicker and less thoughtful behaviors with the objective of (maladaptively) diminishing intense affect (Anestis & Joiner, 2011; Bender, Anestis, Anestis, Gordon, & Joiner, 2012). It is possible that a predisposition to greater reactivity via elevated urgency, combined with an underdeveloped ability to shift attention away from suicidal thoughts via poor shifting may together represent one pathway by which children begin to increase their acquired capability for suicide.

In short, children with a lifetime history of suicidal ideation are characterized by elevations in trait impulsivity while children with a history of attempt show dissociable profiles of cognitive inflexibility and urgency dimensions. Importantly, these findings are compatible with prominent evidence-based theories of suicide, including the Interpersonal Theory of Suicide, Integrated Motivational-Volitional Model of Suicidal behavior (O’Connor & Kirtley, 2018), and the Three Step Theory (Klonsky & May, 2015), all of which underscore the presence of distinct profiles contributing to ideation and attempt. In accordance with these models,
impulsivity profiles observed in the current data can be best characterized as distal predictors of suicide. How these aspects of impulsivity interact with proximal and time-varying risk factors, particularly those with greatest salience in development (e.g., bullying, peer rejection, puberty), will allow for a better understanding of how and when cognitive inflexibility and trait impulsivity poses greatest risk for ideation and the transition of thoughts into attempts during childhood.

**Organization properties of control networks in ideation and attempt**

An examination of organizational properties of brain networks and regions implicated in executive abilities and trait impulsivity revealed that brain topology remained largely intact in childhood suicide, such that whole-brain and network-specific measures of segregation and integration were comparable across children with no suicide history, those endorsing lifetime ideation, and lifetime attempt. Instead, differences were observed in connector hubs of control networks, with clearest evidence of hub disruptions observed in the DLPFC of the FPN among child attempters. Specifically, children with a lifetime history of suicide attempt displayed higher levels of hubness (i.e., between-network connections) relative to both ideators and controls, suggesting that DLPFC represents a robust and notable neural marker in understanding the neural processes involved in the transition from ideation to attempt. Of note, although hubness disruptions in the VLPFC of the VAN and dACC of the CON also emerged among attempters relative to ideators, such differences were not observed when child attempters were compared to controls, warranting some caution in our interpretation of these latter profiles.

Evidence for DLPFC pathology is arguably one of the most frequently reported neural marker associated with suicide, showing reduced activation during executive performance with
increasing suicide ideation (Pu et al., 2015) and reductions in both gray and white matter volumes in adults with suicide ideation and attempts with various mood disorders (Benedetti et al., 2011; Ding et al., 2015; J. P. Hwang et al., 2010; Zhang et al., 2020). The DLPFC has also been the site of protein and molecular pathology in post-mortem studies of completed suicide (Cabello-Arreola et al., 2020; Ernst et al., 2011). In conjunction with findings from the current study, the DLPFC appears to represent a robust site of multimodal dysfunction in suicide, with abnormalities detectable as early as childhood and appearing to most clearly distinguish children who attempt suicide from those with only ideation. It is particularly noteworthy that child attempters display DLPFC hubness disruptions given that their impulsivity profile comprised both cognitive and personality processes, both of which have been associated with DLPFC functioning to varying extents. Specifically, the DLPFC has been known to play an important role in the implementation of control, using internal representations to guide appropriate, task-dependent responses. As such, the DLPFC has been implicated in different executive functions, including set shifting, (J. D. Cohen et al., 1997; Curtis & D’Esposito, 2003; Dove, Pollmann, Schubert, Wiggins, & Yves Von Cramon, 2000; MacDonald, Cohen, Andrew Stenger, & Carter, 2000), the regulation of both negative and positive emotions (Golkar et al., 2012; Mak, Hu, Zhang, Xiao, & Lee, 2009), and trait impulsivity (e.g., negative urgency; Um, Whitt, Revilla, Hunton, & Cyders, 2019). These functions, in conjunction with our pattern of behavioral and neural profiles, raise the possibility that DLPFC disruptions might exacerbate existing suicidal thoughts by undermining proper implementation of control and increasing vulnerabilities to the type of rigid thinking and heightened urgency that may elevate risk suicide attempt. In this way, DLPFC hubness disruptions may represent one neural mechanism by which impulsivity heightens risk for the transition from ideation to attempt. Findings from our mediation analyses,
however, do not show evidence for this hypothesis. In fact, connector hubs did not appear to show significant relationships to any of our measures of impulsivity, a finding that runs counter to our line of reasoning and yet is consistent with puzzling evidence failing to show clear correspondences between cognitive dysfunction reported in suicide and emerging neural disruptions. One speculation for these findings is that DLPFC hubness may be reflecting a host of processes (e.g., cognitive, emotional, motivational)—not just impulsivity. Such processes might be those relevant to acquiring capability, including deficits in emotion regulation and reduced distress tolerance (Anestis & Joiner, 2011, 2012; Bender et al., 2012), as well as environmental factors, like changes in stress. Alternatively, it may be the case that DLPFC hubness has to be considered in tandem with connectivity, functional, and structural alterations, to more precisely understand its role in the ideation-to-attempt shift.

