Association of Excessive Social Media Use with Abnormal White Matter Integrity of the Corpus Callosum

ABSTRACT

Borrowing from findings regarding other problematic behaviors, we posit that excessive social media use (ESMU) can relate to impaired inter-hemispheric connections. These are often reflected in impaired white matter integrity (decreased fractional anisotropy and increased mean diffusivity) of the corpus callosum. We test this idea with diffusion tensor imaging (DTI) data from 20 normal social media users with varying degrees of ESMU. The findings of a Regions of Interest analysis focusing on the corpus callosum indicate that ESMU is associated with increased mean diffusivity in the body and splenium sub-regions of the corpus callosum. Whole-brain Tract Based Spatial Statistics analysis revealed that ESMU is positively associated with mean diffusivity of left superior and inferior longitudinal fasciculi as well as left forceps minor; and that ESMU is positively associated with the fractional anisotropy of the right Corticospinal Tract. It is concluded that inter-hemispheric white matter deficits in the corpus callosum extended to forceps minor, as well as along the ventral semantic path can be associated with ESMU.

Keywords: problematic use; excessive social media use; corpus callosum; forceps minor; Diffusion Tensor Imaging; Facebook; white matter

1. Introduction

The use of social media sites can excite the reward centers of the brain (Meshi et al., 2013; Meshi et al., 2015). Hence, some people may develop excessive use patterns that may provide immediate reinforcing rewards but be disadvantageous in the long-run, and infringe users' normal functioning

(Montag et al., 2017; Montag et al., 2018). Excessive social media use (ESMU) is defined as an excessive behavioral pattern of social media use that has adverse effects on individuals by producing addiction-like symptoms, including salience, withdrawal, mood modification, relapse, conflict, and tolerance" (He et al., 2017b). It can be viewed as a sub-category in the broader spectrum of problematic excessive use of the Internet. We use the term ESMU because agreement regarding the use of the term "addiction" to describe such issues, especially in the context of social media use, is still lacking (Griffiths, 2012; Ryan et al., 2014) and we want to avoid over-pathologizing common, but excessive behaviors (Kardefelt-Winther et al., 2017) until the definition, classification conditions and boundaries of technology addictions mature.

Behaviorally, ESMU can manifest in an imbalance between reward and inhibition brain systems, which results in impaired decision making such that a person emphasizes short-term reinforcing rewards over larger long-term utilitarian rewards (Turel and Qahri-Saremi, 2016). Such disadvantageous decisions underlie many excessive behaviors (Bechara and Damasio, 2005; Bechara and Damasio, 2002). Functionally, ESMU has been associated with hyper-active amygdala-striatal system (Turel et al., 2014); structurally, it has been associated with differences in the amygdala-striatal system but to a lesser extent with prefrontal abnormalities (He et al., 2017a; He et al., 2017b; Montag et al., 2017; Montag et al., 2018).

Another, yet largely overlooked possibility, is the idea that ESMU may also relate to impaired inter-hemispheric connections (Yip et al., 2013). The logic is that when the communication between hemispheres is suboptimal (e.g., when molecule diffusion is isotropic), transfers of information may be too slow or ineffective for analyzing the situation and to mobilize the needed inhibition resources (Zorlu et al., 2013). Such inter-hemispheric connectivity issues (as often manifested in impaired integrity of the corpus callosum) result in deficient decision making ability, as reflected in increased delay discounting (Olson et al., 2009) and poor performance on the Iowa Gambling Task (Brown et al., 2012). Indeed,

reduced effectiveness of the corpus callosum has been demonstrated across many behaviors that involve deficient decision making. These include opiate addiction (Bora et al., 2012), alcoholism (Harris et al., 2008), marijuana use (Arnone et al., 2008), gambling (Joutsa et al., 2011b), substance abuse (Kaag et al., 2017), kleptomania (Grant et al., 2006) and trichotillomania (Chamberlain et al., 2010).

Recent research has also demonstrated that corpus callosum white matter integrity can be associated with excessive use technologies, including the Internet (Lin et al., 2012a; Shin et al., 2013; Yuan et al., 2011) , videogames (Jeong et al., 2016; Weng et al.), and smartphones (Hu et al., 2017). Nevertheless, results have not been consistent. While some point to increased corpus callosum effectiveness in excessive gamers (Jeong et al., 2016), others found decreased effectiveness in excessive Internet users (Bi et al., 2015; Lin et al., 2012a) and gamers (Weng et al., 2013), and others found no corpus callosum microstructure changes in excessive Internet (Yuan et al., 2011) or smartphone (Hu et al., 2017) users. It is noteworthy that such inconsistencies are common in the study of the corpus callosum role in other problematic behaviors; they may stem from differences in samples, duration of behavior and processing methods (Yu et al., 2016); or merely from the idea that diffusivity measures in this area are notoriously difficult due to the “kissing axons” problem (Jbabdi and Johansen-Berg, 2011).

These results imply that corpus callosum structural changes that promote decision making deficits (as often manifested in measures of isotropic diffusivity) may underlie excessive use of technologies, but that such corpus callosum effects may vary from one technology, sample and context to another. Hence, focusing on ESMU is research-worthy, because this is a new context that has not been addressed in prior corpus callosum research. Moreover, if we assume that ESMU is similar to other behaviors in which deficits in weighing short- vs. long-term reward and punishments prevail (e.g., substance abuse, excessive gambling), we can expect to find white matter changes in the corpus callosum that are associated with ESMU.

