Received: 17 March 2021 | Revised: 18 June 2021 | Accepted: 22 June 2021

DOI: 10.1002/hbe2.272

THEORETICAL ARTICLE

WILEY

Show me your smartphone… and then I will show you your brain structure and brain function

Christian Montag[1] | Jon D. Elhai[2,3] | Paul Dagum[4]

[1]Department of Molecular Psychology, Institute of Psychology and Education, Ulm University, Ulm, Germany

[2]Department of Psychology, University of Toledo, Toledo, Ohio

[3]Department of Psychiatry, University of Toledo, Toledo, Ohio

[4]Applied Cognition, Los Altos, California

Correspondence
Christian Montag, Department of Molecular Psychology, Institute of Psychology and Education, Ulm University, Helmholtzstr. 8/1, Ulm 89081, Germany.
Email: mail@christianmontag.de

Abstract

Research in the field of digital phenotyping and mobile sensing has seen a tremendous rise in interest over the last few years. The psychological and psychiatric sciences were early adopters of implementing these promising techniques into their research to better understand the human mind. The most often studied data to predict mental states and traits at the moment represent reaction-time and app usage data from multi-step human-smartphone interactions and digital footprints left from the user's interactions with social media platforms. Interestingly, research that links reaction time measurements and other digital footprints to underlying neurobiology data from magnetic resonance imaging, electroencephalography, or molecular genetics has thus far been mostly lacking. As a starting point for discussion among neuroscientists, in this article, we review the scant literature applying digital phenotyping/mobile sensing to neuroscientific research and outline the potential of this new research approach. With the ubiquity of smartphones, many of these reviewed works focus on smartphone-based-studies in the neuroscientific digital phenotyping/mobile sensing field.

KEYWORDS

digital phenotyping, mobile sensing, neurosciences, personality, psychiatry, psychology, self-report, smartphones

1 | BACKGROUND

Recent years have seen a strong growth in studies using digital phenotyping (DP) and mobile sensing (MS) in diverse areas of science. A search on www.pubmed.gov reveals a rapidly growing number of articles with the terms "digital phenotyping" and "mobile sensing." Figure 1 shows that in 2019 the keyword *digital phenotyping* started to visibly outperform the keyword *mobile sensing*. MS commonly refers to prediction of psychological and other variables via digital traces left on mobile devices such as the smartphone. DP is broader and refers to prediction of mental traits/states via the manifold data sources captured from the Internet of Things (IoT). In the IoT, basically all digital variables ranging from onboard diagnostics in cars to kitchen coffee machines can be used to infer mental processes (Montag & Diefenbach, 2018). Recent work suggests that variables such as patterns of showering behavior and having meals (giving insights into orderliness) might be of relevance to predict academic performance (Cao, Gao, & Zhou, 2019).

2 | PSYCHOLOGICAL/PSYCHIATRIC SCIENCES ARE EARLY ADOPTERS OF DIGITAL PHENOTYPING AND MOBILE SENSING

A search for studies linking digital footprints to neurobiological data makes it evident that the research field is still nascent, likely because

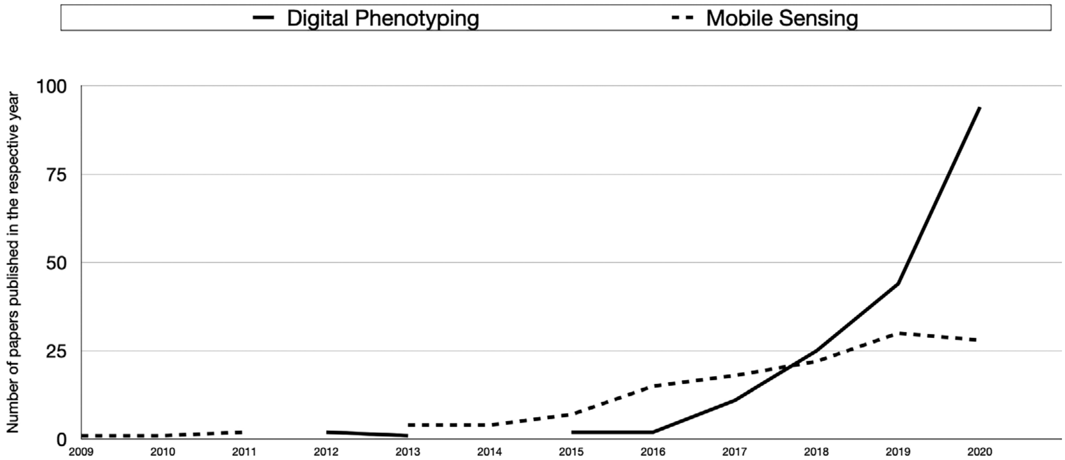

FIGURE 1 The literature on digital phenotyping and mobile sensing is growing fast (search results derived upon typing in "digital phenotyping" and "mobile sensing" in pubmed.gov; accessed on June 30, 2021; data for 2021 not depicted); please note that the numbers represent only rough estimates because the search engine in parts might produce invalid results (and some papers might define digital phenotyping and mobile sensing in different ways than we do)