In addition to its functional specialization in implementing control, the DLPFC’s role in network organization may also provide an informative framework for understanding the patterns of hubness disruption observed in child attempters. Generally, hubs like the DLPFC are considered essential players in preserving an optimal segregation-to-integration balance (Bertolero et al., 2018; Francesco De Pasquale et al., 2013; Gordon et al., 2017; K. Hwang et al., 2013; Oldham & Fornito, 2019), likely via developmental refinements in between-network connections (hubness). Work mapping node-level and network-level trajectories show that age-related changes of several hubs closely parallel network-level changes in segregation and integration. For example, hub reductions in the DLPFC, posterior DLPFC, and VLPFC across development mirror similar rates of age-related segregation of the FPN, DAN, and VAN segregation, respectively. Similarly, patterns of hub increases in the dACC echo increasing CON integration throughout development (Lopez et al., 2020; Marek et al., 2015b). Given these
hub-to-network correspondences, if the FPN is expected to show patterns of increasing segregation with development, facilitated in part by decreasing DLPFC hubness, one might reason that increased childhood DLPFC hubness observed in children with suicide attempts may represent a way in which normative segregation processes are disrupted, overall yielding reduced network segregation needed to support functional FPN specialization (i.e., implementing control). Similar conjectures can be made for VLPFC and dACC hubness, which emerged as less robust findings, yet showed patterns that appeared to respect the diverging profiles of hub development. Specifically, whereas the VLPFC of the VAN showed increased hubness among children with suicide attempts, theoretically compromising optimal VAN segregation, the dACC of the CON showed a divergent profile of decreased hubness among children with suicide attempts, potentially disrupting CON integration with other networks. In this way, hub disruptions observed in child attempters may destabilize normative trajectories of integration and segregation.

**Topology of cognitive and personality-based impulsivity**

Confirmatory brain-behavior relationships revealed expected associations between impulsivity and brain organization. Specifically, lower levels of impulsivity—indicated by improved performance on all measures of executive abilities and lower levels of urgency measures—were associated with varying profiles of network segregation, measured by decreasing patterns of between-network connections. Specifically, DAN segregation, was associated with better performance in executive tasks and lower urgency measures and segregation of virtually all control networks were associated with lower urgency. Of note, this latter profile was observed at the whole brain level (i.e., modularity) and at the network level (i.e., all control networks). Overall, these profiles provide evidence bolstering the notion that a
mostly segregated/modular organization is important in supporting self-control processes relevant to impulsivity. Notably, these brain-behavior associations were modest, though comparable to those revealed by behavioral wide associations studies (BWAS), which suggest that uninflated, connectivity-behavioral associations typically observed in consortiums-sized samples tend to be small (r= 0.14-0.34; Marek et al., 2020).