We focus on corpus callosum white matter integrity in terms of Fractional Anisotropy (FA) and Mean Diffusivity (MD). FA captures the degree of restrictiveness of molecule diffusion along the axon axis. When its value is 0 it means that the diffusion is sporadic in all directions and isotropic; when it is 1, it means that the diffusion is efficient and runs only along the axonal axis. Isotropic diffusion can reflect issues in myelination, axonal integrity and density, axon diameter and fiber crossings (Zatorre et al., 2012). FA is a common index of white matter integrity. Studies found significant association between FA in the corpus callosum and behavioral measures, including addiction (El-Hage et al., 2017; Lin et al., 2012b). For example, Lin et al. (2012b) found that an Internet addiction group had significantly lower FA in the corpus callosum than controls. El-Hage et al. (2017) found that COMT male Val homozygotes had significantly higher FA in the corpus callosum compared to Met-carriers. MD captures the total diffusion, in all directions, within a voxel. It is hence an inverse measure to FA; high values of MD are associated with low myelination (or high demyelination), reduced axonal density and may be indicative of axonal degeneration (Landman et al., 2007). We expect inefficient interhemispheric communication, manifested in reduced FA (Bi et al., 2015) and increased MD (Joutsa et al., 2011a), in people with higher levels of ESMU.

To test this hypothesis, we conduct a DTI study of 20 social media users, which was part of a larger study program that involved functional (Turel et al., 2014) and structural (He et al., 2017a) features of ESMU. We start with hypothesis-driven Region of Interest (ROI) analysis of the three core subdivisions of the corpus callosum (genu, body, and splenium). This split is guided by neurological and neuropsychological evidence that these parts are not functionally equivalent (Eliassen et al., 2000; Fabri and Polonara, 2013). The anterior parts of the corpus callosum are well known to relate to prefrontal and executive function processing, while the middle is more concerned with sensory-motor processing, and the posterior part is more concerned with vision-related processing. Hence, lumping together all tracts in the corpus callosum may be misleading and present a birds-eye-view of white matter integrity

rather than point to specific areas involved in ESMU. We then proceed with a whole-brain voxel-wise analysis (Tract Based Spatial Statistics; TBSS) as a supplemental approach. This is done to provide further support to our ROI analysis, and also to detect if there are other relevant regions, beyond our hypothesized ones, that emerge as significant; these may inform future research. In these analyses we correlate the ESMU scores with white matter integrity measures (FA and MD), after corrections for multiple comparisons and accounting for controls.

2. Methods

2.1. Participants

Twenty normal participants (10 females, Avg_{age}= 20.3 years, SD_{Age}=2.25 years, 18-23) who reported using Facebook and who were free of current and lifetime Axis I diagnoses (as per a short version of the Structural Clinical Interview for DSM-IV we administered) were recruited to participate in this study. The broader study program, which is beyond the scope of this study, employed the same participants for studying functional activations (Turel et al., 2014) and structural changes (He et al., 2017a) that underlie ESMU. While the sample is identical across these studies, the DTI data we use here is independent of prior studies, was collected for the sole purpose of this study, and was not used in prior published research. Hence, the only overlap with prior research is in terms of subjects and the screening surveys used. We focused on Facebook as popular instance of social media to avoid social media type effects. We nevertheless acknowledge that social media can be heterogeneous and studies with other media are warranted.

Participants had on average 4.7 years of Facebook experience (0.4 to 9), used Facebook 8.4 times per day (1–25), and had 743 Facebook contacts, on average (130 to 2500). All of them were self-reportedly healthy and had no medical or mental disorders that should preclude them from participation. All participants gave informed consent to the study procedures, which were approved by

the Institutional Review Boards of California State University, Fullerton and University of Southern California.

2.2. Measures

Excessive social media (Facebook) use was operationalized as a continuous variable, the score of which reflects the frequency of excessive use symptoms users have felt (e.g., withdrawal, loss of control, conflict, relapse, mood changes). These ESMU manifestations were measured with the 14 items of the Compulsive Internet Use instrument (Meerkerk et al., 2009), which were adapted to the case of Facebook (He et al., 2017b). The scale was valid and reliable (α= 0.92, *M*=2.20, SD=0.72 on a 1="never" to 5="very often" scale). Items and their descriptive statistics are given in the Appendix.

2.3. DTI Scanning Procedures

After screening for medical and mental disorders, as well as Facebook use, participants were asked to come to Dana and David Dornsife Cognitive Neuroscience Imaging Center for an MRI scan. They were first asked to read and sign the consent form, and then complete the study survey, which captured demographics, Facebook use statistics and ESMU. The MRI scan took about 20 min to finish. All MRI images were acquired using a 3T Siemens MAGNETOM Tim/Trio scanner at the University of Southern California. Participants lay in the supine position on the scanner bed. Foam pads were used to minimize head motion. Participants were instructed to simply rest but keep their head very still during the scan. The structural image was acquired using T1-weighted 3D-Magnetization Prepared RApid Gradient Echo (MPRAGE) sequence, covering the whole brain with the following scanning parameters: TR/TE = 2530/3.39 ms, flip angel = 7°, matrix = 256 * 256, number of slices = 128, and slice thickness = 1.33 mm. The diffusion-tensor data for each subject were acquired using a diffusion-weighted, single-shot, spin-echo, EPI sequence (TR/TE = 7200/104 ms, matrix = 128 * 128, 49 axial slices, 2.5 mm slice thickness, b-value = 1000 s/mm^2) in 64 directions. A dual spin-echo technique combined with bipolar gradients was employed to minimize the geometric distortion induced by eddy currents.