of the prohibitive cost and resource to acquire neurobiological data at the scale of smartphone digital phenotyping data. We will elaborate on this in more detail in the next section. This is surprising because the psychological and psychiatric sciences have embraced the trend to incorporate digital footprints in their work (Markowetz, Błaszkiewicz, Montag, Switala, & Schlaepfer, 2014; Montag & Elhai, 2019). In an opinion article, former NIH director Tom Insel was very optimistic that "After 40 years of psychiatry becoming more mindless than brainless, perhaps digital phenotyping will help the pendulum swing back toward a fresh look at behavior, cognition, and mood" (Insel, 2017, p. 1216). Although this view might be too optimistic, the psychological sciences for years have been dealing with the so-called replication crisis (Open Science Collaboration, 2015) warranting new solutions. Research incorporating digital footprints to predict mental states could indeed help to address the replication problem of many psychological studies. Before we explain how digital phenotyping/mobile sensing could help to improve the work of scientists in the field of psychology/psychiatry, we reflect on reasons for replication problems. Among these are insufficient sample sizes, lack of statistical power (Anderson & Maxwell, 2017), problems related to measurement error (Loken & Gelman, 2017) and perhaps overreliance on WEIRD samples (Henrich, Heine, & Norenzayan, 2010). Arnett (2008) showed in his analysis that in six prominent psychological journals in 2007, 77% of participants were of European American decent. Such findings question the transferability of results to the broader population. To tackle these problems, beyond strategies proposed by the Open Science Framework, we believe it also will require implementing digital phenotyping/mobile sensing technologies. The smartphone can be a game changer for psychological work (Miller, 2012). It enables scientists to study human behavior in real life more effectively than ever before. Of unique importance, this powerful device enables researchers to conduct studies longitudinally with high ecological validity. In general, research relying on online recruiting strategies could be a solution in tackling the WEIRD problem. Gosling, Sandy, John, and Potter (2010) put it nicely by stating "Wired but not WEIRD." With smartphones, users are connected constantly to the online world and, in contrast to classical research experiments, participants provide richer ecological data. But, this comes at a cost of less control over nuisance factors that impact research hypotheses (Markowetz et al., 2014; Montag, Duke, & Markowetz, 2016).

In addition to the smartphone and its many sensors, the study of digital footprints stemming from human interaction with social media platforms has attracted many scientists to predict personality and other relevant variables. Here, the research field is already beyond a feasibility stage and demonstrated in meta-analyses that the Big Five of Personality, a prominent construct in personality psychology, can be robustly linked to digital traces (Azucar, Marengo, & Settanni, 2018; Marengo & Montag, 2020). But, it also needs to be mentioned that at the moment such a prediction seems to be possible only at the group but not individual person level (upper limit of associations perhaps around .40). Nevertheless, new work suggests that prediction rates might be higher in the near future by relying on other analysis techniques (Peltonen et al., 2020).

3 | STUDIES IMPLEMENTING DIGITAL PHENOTYPING/MOBILE SENSING STRATEGIES IN THE HUMAN NEUROSCIENCES ARE SCARCE

If we move to the neuroscientific literature, a comparable trend to that seen in psychological/psychiatric sciences cannot be seen until today. This again is surprising, as neuroscience often has been the innovation driver regarding development and adoption of new technologies and also the application of new statistical methods.

For instance, machine learning that is only now becoming popular in psychological work (Elhai & Montag, 2020), was embraced by neuroscience years earlier (Helmstaedter, 2015; Moradi, Pepe, Gaser, Huttunen, & Tohka, 2015; Salvatore et al., 2014). Perhaps a natural resistance to include “the study of digital traces” in human neurosciences has to do with the typical setup of an experiment in this area. One of the most prominent and often used technologies in human neurosciences is magnetic resonance imaging (MRI) technology. It can be divided into structural and functional parts. Structural MRI provides researchers insights into individual differences in the brain volume/density/architecture regarding gray and white matter by applying voxel based morphometry analysis to T1 scans or statistical analysis of diffusion weighted brain images. While functional aspects of MRI either relate to the investigation of how a person's brain responds to visual or auditory cues or how one's brain is activated while at rest (for a graphical overview on some of the technologies see works by Markett, Montag, et al. (2018) and Markett, Wudarczyk, et al. (2018)).

