Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

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Can measures of sleep quality or white matter structural integrity predict level of worry or rumination in adolescents facing stressful situations? Lessons from the COVID-19 pandemic

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ABSTRACT

Introduction: COVID-19 has resulted in major life changes to the majority of the world population, particularly adolescents, with social-distancing measures such as home-based schooling likely to impact sleep quality. Increased worry is also likely considering the substantial financial, educational and health concerns accompanying COVID-19. White matter (WM) integrity has been shown to be associated with anxiety and depression symptoms, including worry, as well being closely associated with sleep quality. This study aimed to investigate the associations between pre-COVID sleep quality, WM structural integrity and levels of worry and rumination about COVID.

Methods: $N = 30$ adolescent participants from Queensland, Australia, completed diffusion tensor imaging (DTI) scanning pre-COVID, the Pittsburgh Sleep Quality Index (PSQI) pre and during COVID, and 9 items designed to measure 3 constructs, perceived impact of COVID, general worry, and COVID-specific worry and rumination.

Results: Sleep quality (PSQI total) was significantly poorer during COVID compared with pre-COVID. Sleep onset latency measured pre-COVID was significantly associated with COVID-specific worry and rumination. While the structural integrity of a number of WM tracts (measured pre-COVID) were found to be significantly associated with COVID-specific worry and rumination. Follow-up regression analysis using a model including pre-COVID sleep onset latency, structural integrity of the posterior limb of the internal capsule (PLIC), gender and change in PSQI explained a significant 47% of the variance in COVID-specific worry and rumination.

Conclusions: These findings suggest that adolescents with poor sleep quality and perturbed WM integrity may be at risk of heightened reactivity to future stressful events and interventions should focus on improving sleep onset latency.

1. Introduction

COVID-19 has had a major impact on the lives of people all over the world (Lee, 2020). Even in areas that have been fortunate enough to have low infection rates, day-to-day life has been considerably impacted. Social distancing regulations and home-based

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schooling are novel concepts for the majority of the adolescent population and therefore require investigation into their potential mental health impacts. Anxiety symptoms, particularly worry, is an intuitive target for study under such conditions, given the constant media coverage of infection and death rates along with the financial concerns encountered by many families (Roy et al., 2020).

Studying the impact of COVID-19 social distancing measures on levels of worry in adolescents is especially important given, firstly, that excessive and persistent worry is one of the main symptoms of anxiety disorders (APA, 2013), that anxiety disorders are already the most prevalent of the mental disorders in adolescents (Kessler et al., 2005; Merikangas et al., 2010) and, thirdly, that anxiety disorders are one of the most persistent mental disorders with an average reported duration of over 20 years (Lenze & Wetherell, 2011).

Sleep quality is also closely associated with anxiety symptoms (APA, 2013; Jamieson, Broadhouse, Lagopoulos, & Hermens, 2020) and is another area that has the potential to be impacted during the COVID-19 pandemic. Adolescents have been shown to be particularly susceptible to chronic sleep deprivation due to the combination of a biologically driven circadian rhythm late-shift occurring around puberty and persisting throughout adolescence coupled with the on-going need to wake early for formal activities such as school (Crowley, Acebo, & Carskadon, 2007; Hagenauer, Perryman, Lee, & Carskadon, 2009). The circumstances arising from the COVID-19 pandemic may therefore impact sleep quality in a number of ways. The switch to home-based schooling has the potential to perhaps improve sleep quality if adolescents are allowed to sleep in longer in the mornings before commencing home-based schooling at their own pace. On the other hand, increased levels of worry may have a negative impact on sleep quality potentially combining with the biologically driven circadian rhythm late shift to result in significantly increased sleep onset latency.