**Limitations**

Despite the advantage of a large sample, there are several limitations worth emphasizing in the consideration of our findings. First, measures of psychopathology were based primarily on parent reports, a potential source of confound given modest-to-moderate correspondence between parent and child reported depressive symptoms, a discrepancy even larger for African American and Asian American youth endorsing suicide (J. H. Kim, Chan, McCauley, & Vander Stoep, 2016). Notably, the present study incorporated child reported measures of psychopathology, when available, including child-reported symptoms of lifetime suicide ideation and attempt, attenuating some concerns about potential parent-to-child differences in the endorsement of suicide. Second, the current dataset is cross-sectional, precluding a characterization of temporal relationships between impulsivity measures, organizational brain properties, and suicide status. This presents an issue for determining the extent to which impulsivity and organizational disruptions necessarily elevate suicide risk (antecedents factors) and how much these processes, instead, reflect consequences of endorsing ideation and attempt (consequent factors). Third, we examined what are considered to be distal, long-standing predictors and did not incorporate proximal, time-varying risk factors (e.g., the emergence of a negative life event and fluctuations in stress or hormones), which has emerged in recent studies as equally important factors in assessing suicide risk. A fourth limitation is our use of lifetime
measures of suicidality, which obscure effects that can be attributable to more recent changes in suicide ideation. For example, impulsivity and brain organization deficits observed in child attempters may be most pronounced in attempters who show a resurgence of suicidal thoughts compared to attempters with remitted/past ideation. Acute increases in the severity of suicide ideation or intent may also impact the extent of impulsivity and hub dysfunction. Thus, a meaningful distinction between current verses lifetime suicidality, as well as, the inclusion of dimensional measures of ideation, may offer a richer understanding into shifts from ideation to attempt and the recurrence of attempt. Finally, the present study did not exclude children endorsing non-suicidal self-injury given its high co-occurrence with suicide attempt in youth (Andover, Morris, Wren, & Bruzzese, 2012).

**Future Directions**

A consideration for future resting state functional connectivity work in suicide will be to understand normal variability in connector hubs at the person level and how individual-specific variability in hubness might relate to impulsivity and other factors relevant to suicide. More specifically, work using precision mapping— in which individuals are scanned repeatedly over multiple sessions to obtain functional connectivity data of excellent reliability (>40 minutes of data)— has demonstrated that individuals display specific features in their functional connectivity profile that are not well-captured by more traditional approaches, in which connectivity data are averaged across individuals. Importantly, individual-specific variability appears to be greatest among higher-order cognitive networks, with several frontal regions—including several connector hubs studied here—containing the greatest level of variability in connectivity and network organization (Gratton et al., 2018; Mueller et al., 2015). As such, effects of hubness differences across suicide group may be diminished, also likely obscuring the
detection of stronger brain-behavior relationships (Finn et al., 2017), like impulsivity measures examined here. Because the suicide literature, in particular, has struggled to delineate clear correspondences between separately emerging impulsivity and neural profiles, the eventual application of precision mapping may help clarify the contribution of connector hubs in impulsivity and other suicide-relevant predictors.

**Conclusion**

In a representative and large sample of children endorsing lifetime suicide ideation (N= 849), attempt (N=186), and no history of suicide (N=10,754), our findings revealed that suicide ideation was marked by broad elevations in trait impulsivity while suicide attempt was better characterized by a dissociable impulsivity profile of set-shifting deficits and elevations in urgency measures in girls, more specifically (only elevated urgency in boys). These findings resemble behavioral profiles found in the adolescent and adult suicide literatures, overall underscoring a developmental continuity in the relationship between impulsivity and suicide risk. Behavioral profiles in attempters were accompanied by hub dysfunction, showing greatest evidence for altered hubness in the DLPFC of the FPN relative to ideators. Altered hubs, however, did not emerge as a mechanism by which impulsivity distinguished ideators from attempters, consistent with the idea that the ideation-to-attempt shift is marked by a complex profile of interacting emotional, cognitive, and neural variables. Understanding the contributions of impulsivity and DLPFC in the context of fluctuating and developmentally relevant proximal risk factors (e.g., hormonal changes, stress, peer rejection) will be particularly important in more precisely delineating the emergence of suicidal thoughts and transition to attempts in childhood. These findings provide supporting evidence for the roles that impulsivity (i.e., executive abilities and trait impulsivity) and frontoparietal regions play in suicide ideation and attempt during
childhood, overall extending adolescent- and adult-like profiles of suicide into much younger periods of development.