As the MRI setup is usually not portable (at least not until now) and represents a rather costly research environment, this illustrates the aforementioned hindrance to embracing the potential arising from merging mobile sensing/digital phenotyping techniques with neuroscientific data. From our perspective this is a missed opportunity, because studying digital footprints should not only reveal insights into psychological traits and states, but also into underlying neurobiology (the prevalent view among neuroscientists is that mind arises from matter; Cobb, 2020). Although inference of a person's neurobiology via means of DP/MS might sound ambitious from where we stand today, in the future it might become possible to make such predictions with great precision. We explicitly mention the rapid progress of our society toward even richer data environments and also rapid progress in the field of analysis techniques of big datasets. We feel that while this rapid progress will bring exciting potential to psychological, medical, and neuroscientific sciences to improve treatment of patients suffering from mental and neurological disorders (see also the potential in the area of dementia [Montag & Elhai, 2020]); we need to be attentive to the risk that digital societies including advancements in digital phenotyping/mobile sensing can be a source of misuse, endangering the privacy of billions of humans. For a recent framework on how to reduce harm and increase benefits see the work by Montag, Sindermann, and Baumeister (2020).

4 | AN OVERVIEW OF THE FIRST NEUROSCIENCE STUDIES RELYING ON DIGITAL TRACKING TECHNOLOGIES

We review the neuroscientific research carried out in recent years that applied DP/MS. Before reviewing the scant literature, we mention that much research has been carried out to understand overuse of smartphones/social media or in general the Internet by applying MRI. This research does not fall in the realm of our present review, because here usually self-reports on detrimental aspects of smartphone/Internet use have been linked to individual differences in brain structure/function (see review works by Montag and Becker (2019) and Yao et al. (2017)). We also do not want to focus in the present review on articles “only” relying on ecological momentary assessment (EMA; e.g., a prompt via smartphone to ask a person about his/her own well-being [Schwartz et al., 2019; Webb et al., 2020]). Instead, we focus on passively tracked smartphone data or other data from the IoT linked to MRI or other biological data of interest for the brain sciences.

A small number of pioneering feasibility studies showed that neuroscientific data indeed can be linked to digital footprints. For instance, Montag et al. (2017) investigated gray matter volume of the nucleus accumbens in the context of Facebook usage. A classic setup for studying Facebook use in the neurosciences would have been to link individual differences in gray matter volumes of brain reward circuitry to self-report measures on how much a person uses Facebook or social media in general. Instead, Montag et al. objectively recorded participants' Facebook usage on smartphones and then correlated this information with gray matter volume of the aforementioned brain area. Interestingly, this work was able to observe an inverse association between variables, hence, lower gray matter volumes of the accumbens region went along with longer and higher frequency of Facebook usage. In a recent work by Westbrook et al. (2021) findings from an investigation were presented where actual social media usage was tracked via a smartphone app and linked to PET scan data. The researchers of this study observed that greater social media app interactions were linked to lower capacity of dopamine synthesis in the bilateral putamen, also a region of the striatum. Therefore, Westbrook et al. even linked molecular brain processes to digital recorded smartphone data.

What else has been observed in recent work? In a study by Huckins et al. (2019) smartphone screen time was investigated in the context of resting state fMRI. Greater phone usage (unlock duration) was associated with greater functional connectivity between the subgenual cingulate cortex and nearby ventral prefrontal brain areas (p. 8). A work by Obuchi et al. (2020) also combined resting state fMRI technology with mobile (smartphone) sensing and could establish robust associations between functional connectivity between the ventromedial prefrontal cortex-amygdala and variables from MS (e.g., duration of conversation, about $r = .37$). Another recent study by Tost et al. (2019) applied data from EMA, but most important also information from location tracking (including data from the global positioning system) and hip accelerometers to study associations between wellbeing and exposure to urban green space (of note, also MRI analysis were conducted). Deeper discussion on how tracking technologies can grasp information on environmental features of a person and its combination with neuroscientific variables can be found elsewhere (Reichert et al., 2020a). Also see recent work investigating nonexercise activity in the context of brain data (Reichert et al., 2020b). We also mention recent work studying early-warning signals for multiple sclerosis disease activity via keystroke dynamics of the smartphone also taking into account the MRI data of patients (Twose, Licitra, McConchie, Lam, & Killestein, 2020).