Sleep and anxiety have been shown to be significantly correlated in adolescents ((Jamieson, Broadhouse, Lagopoulos, et al., 2020); Tarokh et al., 2016). Reduced sleep is a criteria of the worry-centric generalized anxiety disorder (APA, 2013), and reduced sleep quality has been associated with higher scores on the Beck Scale for Suicidal Ideation (SSI) (Lee, Cho, Cho, & Kim, 2012), as well as the Beck Anxiety Inventory (BAI) and Beck Depression Inventory (BDI) (Hacimuslar & Karaaslan, 2020). In a recent prospective study, participants who were rated as poor sleepers prior to chronic exposure to stressful circumstances (i.e. medical internship training) were found to be twice as likely to exhibit symptoms of worry, restlessness and difficulty relaxing and to screen as positive for probable generalized anxiety disorders (GAD) than those who were rated as good sleepers (Kalmbach et al., 2019). In the same study, symptoms of sleep onset insomnia (chronic increased sleep onset latency) measured prior to exposure to the chronic stress environment was found to be a strong predictor of anxiety symptoms when exposed to the stressful situation (Kalmbach et al., 2019).

Pre-sleep worry has also been shown to have a negative impact on sleep quality (Harvey, Tang, & Browning, 2005). Worry during the period just prior to sleep following a stressful situation has been shown to have a negative impact on sleep quality for people deemed to have a trait tendency to ruminate (Guastella & Moulds, 2007). Worry has also been associated with an increase in sleep onset latency (Tang & Harvey, 2004) and a study by Harvey and Payne (2002) showed that distracting participants during the pre-sleep period (effectively breaking the worry cycle) reduced the number of distressing thoughts and resulted in reduced sleep onset latency (Harvey & Payne, 2002). The association between stressful events, pre-sleep rumination and sleep onset latency has also been demonstrated using both subjective (next day questionnaire) and objective (wrist worn actigraphy device) measures (Zoccola, Dickerson, & Lam, 2009).

Other factors influencing inter-individual differences in levels of worry about stressful situations must also be considered. Of particular interest are previous findings suggesting alterations in WM structural integrity may be associated with symptoms related to anxiety and depression (Baur, Hanggi, & Jancke, 2012; Kim & Whalen, 2009; Korgaonkar et al., 2011; Zuo et al., 2012). For instance, it has been suggested that the ability to successfully reappraise an adverse situation may be dependent upon the structural integrity of WM tracts providing connectivity between the amygdala and Prefrontal cortex (PFC) (d'Arbeloff et al., 2018). Fractional anisotropy (FA) is a measure of the directionality of water diffusion in the brain and is commonly reported as a representation of the structural integrity of WM tracts (Mori & Tournier, 2007). A number of studies have reported correlations between reduced FA of PFC-limbic WM tracts and the increased likelihood of suffering anxiety disorders (Baur et al., 2012; Ho et al., 2017; Kim & Whalen, 2009; Phan et al., 2009).

Sleep quality and the structural integrity of WM tracts have also been shown to be closely associated. In animal studies, Bellesi et al. (2018) found chronic sleep loss in adolescent rats led to a thinning of the myelin sheath (Bellesi et al., 2018). Conversely, good sleep has been shown to promote gene expression involved in the formation and maintenance of myelin in rodents (Bellesi, 2015). Preliminary findings have also demonstrated the relationship between sleep quality and FA values of WM tracts in a study of early adolescent human participants (Jamieson et al., 2020).

Depressive symptoms and ruminating have also been associated with structural changes in WM tracts (Zuo et al., 2012). Zuo et al. (2012) compared depressed participants with healthy controls and reported altered WM structural integrity in the frontal lobe, parietal lobe and limbic system. Importantly, Zuo et al. (2012) also found that greater WM alteration was associated with a greater level of rumination (Zuo et al., 2012). Korgaonkar et al. (2011) also compared participants with symptoms of depression and healthy controls and found a significant reduction in WM FA values in the limbic system, dorsolateral PFC, and thalamus in the group experiencing symptoms of depression (Korgaonkar et al., 2011).

In the current study, participants completed the Pittsburgh Sleep Quality Index (PSQI) and diffusion tensor imaging (DTI) prior to the COVID pandemic (pre-COVID) and then, at a subsequent assessment timepoint, completed the PSQI and the COVID Worry Impact Questionnaire (CWIQ) a 9-item questionnaire designed to measure three specific constructs, that is, general level of worry, level of specific worry and rumination about COVID and the perceived impact of COVID on family health and finances. This questionnaire was undertaken remotely via phone or laptop/computer tablet during the COVID lockdown period ("during COVID"). Thus, the current study aims to determine whether, in early adolescents, there is an association between: (1) sleep quality pre-COVID and sleep quality during COVID; (2) pre-COVID sleep measures and COVID specific worry; and (3) pre-COVID WM integrity and COVID specific worry.