2.4. ***ROI Analysis***

We tested whether the sample has sufficient power for ROI analyses using the a-priori approach with G*Power (version 3.1.9.2). Findings indicated that given a large effect size of correlations (r = 0.5), a sample of 19 is needed to get a statistical power lager than 0.95 with $\alpha = 0.05$. It hence suggested that our sample size of 20 is sufficiently powered for the ROI analysis.

The DTI data were processed by FMRIB's Diffusion Toolbox (FDT) implemented in FSL. Diffusion data were corrected for eddy currents and possible head motion with *eddy_correct*. The direction of gradient was also corrected based on the results of eddy current correction using *fdt_rotate_bevecs* function. Images were then skull-stripped (Smith, 2002), registered to the structural images using FLIRT (Andersson et al., 2007a, b), aligned to MNI space using FNIRT (Andersson et al., 2007a, b), and re-sampled to 1 mm^3. FA and MD were reconstructed by fitting a diffusion tensor model at each voxel. To test our hypothesis, region of interest (ROI) analysis was performed using structurally-defined white matter regions. According to the ICBM-DTI-81 white-matter labels atlas (available in FSL), three sub-regions of the corpus callosum (the genu, the body, and the splenium) were selected as ROIs. These white matter tract labels were created by hand segmentation of a standard-space averages of diffusion MRI tensor maps from 81 subjects, provided by the ICBM DTI workgroup (Mori et al., 2005). By applying a nonlinear spatial normalization (computed during TBBS procedure), the ROI was co-registered to the B0 map of each subject. The mean FA was then computed in the ROI for each subject. Robust regression was used for all correlation to minimize the impact of outliers using *robustfit* command implemented in the MATLAB Statistics Toolbox. False discovery rate was used to adjust results for family-wise errors caused by testing multiple ROIs.

2.5. Supplemental Voxel-wise TBSS Analysis

To supplement the ROI analysis, voxel-wise statistical analysis of the FA and MD data was carried out using TBSS (Smith et al., 2006), part of FSL. The mean FA image was created and thinned to create a

mean FA skeleton that represented the centers of all tracts common to the group. Each subject's aligned FA and MD data were then projected onto this skeleton and the resulting data were fed into voxel-wise cross-subject statistical analysis. Finally, the resulting skeletonized FA and MD images were correlated with ESMU scores using non-parametric permutation methods (Randomise v2.1 in FSL, Nichols and Holmes, 2002) with age as a covariate. The null distribution at each voxel was constructed using 10,000 random permutations of the data. TFCE (Threshold Free Cluster Enhancement) was used to correct for multiple comparisons across the whole brain. TFCE has been suggested to have better sensitivity than other clustering methods (Salimi-Khorshidi et al., 2011b; Salimi-Khorshidi et al., 2011a; Smith and Nichols, 2009). Significance was set at $p < 0.025$ to account for family-wise errors caused by testing both FA and MD images.

3. Results

After controlling for age, we found in the ROI-based analysis a significant positive correlation between the MD in both the body and the splenium of corpus callosum (CC) and ESMU score (**Table 1**). However, the correlation between the MD in the body of CC and ESMU score was not significant after FDR correction. No other correlations were significant.

In the TBSS analysis, after controlling for age, we found that the FA of right corticospinal tract (MNI coordinates 10, -25, 55, **Table 2** and **Figure 1**) was positively correlated with ESMU score. No region showed negative correlation with ESMU score. After controlling for age, we found that the MD of the left superior longitudinal fasciculus (two clusters, MNI coordinates -42, -57, 9 and -32, -44, 30, **Table 2** and **Figure 1**), inferior longitudinal fasciculus (MNI coordinates -23, -57, 25, **Table 2** and **Figure 1**), and left forceps minor (MNI coordinates -12, 59, -6, **Table 2** and **Figure 1**) were positively correlated with ESMU score. No regions showed negative correlation with ESMU score.

4. Discussion

This study sought to extend the understanding of the neural basis of ESMU. Prior research indicated that ESMU can be associated with changes in functional activation and grey matter structure of reward systems in the brain (He et al., 2017a; He et al., 2017b; Turel et al., 2014). We posited that it is also possible that ESMU is linked to changes in white matter microstructure, especially in the corpus callosum, because reduced corpus callosum white matter integrity underlie many excessive behaviors (Krain and Castellanos, 2006; Pfefferbaum et al., 2010), including the excessive use of various technologies (Bi et al., 2015; Jeong et al., 2016; Lin et al., 2012a; Wang et al., 2016; Weng et al., 2013).

The findings of the ROI analysis provided some support for this view by showing positive correlation between the MD of the body and splenium sub-regions of the corpus callosum and ESMU. Hence, it is possible that ESMU is associated, at least in part, with inter-hemispheric communication deficits. This is in line with several studies on excessive Internet use (e.g., Lin et al., 2012a), but contradicts other findings that revealed less isotropic (more effective) molecule flow in the corpus callosum of excessive gamers (Jeong et al., 2016). These studies differ along several dimensions, including the population, scale used for measuring excessive behavior and the target technology. Such differences can explain inconsistent results (Yu et al., 2016) and suggest that it is possible that the nature of the rewarding technology (e.g., social media vs. video games) may be one reason for such differences. Difficulty to accurately record diffusion measures in the corpus callosum may be another reason for such inconsistencies (Jbabdi and Johansen-Berg, 2011).We hence call for more research on the role of the corpus callosum in ESMU and the excessive use of other technologies. Future research may also examine the underlying reasons for increased MD (possibly including: low myelination, high demyelination, reduced axonal density, axonal degeneration, etc.).