Figures and Tables

Figure 1. Study Design depicting specific aims. Group differences were examined between ideators relative to controls and separately for ideators relative to attempters.
Figure 2. Executive functioning and trait impulsivity in suicide. A) Behavioral associations between executive functioning, trait impulsivity, and age (X denotes non-significant correlations) B) Significant group and sex differences in set-shifting abilities. C) Significant group differences in trait impulsivity measures. For models examining group differences (B and C), primary predictors of interest were ‘Control v. Ideation’ and ‘Ideation v. Attempt,’ both denoted by black asterick). To confirm that attempters’ profile of impairment held relative to both ideators and controls, secondary analyses modeling Attempt v. Control were also examined and are denoted by gray astericks.
Figure 3. Connector hub disruptions in suicide. Relative to ideators, child attempters display higher participation coefficient (hubness) in the DLPFC of the FPN, VLPFC of the VAN, and concurrent reductions in hubness in the dACC of the CON (denoted in solid line). To confirm that attempters’ profile of impairment held relative to both ideators and controls, secondary analyses modeling Attempt v. Control were also examined, revealing that only the DLPFC of the FPN displayed clear evidence of hubness disruptions (denoted in dashed line), such that attempters displayed greater between-network connections relative to ideators and controls (depicted in bottom panel). DLPFC: Dorsolateral Prefrontal Cortex; VLPFC: Ventrolateral Prefrontal Cortex; dACC; Dorsal Anterior Cingulate Cortex; FPN: Frontoparietal Network; VAN: Ventral Attention Network; CON: Cinguloopercular network.
Figure 4. Hubness disruptions as a mechanism by which impulsivity elevates risk for transitioning from ideation to attempt. Hubness of the DLPFC of the FPN (yellow), VLPFC of the VAN (teal), and dACC of the CON (purple) were examined as a potential mediator in the relationship between impulsivity and suicide status (i.e., Ideation v. Attempt). DLPFC:
Dorsolateral Prefrontal Cortex; VLPFC: Ventrolateral Prefrontal Cortex; dACC; Dorsal Anterior Cingulate Cortex; FPN: Frontoparietal Network; VAN: Ventral Attention Network; CON: Cinguloopercular network.

Figure 5. Confirmatory brain-behavior relationships. To confirm that low impulsivity was associated with greater segregation, brain-behavior relationships were conducted, revealing that A) lower trait impulsivity was associated with overall higher whole-brain segregation; B and C) better executive abilities were associated with increasing DAN and CON segregation and; D and E) lower trait impulsivity was associated with FPN, DAN, VAN, and CON segregation.