Furthermore, this study seeks to extend on previous findings linking sleep quality to distress (Jamieson et al., 2020), pre-sleep worry to sleep measures including sleep onset latency (Wicklow & Espie, 2000), and sleep quality to WM integrity (Jamieson, Schwenn, et al., 2020) that have been demonstrated cross-sectionally, by determining whether sleep quality and/or WM integrity prior to a stressful event (in this case COVID) is significantly associated with specific worry about that event. Accordingly, it is hypothesised that: (i) sleep quality reported by adolescents during COVID would be worse compared to their pre-COVID sleep quality; (ii) poor sleep quality pre-COVID will be associated with increased COVID specific worry and rumination; and (iii) perturbed WM integrity pre-COVID will be associated with increased COVID specific worry and rumination.

2. Methods

Ethical approval

Ethical approval was granted by the University Human Research Ethics Department as part of the Longitudinal Adolescent Brain Study (LABS) project. (A181064). Informed assent and consent was obtained from all participants and their guardian/s.

2.1. Participants

$N = 30$ participants completed remote assessments during the COVID-19 pandemic. Participant data were obtained from LABS being undertaken at the University of the Sunshine Coast - Thompson Institute. Inclusion criteria for LABS was that at study entry all participants were 12 years of age and in grade 7 (first year of secondary school). Participants were recruited from the Sunshine Coast Region and were proficient in spoken and written English. Participants who reported suffering from a major neurological disorder, intellectual disability, major medical illness or who reported having sustained a head injury that involved loss of consciousness for greater than 30 min were excluded.

2.2. Procedure

As part of the ongoing longitudinal study, participants undergo a battery of neuropsychological and neuroimaging testing on a 4 monthly basis for 5 years. Following approval from the University of the Sunshine Coast Human Research Ethics Committee, existing LABS participants who were scheduled for their next study visit at the time of the COVID-19 suspension of face-to-face research were offered the opportunity to undertake their assessment remotely allowing for the continued collection of self-report data. The remote assessment period commenced on the April 6, 2020 and ran until the June 19, 2020. Participants completed the Pittsburgh Sleep Quality Index (PSQI) and diffusion tensor imaging (DTI) prior to COVID-19 and then completed the PSQI and a 9-item questionnaire designed to measure 3 specific constructs, 1) the perceived impact of COVID-19 on health and finances, 2) general level of worry, and 3) level of worry and rumination over COVID specifically remotely during COVID-19 (via video-call link).

2.3. Sleep quality measure

Participants undertook the PSQI as part of the self-report questionnaire at the timepoint pre-COVID and then remotely during COVID. The PSQI is an 18-item self-report, retrospective (past month) questionnaire (Buysse, Reynolds, Monk, Berman, & Kupfer, 1989). The PSQI is designed to measure seven components of sleep: subjective sleep quality, sleep latency, sleep duration, sleep efficiency, sleep disturbance, sleep medication use, and daytime dysfunction. Responses are provided on a four-point Likert scale and tallied to give an overall score. Subscale scores are rank-ordinal in nature, however, the PSQI total score, which is calculated by the summation of all seven subscale scores, can be treated as a continuous variable with potential scores ranging from 0 to 21, with lower scores indicating better sleep quality. Buysse et al. (1989) suggest that scores of 5 or higher indicate poor sleep quality (Buysse et al., 1989). Although the PSQI was initially validated using an adult sample (Buysse et al., 1989) it has since been shown to be a reliable and valid measure of sleep quality and quantity for use in a wide range of populations including adolescents and young adults (de la Vega et al., 2015; Raniti, Waloszek, Schwartz, Allen, & Trinder, 2018). The PSQI subscale score of sleep duration is reported in hours and minutes in the current study to increase accuracy.