The TBSS analysis accounted for multiple whole-brain comparisons and was hence much more conservative compared to the ROI analysis. It revealed no direct corpus callosum associations with

ESMU. However, it indicated that the forceps minor, an extension of the corpus callosum into the frontal cortex, has increased MD in higher ESMU cases. This is consistent with findings of decreased FA in in the forceps minor in high BMI cases (Papageorgiou et al., 2017) and HIV plus women with a history of cocaine dependence (Wakim et al., 2017). It is inconsistent with findings of increased FA in forceps minor in excessive gamers (Jeong et al., 2016). Such differences regarding forceps minor can imply that findings regarding ESMU can differ from findings regarding the excessive use of other technologies. Nevertheless, they can be similar in terms of microstructure changes to other excessive and problematic behaviors (e.g., Wakim et al., 2017). The findings also imply that the connection between the corpus callosum and the lateral and medial surfaces of the frontal lobes can be sub-optimal in people with high ESMU scores, as reflected in their elevated MD of the forceps minor. This may explain their limited inhibition abilities (e.g., impaired forceps minor has been observed in children with Tourette syndrome, see Jackson et al., 2011), and should be examined in future research.

It is also interesting to consider the elevated MD observed in the TBSS analysis in Superior and Inferior Longitudinal Fasciculi. These tracts connect visual cortices to parietal and frontal regions. They are therefore involved in social-semantic meaning associations and retrieval and recording of memories; they run along the ventral semantic path (Duffau et al., 2013). Indeed, deficits in these tracts, such as reduced FA of the left superior longitudinal fasciculus were associated with reduced working memory and schizophrenia (Karlsgodt et al., 2008). In our case we found increased MD along these tracts in people with high ESMU scores. This means that these tracts are less efficient in their case, which can explain why they may fail to attach negative memories and warnings to visual stimuli associated with social media in order to mobilize inhibition (Turel et al., 2014), or why they distort perception related to social media use (Turel et al., 2018). While reasonable, such potential explanations merit further research.

The positive correlation between the FA values in the corticospinal tract and ESMU scores is also noteworthy. This reflects a strengthening of the corticospinal pathway as a function of ESMU. Given the functional role of the corticospinal tract in controlling motor movements, and especially the movements of the thumb and fingers in the upper limb, this positive relationship is consistent with this pathway strengthening finding. It can imply that this path is adapted in people with high ESMU scores who are likely to engage in more keyboard strokes and mouse movements compared to low ESMU cases. This idea, though, requires further research.

Several limitations of the study should be acknowledged. First, the sample was relatively small and focused only on Facebook users. While it seemed to have sufficient power for the ROI-analysis, we caution readers to interpret the results as preliminary, and call future studies to re-validate our model using larger sample sizes, and with other social media and technologies. Second, while we detected white matter microstructure associations with ESMU and suggested possible explanations for such associations, we did not test the underlying reasons for them. Moreover, we only tested FA and MD as measures of white matter integrity. Future studies should consider analyzing additional parameters (for example, radial diffusivity, RD,). FA alone might not be a good measure due to the many fibers crossing in this region; we included MD in this paper, but other measures can also shed light on the role of the corpus callosum in ESMU. Third, while the DTI results are unique for this study, the fact that the sample used here was also employed in other studies focusing on other aspects of ESMU may increase the over-representation of our sample in the literature. In order to better capture knowledge regarding the population of social media users, more research is needed, and further caution regarding over-interpreting our findings is warranted. Fourth, we assumed that social media use is rewarding for people with ESMU; we hence ignored possible tormenting aspects such as cyberbullying. We call for future research to account for such facets. Fifth, we measured ESMU using symptoms that resemble behavioral addictions. The definition and measurement of ESMU and its relation to addictive behaviors may evolve

over time. Hence, caution should be exercised when interpreting our results and they should be updated in the future to reflect changes in our understanding of the ESMU concept.

Lastly, tractography techniques are imperfect. Limitations include radial and transverse inaccuracies, as manifested in limited ability to distinguish among fiber configurations, such as crossing, kissing and fanning, dealing with errors and estimating accuracy, and determining polarity (Jbabdi and Johansen-Berg, 2011). Nevertheless, unlike other regions with many fiber crossings, bending, and kissing, such as Centrum Semiovale, the corpus callosum is known to have a major direction of fibers. Following Jbabdi et al. (2010), we tested this by dividing the *f1* and f2 values for all three corpus callosum sub-regions; the resultant values were very small (less than 0.05), suggesting that there is predominant direction in all three sub-regions. Nevertheless, future research may consider techniques for a more nuanced understanding of the observed micro-structure differences (Behrens et al., 2007; Douaud et al., 2011; Sotiropoulos et al., 2013; Tomassini et al., 2007).

5. Conclusion

This study demonstrated that ESMU may be associated with deficits in interhemispheric connection and in the communication along the ventral semantic path. These are reflected in increased mean diffusivity in key regions of the corpus callosum, extending to the forceps minor, and increased mean diffusivity of the left Superior and Inferior Longitudinal Fasciculi. We call for future research to further examine the important emerging issue of ESMU.

Disclosure statement

The authors declare no conflict of interest.

Author contributions

Conception and design of the study: OT, QH, AB; acquisition and analysis of data: OT, QH; drafting the manuscript or figures: OT, QH, AB.

Funding Information

QH was supported by research grants from the National Natural Science Foundation of China (31400959), Entrepreneurship and Innovation Program for Chongqing Overseas Returned Scholars (cx2017049), and Fundamental Research Funds for Central Universities (SWU1809003 and SWU1709106).