DLPFC: Dorsolateral Prefrontal Cortex; VLPFC: Ventrolateral Prefrontal Cortex; dACC; Dorsal Anterior Cingulate Cortex; FPN: Frontoparietal Network; DAN: Dorsal Attention Network; VAN: Ventral Attention Network; CON: Cinguloopercular network.
<table>
<thead>
<tr>
<th>Outcome</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Impulsivity</strong></td>
<td></td>
</tr>
<tr>
<td>Cognitive measures:</td>
<td></td>
</tr>
<tr>
<td>Set Shifting – TBX Dimensional Card Sort Task</td>
<td>- Matching cards to a target card based on rules (e.g., shape, color) that change/shift over the course of the task</td>
</tr>
<tr>
<td>Working Memory- TBX List Sorting Task</td>
<td>- Sort and sequence auditory and visual stimuli</td>
</tr>
<tr>
<td>Inhibition- TBX Flanker Inhibitory Control Task</td>
<td>- Respond to the orientation of target stimuli while inhibiting response to non-target stimuli</td>
</tr>
<tr>
<td>Personality measures:</td>
<td></td>
</tr>
<tr>
<td>Negative Urgency- UPPS-P</td>
<td>- Tendency to act hastily in the face of negative affect</td>
</tr>
<tr>
<td>Positive Urgency- UPPS-P</td>
<td>- Tendency to act hastily in the face of positive affect</td>
</tr>
<tr>
<td>Lack of Perseverance- UPPS-P</td>
<td>- Difficulties planning and weighing consequences of behavior</td>
</tr>
<tr>
<td>Lack of Planning- UPPS-P</td>
<td>- Difficulties sustaining attention or motivation</td>
</tr>
<tr>
<td>Sensation Seeking- UPPS-P</td>
<td>- Tendency to seek out novel and/or stimulating experiences</td>
</tr>
<tr>
<td><strong>Network organization</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Whole Brain Metrics:</strong></td>
<td></td>
</tr>
<tr>
<td>Modularity</td>
<td>- Whole brain segregation; the extent to which the brain can be divided into segregated modules</td>
</tr>
<tr>
<td>Global Efficiency</td>
<td>- Whole brain integration of information transfer</td>
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<tr>
<td><strong>Network Metrics:</strong></td>
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<td>Average Participation Coefficient</td>
<td>- Between network connections density of a given network</td>
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<tr>
<td><strong>Hubs:</strong></td>
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<td>Nodal Participation Coefficient</td>
<td>- Between network connections density of a given brain region</td>
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Table 1. Outcome variables of interest
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<td>Age (Months)</td>
<td>11,780</td>
<td>119 (7.46)</td>
<td>118 (7.49)</td>
<td>119 (7.36)</td>
<td>0.230</td>
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<tr>
<td>Gender</td>
<td>11,780</td>
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<td></td>
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<tr>
<td>F</td>
<td>5197 (48%)</td>
<td>359 (42%)</td>
<td>77 (41%)</td>
<td>0.806</td>
<td>&lt;0.001</td>
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<tr>
<td>M</td>
<td>5548 (52%)</td>
<td>490 (58%)</td>
<td>109 (59%)</td>
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<tr>
<td>Depressive Sxs</td>
<td>11,775</td>
<td>1.17 (1.90)</td>
<td>1.97 (2.60)</td>
<td>3.13 (3.33)</td>
<td>&lt;0.001</td>
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<tr>
<td>IQ</td>
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<td>107 (17.0)</td>
<td>107 (16.8)</td>
<td>103 (18.8)</td>
<td>0.840</td>
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<td>SES</td>
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<tr>
<td>0</td>
<td>8472 (79%)</td>
<td>634 (75%)</td>
<td>119 (64%)</td>
<td>0.350</td>
<td>0.550</td>
</tr>
<tr>
<td>1</td>
<td>958 (8.9%)</td>
<td>83 (9.8%)</td>
<td>22 (12%)</td>
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<td></td>
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<tr>
<td>2</td>
<td>626 (5.8%)</td>
<td>56 (6.6%)</td>
<td>15 (8.1%)</td>
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<tr>
<td>3</td>
<td>330 (3.1%)</td>
<td>24 (2.8%)</td>
<td>17 (9.1%)</td>
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</tr>
<tr>
<td>4</td>
<td>186 (1.7%)</td>
<td>27 (3.2%)</td>
<td>6 (3.2%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>111 (1.0%)</td>
<td>16 (1.9%)</td>
<td>6 (3.2%)</td>
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<tr>
<td>6</td>
<td>41 (0.4%)</td>
<td>7 (0.8%)</td>
<td>1 (0.5%)</td>
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<tr>
<td>7</td>
<td>21 (0.2%)</td>
<td>2 (0.2%)</td>
<td>0 (0%)</td>
<td></td>
<td></td>
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<tr>
<td>#FramesRetained</td>
<td>7,552</td>
<td>1070 (249)</td>
<td>1074 (249)</td>
<td>1020 (234)</td>
<td>0.670</td>
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<tr>
<td>Framewise Displacement</td>
<td>7,552</td>
<td>0.192 (0.193)</td>
<td>0.191 (0.188)</td>
<td>0.218 (0.238)</td>
<td>0.870</td>
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</tbody>
</table>

*Table 2. Demographic, clinical, and motion characteristics across suicide cohorts*

*Statistics presented: mean (SD); n (%)*


Cabello-Arreola, A., Ho, A. M. C., Ozerdem, A., Cuellar-Barboza, A. B., Kucuker, M. U.,