2.4. COVID Worry Impact Questionnaire (CWIQ)

Participants completed the CWIQ, a brief (9-item) questionnaire designed to measure 3 specific constructs related to the COVID-19 lockdown measures, 1) general level of worry, 2) level of specific worry and rumination about COVID and 3) the perceived impact of COVID on family health and finances. The perceived impact of COVID-19 was measured using 7 items adapted from a scale developed to measure the impact on residents of Christchurch following the 2010 Christchurch earthquake (Dorahy & Kannis-Dymand, 2012). The 7 items showed good internal consistency (Cronbach's alpha .7) and asked participants to report on a 4 point Likert-type scale the perceived impact that the COVID-19 pandemic is having on themselves and their family's health and finances.

General worry was measured using 1 item adapted from the Spence children's anxiety scale (Spence, 1998). Participants were asked to provide an answer on a 4 point Likert-type scale to the question: "Over the past month, how often have you spent worrying about things?" This item was included to attempt to differentiate between the participant's general level of worry (trait worry) and COVID specific worry and rumination (state worry).

Level of worry and rumination over COVID specifically was measured using an item adapted from Bennett and Wells (2010). Bennett and Wells used a single item to measure level of rumination over the impact of a traumatic event and found this single item measure of rumination to be significantly correlated with their outcome measures which included the Impact of Events scale (Horowitz, Wilner, & Alvarez, 1979) and the posttraumatic diagnostic scale (Foa et al., 2016).

2.5. MRI acquisition

MRI scanning was undertaken during the pre-COVID visit (approximately 4 months prior to the "during COVID" remote appointment). All scans were acquired on a 3 Tesla Siemens (Erlangen, Germany) Skyra MRI scanner using a 64-channel head and neck coil. Structural MRI was performed using a Magnetization Prepared Rapid Acquisition Gradient Echo (MP-RAGE) T1-weighted sequence (TR = 2200 ms, TE = 1.76/850 ms, Resolution = 0.9/0.9/0.9, FOV 240 mm).

Diffusion weighted images (DWI) were acquired using a single shot spin-echo EPI technique, optimized for minimum error using tensor measurement, enabling measurement of white matter microstructure. It included a 96-direction DWI optimized for determining crossing fibres (56 slices, no slice gap, slice thickness = 2.0 mm, in-plane resolution = 2 × 2mm; TR = 3300 msec, TE = 115msec, FOV 228 mm, 3 B-values or "shells" were acquired at 30 at b = 1000 s/mm2, 60 at b = 2500s/mm2 and 6 at b = 0 repetitions). Duration: 9 min. A reversed phase encoding "blip down" sequence with 6 b = 0 repetitions was also be acquired for EPI distortion correction during post processing. Duration 1 min.

2.6. Image processing

Preprocessing of raw images was carried out using FSL (Smith et al., 2004). B0 images were extracted in the AP and PA directions and merged using fslroi and fslmerge tools followed by susceptibility distortion correction using the fsl topup tool (Andersson, Skare, & Ashburner, 2003) and distortion correction using eddy (Andersson & Sotiropoulos, 2016). Following visual inspection of each participant's preprocessed image, 7 participants were removed from TBSS processing due to metal and motion artifacts leaving $n = 23$.

Voxelwise statistical analysis of the FA data was then carried out using TBSS (Tract-Based Spatial Statistics) (Smith et al., 2006), part of the FSL software suite (Smith et al., 2004). First, FA images were created by fitting a tensor model to the raw diffusion data using FDT, and then brain-extracted using BET (Smith, 2002). All FA data were then aligned into common space using the nonlinear registration tool FNIRT, which uses a b-spline representation of the registration warp field (Rueckert et al., 1999). Then, the mean FA image was created and thinned to create a mean FA skeleton which represents the centres of all tracts common to the group with each subject's aligned FA data then projected onto this skeleton.