References

Andersson, J.L.R., Jenkinson, M., Smith, S., 2007a. Non-linear optimisation. FMRIB technical report TR07JA1 from www.fmrib.ox.ac.uk/analysis/techrep

Andersson, J.L.R., Jenkinson, M., Smith, S., 2007b. Non-linear registration, aka Spatial normalisation. FMRIB technical report TR07JA2 from www.fmrib.ox.ac.uk/analysis/techrep.

Arnone, D., Barrick, T.R., Chengappa, S., Mackay, C.E., Clark, C.A., Abou-Saleh, M.T., 2008. Corpus callosum damage in heavy marijuana use: Preliminary evidence from diffusion tensor tractography and tract-based spatial statistics. NeuroImage 41, 1067-1074.

Bechara, A., Damasio, A.R., 2005. The somatic marker hypothesis: A neural theory of economic decision. Games and Economic Behavior 52, 336-372.

Bechara, A., Damasio, H., 2002. Decision-making and addiction (part I): impaired activation of somatic states in substance dependent individuals when pondering decisions with negative future consequences. Neuropsychologia 40, 1675-1689.

Behrens, T.E., Berg, H.J., Jbabdi, S., Rushworth, M.F., Woolrich, M.W., 2007. Probabilistic diffusion tractography with multiple fibre orientations: What can we gain? Neuroimage 34, 144-155.

Bi, Y.Z., Yuan, K., Feng, D., Xing, L.H., Li, Y.D., Wang, H.M., Yu, D.H., Xue, T., Jin, C.W., Qin, W., Tian, J., 2015. Disrupted inter-hemispheric functional and structural coupling in Internet addiction adolescents. Psychiatry Research-Neuroimaging 234, 157-163.

Bora, E., Yucel, M., Fornito, A., Pantelis, C., Harrison, B.J., Cocchi, L., Pell, G., Lubman, D.I., 2012. White matter microstructure in opiate addiction. Addiction Biology 17, 141-148.

Brown, W.S., Anderson, L.B., Symington, M.F., Paul, L.K., 2012. Decision-Making in Individuals with Agenesis of the Corpus Callosum: Expectancy-Valence in the Iowa Gambling Task. Archives of Clinical Neuropsychology 27, 532-544.

Chamberlain, S.R., Hampshire, A., Menzies, L.A., et al., 2010. Reduced brain white matter integrity in trichotillomania: A diffusion tensor imaging study. Archives of General Psychiatry 67, 965-971.

Douaud, G., Jbabdi, S., Behrens, T.E., Menke, R.A., Gass, A., Monsch, A.U., Rao, A., Whitcher, B., Kindlmann, G., Matthews, P.M., 2011. DTI measures in crossing-fibre areas: increased diffusion anisotropy reveals early white matter alteration in MCI and mild Alzheimer's disease. Neuroimage 55, 880-890.

Duffau, H., Herbet, G., Moritz-Gasser, S., 2013. Toward a pluri-component, multimodal, and dynamic organization of the ventral semantic stream in humans: lessons from stimulation mapping in awake patients. Frontiers in Systems Neuroscience 7, 44.

El-Hage, W., Clery, H., Andersson, F., Filipiak, I., Thiebaut de Schotten, M., Gohier, B., Surguladze, S., 2017. Sex-specific effects of COMT Val158Met polymorphism on corpus callosum structure: A whole-brain diffusion-weighted imaging study. Brain Behav 7, e00786.