Myung, W., Han, C. E., Fava, M., Mischoulon, D., Papakostas, G. I., Heo, J. Y., … Jeon, H. J. (2016). Reduced frontal-subcortical white matter connectivity in association with suicidal
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https://doi.org/10.1007/s10608-011-9419-2

https://doi.org/10.1016/j.yhbeh.2008.02.018

https://doi.org/10.1038/tp.2017.84

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https://doi.org/10.1177/1073191116645907


Acquired Capability Component of the Interpersonal-Psychological Theory of Suicide. *Suicide and Life-Threatening Behavior.* https://doi.org/10.1521/suli.2010.40.3.266


Yen, S., Shea, M. T., Sanislow, C. A., Skodol, A. E., Grilo, C. M., Edelen, M. O., … Gunderson,


### Supplement Tables

**Supplement Table 1.** Group differences in cognitive and personality measures of impulsivity

<table>
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<tr>
<th></th>
<th>Control v. Ideation</th>
<th>Ideation v. Attempt</th>
<th>Sex</th>
<th>I v. A * Gender (F)</th>
<th>C v. I * Gender (F)</th>
<th>R² (fixed)</th>
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<tr>
<td><strong>Set Shifting</strong></td>
<td>0.50</td>
<td>-3.75 **</td>
<td>-1.48 *</td>
<td>4.44 **</td>
<td>0.11</td>
<td>0.11</td>
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<tr>
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<td>(T = 0.86, p = 0.39)</td>
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<td>(T = -2.05, p = 0.04)</td>
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<td>**0.85 *****</td>
<td>0.41 ***</td>
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<tr>
<td><strong>Positive Urgency</strong></td>
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<td>**0.79 **</td>
<td>0.43 ***</td>
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<tr>
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<td>-0.06</td>
<td>0.25 ***</td>
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<td>0.02</td>
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<td><strong>Lack of Planning</strong></td>
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<td>0.50 ***</td>
<td>0.02</td>
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<tr>
<td><strong>Sensation Seeking</strong></td>
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<td>0.69 *</td>
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Data controlled for Age (in months), depressive symptoms, hopelessness, IQ, and SES. *** p < 0.001; ** p < 0.01; * p < 0.05
Supplement Table 2. Group differences in brain topology

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<th>Ideation v. Attempt</th>
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<th>C v. I * Gender (F)</th>
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<td>-0.00 ** ***</td>
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<td>Global Efficiency</td>
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<td>-0.00</td>
<td>0.00 ** ***</td>
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<td>0.01 ** ***</td>
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<td>VAN PC</td>
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<td>0.01 ** ***</td>
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<td>DLPFC of FPN</td>
<td>0.01</td>
<td>0.03 *</td>
<td>0.02 ** ***</td>
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<td>dACC of CO/SN (028)</td>
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<td>Posterior DLPFC of DAN (043)</td>
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<td>0.03</td>
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<td>VLPFC of VAN (80)</td>
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Bold: Significant after FDR correction (p<.05). Data controlled for Age (in months), depressive symptoms, hopelessness, IQ, SES, numbers of frames retained, and framewise displacement. *** p < 0.001; ** p < 0.01; * p < 0.05
Supplement Table 3. Confirmatory brain-behavior relationships

<table>
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<th>Modularity</th>
<th>9.93</th>
<th>10.56</th>
<th>10.80</th>
<th>-1.38</th>
<th>-4.99*</th>
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<td>(T = 1.89, p = 0.06)</td>
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<tr>
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<td>-3.31</td>
<td>-10.14</td>
<td>3.16</td>
<td>5.86*</td>
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<td>(T = 2.06, p = 0.04)</td>
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<td>(T = -0.36, p = 0.72)</td>
<td>(T = -0.04, p = 0.97)</td>
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</tbody>
</table>

**Bold:** Significant after FDR correction (p<.05). Data controlled for Age (in months), depressive symptoms, hopelessness, IQ, SES, numbers of frames retained, and framewise displacement. *** p < 0.001; ** p < 0.01; * p < 0.05