2.7. Statistical analysis

SPSS® Version 26 (SPSS Inc., Chicago, Illinois, USA) was used to produce descriptive statistics. To test the first hypothesis a repeated measures analysis of variance (rmANOVA) was undertaken with timepoint (i.e. pre-COVID and during COVID) entered as the within subjects factor. PSQI total, Bedtime, Sleep latency, Wake time, Actual sleep duration and daytime dysfunction were entered as the Independent variables and Gender (female, male) entered as the between groups variable. To test the second hypothesis bivariate correlational analyses were undertaken between the pre-COVID PSQI scores and the 3 constructs of impact, general worry, and COVID-specific worry and rumination. Due to the PSQI subscale scores and the impact, worry, and COVID-specific worry items being rank ordinal, Spearman's rho are reported. To test the final hypothesis a bivariate correlational analysis was undertaken between participants' WM FA values measured at the timepoint prior to the COVID-19 pandemic and the 3 constructs of impact, general worry, and COVID specific worry and rumination. Again Spearman's rho are reported. As the correlational analysis are exploratory no corrections for multiple comparisons are made. Follow-up linear regression analysis was then undertaken with COVID specific worry and rumination entered as the dependent variable, and pre-COVID sleep onset latency, gender, PSQI change (change in PSQI score from pre-COVID to during COVID) and FA value of the PLIC entered as the predictor variables.

3. Results

During the COVID-19 lockdown period $N = 30$ participants (43% female) undertook the PSQI, impact, general worry, and COVID-

Table 1
Mean (with standard error) and rmANOVA significance results of pre-COVID and during COVID comparisons for overall sleep quality (PSQI total) and PSQI subscales.

	Pre- Covid Mean (SE)	During Covid Mean (SE)	*F*	Sig	Partial η^2
PSQI Total**	3.15 (0.36)	3.91 (0.34)	10.04	.004	.271
Bedtime (pm)	9.40 (0.21)	9.58 (0.24)	2.449	.129	.083
Sleep onset latency mins	25.63 (4.14)	28.19 (6.83)	.228	.637	.008
Wake time (am)*	6.52 (0.30)	7.43 (0.30)	6.85	.014	.202
Actual sleep hours**	8.54 (0.17)	9.23 (0.20)	8.74	.006	.244
Daytime dysfunction	0.46 (0.11)	0.64 (0.12)	2.56	.121	.087

Note: ** indicates $p < .01$, * indicates sig at $p < .05$.

specific worry and rumination items remotely. Mean age for the sample during this period was 14.02 years (range 12.93–14.85). Table 1 shows a comparison of measures taken pre-COVID with those taken for the same participants during COVID. Repeated measures ANOVA results showed significant changes in sleep quality, wake time and actual sleep duration. Gender was entered as a between-groups factor with no significant gender-based differences found.

Table 2 shows the results from a bivariate correlational analysis between pre-COVID PSQI total and subscale scores and the 3 constructs of, impact, general worry, and COVID specific worry/rumination measured during the COVID lockdown period.

Table 3 shows the correlations between the pre-COVID FA values from the WM tracts and the 3 constructs of, impact, general worry, and COVID specific worry/rumination measured during the COVID lockdown period. Significant positive associations were found between COVID specific worry/rumination measure and the PLIC and anterior corona radiata. While significant negative correlations were found between general worry and the cingulate gyrus and splenium of the corpus callosum.

To further address hypotheses 2 and 3 follow-up linear regression analysis was then undertaken with the worry/ruminating about COVID item entered as the dependent variable. Pre-COVID sleep latency was selected from the sleep measures as it showed the strongest association with any of the worry measures (see Table 2). The PLIC was chosen due to it demonstrating the strongest association of the WM tracts with any of the worry measures (see Table 3). PSQI change was added in to the regression analysis to test for the impact of overall sleep quality change (pre-COVID to during COVID) and gender was also entered in order to measure the potential impact of gender differences. The overall model was found to be a significant predictor of worry/rumination about COVID ($R^2 = .469$, $F(4, 18) = 3.97$, $p = .018$). Independently both pre-COVID sleep onset latency and the pre-COVID FA value of the PLIC were found to be significant predictors of worry during COVID after controlling for gender and change in PSQI score (see Table 4).