Eliassen, J.C., Baynes, K., Gazzaniga, M.S., 2000. Anterior and posterior callosal contributions to simultaneous bimanual movements of the hands and fingers. Brain 123, 2501-2511.
Fabri, M., Polonara, G., 2013. Functional Topography of Human Corpus Callosum: An fMRI Mapping Study. Neural Plasticity 2013, 251308.
Grant, J.E., Correia, S., Brennan-Krohn, T., 2006. White matter integrity in kleptomania: A pilot study. Psychiat. Res. 147, 233-237.
Griffiths, M.D., 2012. Facebook addiction: Concerns, critics, and recommendations: A response to Andereassen and colleagues. Psychol. Rep. 110, 518-520.
Harris, G.J., Jaffin, S.K., Hodge, S.M., Kennedy, D., Caviness, V.S., Marinkovic, K., Papadimitriou, G.M., Makris, N., Oscar-Berman, M., 2008. Frontal white matter and cingulum diffusion tensor imaging deficits in alcoholism. Alcoholism-Clinical and Experimental Research 32, 1001-1013.
He, Q., Turel, O., Bechara, A., 2017a. Brain anatomy alterations associated with Social Networking Site (SNS) addiction. Sci. Rep. 7, 1-8.
He, Q., Turel, O., Brevers, D., Bechara, A., 2017b. Excess social media use in normal populations is associated with amygdala-striatal but not with prefrontal morphology. Psychiatry Research-Neuroimaging 269, 31-35.
Hu, Y., Long, X., Lyu, H., Zhou, Y., Chen, J., 2017. Alterations in White Matter Integrity in Young Adults with Smartphone Dependence. Front. Hum. Neurosci. 11, 532.
Jackson, S.R., Parkinson, A., Jung, J., Ryan, S.E., Morgan, P.S., Hollis, C., Jackson, G.M., 2011. Compensatory Neural Reorganization in Tourette Syndrome. Current Biology 21, 580-585.
Jbabdi, S., Behrens, T.E., Smith, S.M., 2010. Crossing fibres in tract-based spatial statistics. Neuroimage 49, 249-256.
Jbabdi, S., Johansen-Berg, H., 2011. Tractography: Where Do We Go from Here? Brain Connectivity 1, 169-183.
Jeong, B.S., Han, D.H., Kim, S.M., Lee, S.W., Renshaw, P.F., 2016. White matter connectivity and Internet gaming disorder. Addiction Biology 21, 732-742.
Joutsa, J., Saunavaara, J., Parkkola, R., Niemela, S., Kaasinen, V., 2011a. Extensive abnormality of brain white matter integrity in pathological gambling. Psychiatry Res 194, 340-346.
Joutsa, J., Saunavaara, J., Parkkola, R., Niemela, S., Kaasinen, V., 2011b. Extensive abnormality of brain white matter integrity in pathological gambling. Psychiatry Research-Neuroimaging 194, 340-346.
Kaag, A.M., van Wingen, G.A., Caan, M.W.A., Homberg, J.R., van den Brink, W., Reneman, L., 2017. White matter alterations in cocaine users are negatively related to the number of additionally (ab)used substances. Addiction Biology 22, 1048-1056.
Kardefelt-Winther, D., Heeren, A., Schimmenti, A., van Rooij, A., Maurage, P., Carras, M., Edman, J., Blaszczynski, A., Khazaal, Y., Billieux, J., 2017. How can we conceptualize behavioural addiction without pathologizing common behaviours? Addiction 112, 1709-1715.
Karlsgodt, K.H., van Erp, T.G.M., Poldrack, R.A., Bearden, C.E., Nuechterlein, K.H., Cannon, T.D., 2008. Diffusion tensor imaging of the superior longitudinal fasciculus and working memory in recent-onset schizophrenia. Biological Psychiatry 63, 512-518.
Krain, A.L., Castellanos, F.X., 2006. Brain development and ADHD. Clinical Psychology Review 26, 433-444.
Landman, B.A., Farrell, J.A.D., Jones, C.K., Smith, S.A., Prince, J.L., Mori, S., 2007. Effects of diffusion weighting schemes on the reproducibility of DTI-derived fractional anisotropy, mean diffusivity, and principal eigenvector measurements at 1.5T. Neuroimage 36, 1123-1138.
Lin, F., Zhou, Y., Du, Y., Qin, L., Zhao, Z., Xu, J., Lei, H., 2012a. Abnormal White Matter Integrity in Adolescents with Internet Addiction Disorder: A Tract-Based Spatial Statistics Study. PLoS One 7.
Lin, F., Zhou, Y., Du, Y., Qin, L., Zhao, Z., Xu, J., Lei, H., 2012b. Abnormal white matter integrity in adolescents with internet addiction disorder: a tract-based spatial statistics study. PLoS One 7, e30253.

Meerkerk, G.J., Van Den Eijnden, R.J.J.M., Vermulst, A.A., Garretsen, H.F.L., 2009. The Compulsive Internet Use Scale (CIUS): Some Psychometric Properties. Cyberpsychol. Behav. 12, 1-6.
Meshi, D., Morawetz, C., Heekeren, H.R., 2013. Nucleus accumbens response to gains in reputation for the self relative to gains for others predicts social media use. Front. Hum. Neurosci. 7.
Meshi, D., Tamir, D.I., Heekeren, H.R., 2015. The Emerging Neuroscience of Social Media. Trends in Cognitive Sciences 19, 771-782.
Montag, C., Markowetz, A., Blaszkiewicz, K., Andone, I., Lachmann, B., Sariyska, R., Trendafilov, B., Eibes, M., Kolb, J., Reuter, M., Weber, B., Markett, S., 2017. Facebook usage on smartphones and gray matter volume of the nucleus accumbens. Behav. Brain Res. 329, 221-228.
Montag, C., Zhao, Z., Sindermann, C., Xu, L., Fu, M., Li, J., Zheng, X., Li, K., Kendrick, K.M., Dai, J., Becker, B., 2018. Internet Communication Disorder and the structure of the human brain: initial insights on WeChat addiction. Sci. Rep. 8, 2155.
Mori, S., Wakana, S., Van Zijl, P.C., Nagae-Poetscher, L., 2005. MRI atlas of human white matter. Elsevier.
Nichols, T., Holmes, A., 2002. Nonparametric permutation tests for functional neuroimaging: a primer with examples. Human Brain Mapping 15, 1-25.
Olson, E.A., Collins, P.F., Hooper, C.J., Muetzel, R., Lim, K.O., Luciana, M., 2009. White Matter Integrity Predicts Delay Discounting Behavior in 9-to 23-Year-Olds: A Diffusion Tensor Imaging Study. Journal of Cognitive Neuroscience 21, 1406-1421.
Papageorgiou, I., Astrakas, L.G., Xydis, V., Alexiou, G.A., Bargiotas, P., Tzarouchi, L., Zikou, A.K., Kiortsis, D.N., Argyropoulou, M.I., 2017. Abnormalities of brain neural circuits related to obesity: A Diffusion Tensor Imaging study. Magnetic Resonance Imaging 37, 116-121.
Pfefferbaum, A., Rosenbloom, M.J., Fama, R., Sassoon, S.A., Sullivan, E.V., 2010. Transcallosal White Matter Degradation Detected With Quantitative Fiber Tracking in Alcoholic Men and Women: Selective Relations to Dissociable Functions. Alcoholism-Clinical and Experimental Research 34, 1201-1211.
Ryan, T., Chester, A., Reece, J., Xenos, S., 2014. The uses and abuses of Facebook: A review of Facebook addiction. J. Behav. Addict. 3, 133-148.
Salimi-Khorshidi, G., Smith, S.M., Nichols, T.E., 2011a. Adjusting the effect of nonstationarity in cluster-based and TFCE inference. Neuroimage 54, 2006-2019.
Salimi-Khorshidi, G., Smith, S.M., Nichols, T.E., 2011b. Adjusting the effect of nonstationarity in cluster-based and TFCE inference. NeuroImage 54, 2006-2019.
Shin, H.I., Yoon, H.S., Kang, H.G., Ahn, H.M., Kim, S.H., 2013. Internet addiction disorder and alterations in white matter integrity: A DTI study. Journal of Cognitive Neuroscience, 214-214.
Smith, S., 2002. Fast robust automated brain extraction. Human Brain Mapping 17, 143-155.
Smith, S., Jenkinson, M., Johansen-Berg, H., Rueckert, D., Nichols, T., Mackay, C., Watkins, K., Ciccarelli, O., Cader, M., Matthews, P., 2006. Tract-based spatial statistics: voxelwise analysis of multi-subject diffusion data. Neuroimage 31, 1487-1505.
Smith, S.M., Nichols, T.E., 2009. Threshold-free cluster enhancement: Addressing problems of smoothing, threshold dependence and localisation in cluster inference. Neuroimage 44, 83-98.
Sotiropoulos, S.N., Jbabdi, S., Xu, J., Andersson, J.L., Moeller, S., Auerbach, E.J., Glasser, M.F., Hernandez, M., Sapiro, G., Jenkinson, M., 2013. Advances in diffusion MRI acquisition and processing in the Human Connectome Project. Neuroimage 80, 125-143.
Tomassini, V., Jbabdi, S., Klein, J.C., Behrens, T.E.J., Pozzilli, C., Matthews, P.M., Rushworth, M.F.S., Johansen-Berg, H., 2007. Diffusion-weighted Imaging tractography-based parcellation of the human lateral premotor cortex identifies dorsal and ventral subregions with anatomical and functional specializations. J. Neurosci. 27, 10259-10269.
Turel, O., Brevers, D., Bechara, A., 2018. Time distortion when users at-risk for social media addiction engage in non-social media tasks. Journal of Psychiatric Research 97, 84-88.

Turel, O., He, Q., Xue, G., Xiao, L., Bechara, A., 2014. Examination of neural systems sub-serving Facebook "addiction". Psychol. Rep. 115, 675-695.
Turel, O., Qahri-Saremi, H., 2016. Problematic use of social networking sites: Antecedents and consequence from a dual system theory perspective. J. Manage. Inform. Syst. 33, 1087-1116.
Wakim, K.M., Molloy, C.J., Bell, R.P., Ross, L.A., Foxe, J.J., 2017. White Matter Changes in HIV plus Women with a History of Cocaine Dependence. Frontiers in Neurology 8.
Wang, Y., Zou, Z., Song, H., Xu, X., Wang, H., d'Oleire Uquillas, F., Huang, X., 2016. Altered Gray Matter Volume and White Matter Integrity in College Students with Mobile Phone Dependence. Frontiers in Psychology 7, 597.
Weng, C.-B., Qian, R.-B., Fu, X.-M., Lin, B., Han, X.-P., Niu, C.-S., Wang, Y.-H., Gray matter and white matter abnormalities in online game addiction. European Journal of Radiology 82, 1308-1312.
Weng, C.-B., Qian, R.-B., Fu, X.-M., Lin, B., Han, X.-P., Niu, C.-S., Wang, Y.-H., 2013. Gray matter and white matter abnormalities in online game addiction. Eur. J. Radiol. 82, 1308-1312.
Yip, S.W., Lacadie, C., Xu, J.S., Worhunsky, P.D., Fulbright, R.K., Constable, R.T., Potenza, M.N., 2013. Reduced genual corpus callosal white matter integrity in pathological gambling and its relationship to alcohol abuse or dependence. World Journal of Biological Psychiatry 14, 129-138.
Yu, D.H., Yuan, K., Zhang, B.H., Liu, J.X., Dong, M.H., Jin, C.W., Luo, L., Zhai, J.Q., Zhao, L., Zhao, Y., Gu, Y., Xue, T., Liu, X., Lu, X.Q., Qin, W., Tian, J., 2016. White matter integrity in young smokers: a tract-based spatial statistics study. Addiction Biology 21, 679-687.
Yuan, K., Qin, W., Wang, G.H., Zeng, F., Zhao, L.Y., Yang, X.J., Liu, P., Liu, J.X., Sun, J.B., von Deneen, K.M., Gong, Q.Y., Liu, Y.J., Tian, J., 2011. Microstructure Abnormalities in Adolescents with Internet Addiction Disorder. PLoS One 6.
Zatorre, R.J., Fields, R.D., Johansen-Berg, H., 2012. Plasticity in gray and white: neuroimaging changes in brain structure during learning. Nat. Neurosci. 15, 528-536.
Zorlu, N., Gelal, F., Kuserli, A., Cenik, E., Durmaz, E., Saricicek, A., Gulseren, S., 2013. Abnormal white matter integrity and decision-making deficits in alcohol dependence. Psychiatry Research-Neuroimaging 214, 382-388.