4. Discussion

The impact of the COVID-19 pandemic on the mental health of adolescents is largely unknown. Changes to school day routines has the potential to lead to changes in bed and wake time, sleep duration and sleep quality. Adolescent anxiety and worry levels are also likely to be impacted due to social distancing and isolation from peers, stress related to family or personal financial hardship due to loss of employment or reduction in work hours, and fear of contracting COVID-19 exasperated by continuous news updates of death tolls and infection rates. The relationship between sleep and distress is well established (Jamieson et al., 2020). Previous findings also suggest that sleep onset latency may influence the impact of chronic stressful situations on anxiety symptoms (Kalmbach et al., 2019) while symptoms of depression and anxiety including rumination and worry have been associated with changes in the structural integrity of WM (Baur et al., 2012; Kim & Whalen, 2009; Korgaonkar et al., 2011; Zuo et al., 2012).

The current study aimed to investigate whether, in early adolescents, there is an association between: (1) sleep quality pre-COVID and sleep quality during COVID; (2) pre-COVID sleep measures and COVID specific worry; and (3) pre-COVID WM integrity and COVID specific worry. It was hypothesised that: (i) sleep quality reported by adolescents during COVID would be worse compared to their pre-COVID sleep quality; (ii) poor sleep quality pre-COVID will be associated with increased COVID specific worry and rumination; and (iii) perturbed WM integrity pre-COVID will be associated with increased COVID specific worry and rumination.

Regarding our first hypothesis, self-reported sleep quality measured using the PSQI global score was shown to be significantly poorer during COVID than pre-COVID. The relationship between reduced sleep quality and the increased likelihood of anxiety disorders in adolescents is well documented in the research literature (Lee et al., 2012; Tarokh et al., 2016) and clinically through the inclusion of sleep disturbance as a criteria for the diagnosis of many anxiety disorders in the DSM-5 (APA, 2013). And it seems likely that the importance of good sleep quality is of even greater importance during the stressful circumstances of a global pandemic. This finding provides guidance for future stressful events such as health pandemics or natural disasters. The maintenance of sleep quality during future 'lock-down' situations should be a priority. Prioritising sleep quality needs to be of high importance and communicated to parents and adolescents perhaps through schools or government health advertisements.

In accordance with our second hypothesis, a significant correlation was found between pre-COVID sleep onset latency and the measure of COVID-specific worry and rumination. Additionally we found a significant correlation between pre-COVID sleep onset latency and general worry, however no significant correlations were found between the sleep measures and the 7 impact items. These findings support those reported by Kalmbach et al. (2019) which demonstrated that prior poor sleep quality and increased sleep onset latency predicted anxiety symptoms including worry under future stressful situations and suggest that perhaps a level of resilience to the impact of future stressful situations could be established by focusing on reducing sleep onset latency in the adolescent population.

Table 2
Bivariate correlational coefficients between Pre-COVID sleep measures (PSQI) and the impact, general worry, and COVID specific worry/rumination constructs measured during the COVID lockdown period.

	Pre-COVID sleep onset latency	Pre-COVID sleep disturbance	Pre-COVID subjective sleep quality	Pre-COVID daytime dysfunction	Pre-COVID PSQI total score
Impact (7 item total) (*p* value)	.340 (.066)	.322 (.083)	.167 (.378)	.188 (.321)	.230 (.230)
General worry (*p* value)	.415 (.023)*	.285 (.127)	.265 (.158)	.163 (.390)	.270 (.157)
Worry/ruminating about COVID (*p* value)	.428 (.018)*	.142 (.454)	.210 (.265)	.211 (.263)	.277 (.145)

Note: Spearman's rho reported. * indicates *p* value < .05 (uncorrected *p* values reported).
PSQI Sleep Med subscale was omitted from table as all participants scored reported no use in past month.

Table 3
Bivariate correlational coefficients between fractional anisotropy (FA) values of white matter tracts and the worry measures.