Tables

Table 1: ROI correlation with ESMU

ROIs	FA	MD
Genu of CC	$r(17) = -0.004$, FDR corrected p = 0.49	$r(17) = 0.177$, FDR corrected $p = 0.23$
Body of CC	$r(17) = -0.067$, FDR corrected p = 0.59	$r(17) = 0.412$, FDR corrected $p = 0.06$[a]
Splenium of CC	$r(17) = -0.129$, FDR corrected p = 0.88	$r(17) = 0.486$, FDR corrected $p = 0.05$[*]

CC: Corpus Callosum, ROI: Region of Interest, FA: Fractional Anisotropy, MD: Mean Diffusivity

[a]: not significant after FDR correction; [*]: significant after FDR correction.

Table 2: Summary of whole-brain voxel-wise TBSS results

L/R	Brain region	No. of Voxels	Peak Coordinates (*x, y, z*)	Geometric Center Coordinates (*x, y, z*)	TFCE corrected *p*
FA SHOWED POSITIVE CORRELATION WITH ESMU					
R	Corticospinal Tract	90	10, -25, 55	8.3, -24.4, 55.5	< 0.003
FA SHOWED NEGATIVE CORRELATION WITH ESMU					
NONE					
MD SHOWED POSITIVE CORRELATION WITH ESMU					
L	Superior Longitudinal Fasciculus	276	-42, -57, 9	-44.9, -55.2, 3.1	< 0.001
L	Superior Longitudinal Fasciculus	231	-32, -44, 30	-33.3, -50.4, 27.5	< 0.001
L	Inferior Longitudinal Fasciculus	148	-23, -57, 25	-21.9, -56.9, 26.6	< 0.002
L	Forceps Minor	113	-12, 59, -6	-9.5, 55.4, -12.0	< 0.002
MD SHOWED NEGATIVE CORRELATION WITH ESMU					
NONE					

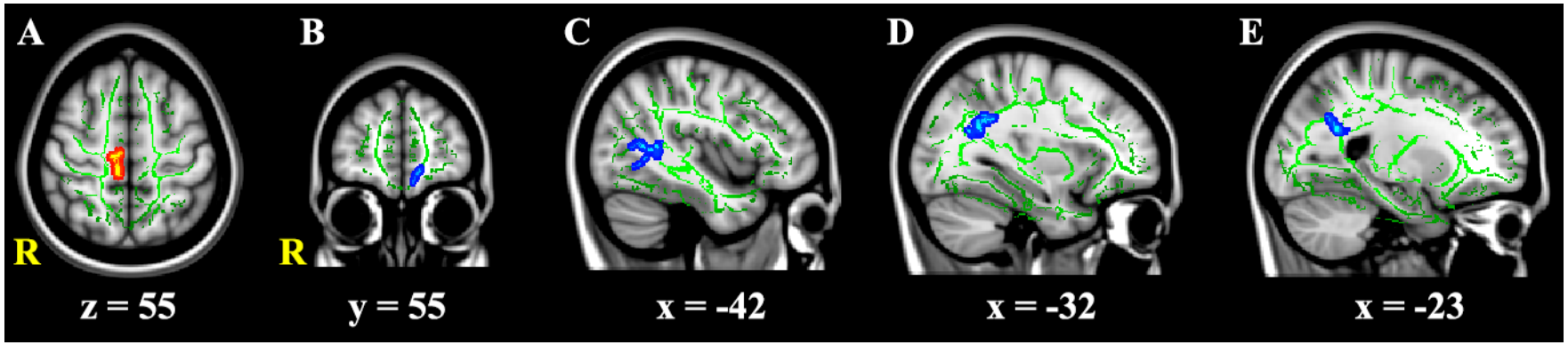
L: Left, R: Right, TBSS: Tract Based Spatial Statistics, FA: Fractional Anisotropy, MD: Mean Diffusivity

Note: Voxel size in the TBSS analysis is 1 mm × 1 mm × 1 mm = 1 mm^3. All results are in MNI space.

Figure Caption

Figure 1: Axial (A and B) and Sagittal (C, D, and E) slices showed the FA (in red) and MD (in blue) correlation with ESMU. The mean FA skeleton is shown in green. All clusters were expanded using the *tbss_fill* function to better illustrate the location. TBSS results suggested that FA value in right corticospinal tract (A) positively correlated with ESMU, and MD value in left forceps minor (B), left superior longitudinal fasciculus (C and D), and left inferior longitudinal fasciculus (E) positively correlated with ESMU. Yellow letter R represents the right hemisphere. Numbers below the slices indicate the slice number in the MNI space.

Figure 1



Appendix

Survey Items

How often…. (1=Never, 5=Very Often)	Mean	SD
- do you find it difficult to stop using Facebook when you are online [or bored]?	3.35	1.09
- do you continue to use Facebook despite your intention to stop?	3.05	1.19
- do others (e.g., parents, siblings, friends) say you should use Facebook less?	1.85	0.99
- do you prefer to use Facebook instead of spending time with others (e.g., family, friends)?	2.05	1.10
- are you short of sleep because of Facebook?	1.55	0.76
- do you think about Facebook even when not online?	1.55	0.76
- do you look forward to your next Facebook session?	1.85	1.27
- do you think you should use Facebook less often?	2.00	0.86
- have you unsuccessfully tried to spend less time on Facebook?	2.30	0.98
- do you rush through your homework or chores in order to use Facebook?	2.95	1.28
- do you neglect your daily obligations (school, chores, or family life) because you prefer to use Facebook?	2.35	1.09
- do you use Facebook when you are feeling down?	1.50	0.69
- do you use Facebook to escape from your sorrows or get relief from negative feelings?	2.00	1.03
- do you feel restless, frustrated, or irritated when you cannot use Facebook?	2.45	1.00