	PLIC	Ant Corona Radiata	SLF	Cingulate gyrus	Cingulate hipp	UF	Genu	Splenium	ALIC
Impact (7 item total) (*p* value)	-.093 (.671)	-.153 (.486)	-.179 (.413)	-.108 (.617)	.019 (.930)	.078 (.716)	-.004 (.986)	-.161 (.462)	-.177 (.409)
General worry (*p* value)	-.355 (.097)	-.355 (.097)	-.393 (.064)	-.447 (.028)*	.027 (.902)	-.152 (.478)	-.246 (.258)	-.454 (.029)*	-.348 (.096)
Worry/ruminating about COVID (*p* value)	.522 (.011)*	.455 (.029)*	.258 (.235)	.037 (.862)	.267 (.218)	.203 (.342)	.356 (.095)	.300 (.164)	.356 (.088)

Note: Spearman's rho reported, * indicates p value $< .05$ (uncorrected p values reported).
Abbreviations in table: Posterior limb of the internal capsule (PLIC), Anterior (Ant) Corona Radiata, Corpus callosum (CC), Superior longitudinal fasciculus (SLF), Uncinate fasciculus (UF), Anterior limb of the internal capsule (ALIC).

Table 4
Linear regression coefficients output for model with worry/ruminating about COVID entered as the dependent variable.

	B	S.E.	t	sig
Pre-COVID sleep onset latency	.296	.210	2.258	.037*
Gender	-.076	.210	-.362	.721
PLIC Bil FA	12.70	5.286	2.403	.027*
PSQI Change	.047	.089	.536	.599

Note: * indicates p value $< .05$.
PSQI Change – change in PSQI total score pre-COVID to during COVID.
Dependent variable: Worry/ruminating about COVID.
Bil = Bilateral.

Educating children and adolescents about practicing good sleep hygiene before bed could be hugely beneficial here. Perhaps school-based programs educating students on the benefits of sleep hygiene basics such as; darkening the bedroom, powering down devices, not using devices before bed, cooling down the room, not clock watching, and teaching pre-sleep metacognitive and meditation techniques to help quiet the mind (National Sleep Foundation, N.D.). The National Sleep Foundation also suggests keeping a diary or to-do list to reduce pre-sleep rumination about tasks and that writing them down can allow the individual to clear the mind of concerns and perhaps reduce sleep onset latency (National Sleep Foundation, N.D.)

In accordance with our third hypothesis, significant positive associations were found between the structural integrity of the PLIC and anterior corona radiata and the COVID-specific worry and rumination item. Participants with increased structural integrity of the PLIC and anterior corona radiata were more likely to have increased COVID-specific worry and rumination. We also found significant negative correlations between the cingulate gyrus and splenium of the corpus callosum and the measure of general worry. That is participants who showed decreased structural integrity of the cingulate gyrus and splenium of the corpus callosum were more likely to report increased general worry. This trend exists across the WM tracts investigated showing that increased structural integrity is associated with COVID-specific worry and rumination while decreased structural integrity is associated with increased general worry. This perhaps suggests that the state specific nature of COVID-specific worry and rumination maybe associated with increased structural connectivity between specific brain regions while general (trait) worry maybe associated with reduced structural connectivity. Further research investigating these WM tracts in clinical populations and populations facing state specific worry is needed to help tease apart this relationship.

Follow-up regression analysis found that a model containing pre-COVID sleep onset latency, PLIC structural integrity, PSQI change (pre-COVID to during COVID) and gender explained a significant 47% of the variance in COVID-specific worry and rumination. Pre-COVID sleep onset latency was chosen as the sleep measure due to it being the only sleep measure that showed a significant relationship with general worry and COVID-specific worry and rumination. The PLIC was chosen over the other WM tracts due to it showing the highest association with any of the three impact and worry constructs. Gender and PSQI change were added to the model to investigate the impact that they may have on COVID-specific worry and rumination. Both pre-COVID sleep onset latency and the structural integrity of the PLIC contributed significantly to the model after controlling for the effects of overall changes in sleep quality suggesting that perhaps measures of sleep onset latency and structural integrity of the PLIC may be able to be used as predictors of susceptibility to future stressful situations and also that improving sleep onset latency may provide a form of defense.

Some limitations of the current study need to be acknowledged. Firstly, while the findings provided in this study provide important insights, the novel circumstances that resulted from the COVID-19 pandemic make the comparison of findings with recent studies conducted under similar circumstances difficult. This means that findings such as those reported here need to be considered as preliminary and are therefore in need of replication. Secondly, making inferences regarding structural integrity and myelination of WM tracts from FA values can be misleading. FA values may reflect a number of biological properties of WM tracts including differing levels of myelin, loss of axons or increase in axonal density, increased axonal diameter, lack of directional coherence and reduced neural branching (Feldman, Yeatman, Lee, Barde, & Gaman-Bean, 2010; Lagopoulos et al., 2013; Soares, Marques, Alves, & Sousa, 2013; Thomason & Thompson, 2011). It is important to keep this in mind when interpreting diffusion-derived estimates of WM structure.

Thirdly, TBSS uses information derived from the mean skeletonized FA of each WM tract. This can result in some information being missed. Future replication should look at change in FA along the tract and how variability correlates with worry measures, and also a whole brain tractography approach to provide insight into structural networks and worry.

Fourthly, the current study does not allow for the control of existing confounds such as trait anxiety which could impact COVID-specific worry and levels of general worry. This should be kept in mind when interpreting the findings. It is also unclear if pre-COVID differences in WM integrity resulted in level of general worry or COVID-specific worry and rumination, or if pre-existing conditions such as early life stress or anxiety symptoms lead to reduced WM integrity and 'concurrently' an increased susceptibility to worry about COVID-19. A fifth limitation is the use of a retrospective self-report measure for sleep quality is a limitation of the current study due to the subjective nature of self-report measures and possible recall bias. The PSQI was chosen due to its demonstrated validity and reliability, as well as its convenience and feasibility given the multi-modal, complex protocols of LABS. The PSQI has been shown to be a valid and reliable measure of sleep quality for studies of adolescents (de la Vega et al., 2015; Raniti et al., 2018) and has demonstrated convergent validity with measures of anxiety in an adolescent sample (Raniti et al., 2018). While the PSQI provided valuable information under circumstances when face-to-face methods of sleep measurement were not possible, it is acknowledged that future replication of this study would benefit from the inclusion of an objective measure of sleep quality such as polysomnography or actigraphy to provide an objective measure of sleep quality. Finally, the correlational analysis reported in Tables 2 and 3 were exploratory and as such no correction for multiple comparisons were made. This needs to be kept in mind when considering these findings.

5. Conclusion

COVID-19 has had a significant impact on the lives of people all over the world. Studies into the physical and mental health impacts of social distancing measures are of vital importance to help us to prepare for similar future events should they arise. The results from this study provide important insights into the impact of COVID-19 on sleep quality and worry. They suggest that addressing sleep onset latency issues early may reduce susceptibility to future stressful events. They also propose a possible role for measures of WM structural integrity of the PLIC and anterior corona radiata in predicting worry during stressful events.

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Appendix

Coronavirus Worry and Impact Questionnaire (CWIQ).

The items below have been adapted from established scales as noted.

Over the past month, how often have you spent time worrying about things?			
Never (0)	Sometimes (1)	Often (2)	All of the time (3)
Over the **past month**, how much of the time have you worried or gone over and over in your mind about Coronavirus (COVID-19).			
Never (0)	Sometimes (1)	Often (2)	All of the time (3)

Adapted from the *Spence Children's Anxiety Scale* (SCAS): Spence, S. H. (1998). A measure of anxiety symptoms among children. *Behaviour Research and Therapy*, *36*(5), 545–566. Bennett, H., & Wells, A. (2010). Metacognition, memory disorganization and rumination in posttraumatic stress symptoms. *Journal of Anxiety Disorders*, *24*, 318–325.

Impact of the Coronavirus (COVID-19) (7 items).

Over the past month, how much has the Coronavirus (COVID-19) affected …				
	Never (0)	Sometimes (1)	Often (2)	All of the time (3)
you and your family?				
your parent's jobs?				
your family being able to buy things like food?				
your health?				
your family's health?				
your grandparent's health?				
you and your family having to self-isolate or stay at home for a long period of time?				

Adapted from: Dorahy, M. J., & Kannis-Dymand, L. (2012). Psychological distress following the 2010 Christchurch earthquake: A community assessment of two differentially affected suburbs. *Journal of Loss and Trauma*. 17, 203–217.

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