Without doubt, MRI represents an important technology to study the brain in human neurosciences, but other neuroscientific

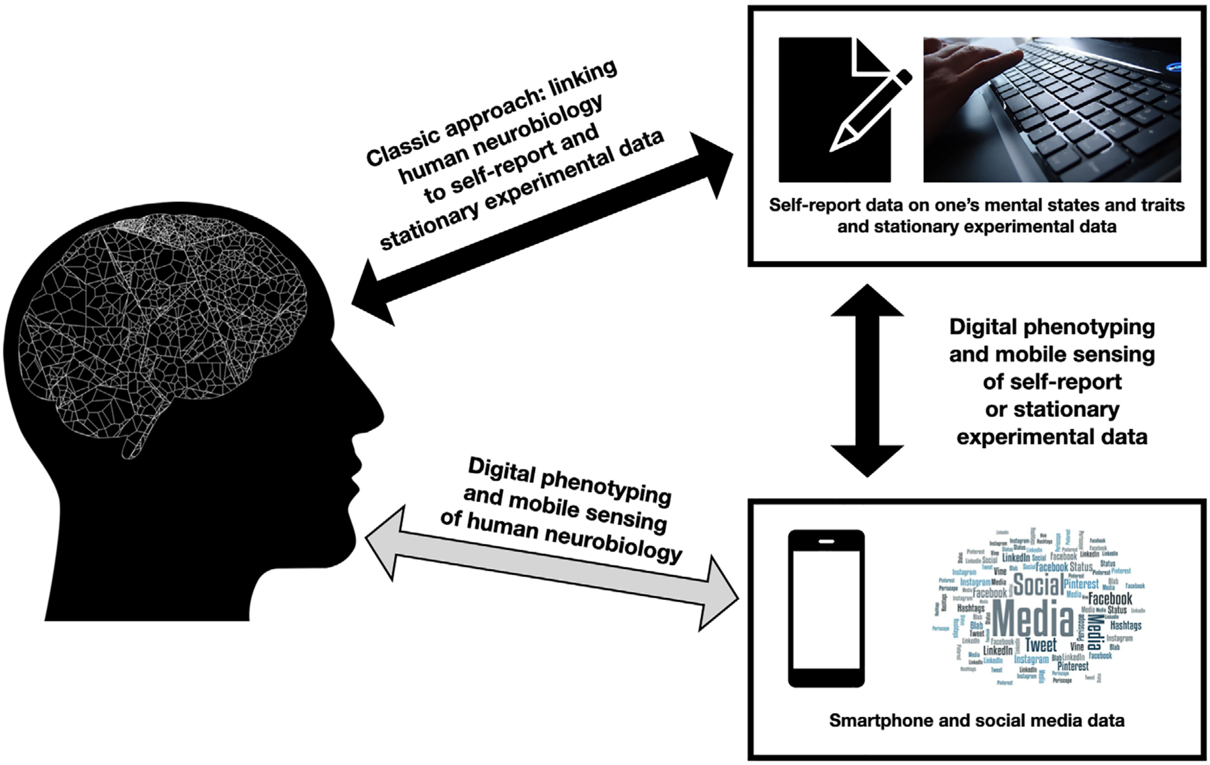

FIGURE 2 Digital phenotyping/mobile sensing is often applied in the psychological/psychiatric sciences. Moreover, the classic experimental setups in the human neurosciences foresee the combination of EEG/MRI/PET data with self-report data or experimental data such as answers provided in or outside the scanner. The gray arrow depicts the fusion of digital footprints with neuroscientific data (EMA is explicitly not mentioned here, as it falls in the realm of self-report information). Picture elements are also taken from Pixabay.com (license free)

technologies are also useful to shed light onto different layers of the human mind. For example, electroencephalography (EEG) has advantages compared to MRI with respect to recording of temporal resolutions of cortical brain activity (although it is also important to note that EEG is less suitable to record brain activity in subcortical regions of the brain). In the context of the present review, an interesting EEG study by Balerna & Ghosh (2018) successfully linked smartphone touchscreen behavior to activity in sensorimotor areas of the brain. In addition, we want to point to new interesting insights by Duckrow, Ceolini, Zaveri, Brooks, & Ghosh (2021) linking smartphone behavior toward epileptiform activity recorded from an implanted device in the brain.

Another starting point to understand the human mind represents molecular genetics. Here also initial studies have been published demonstrating feasibility to link the world of human genetics to real-world behavior. In a study by Sariyska, Rathner, Baumeister, and Montag (2018), a genetic marker of the oxytocin receptor gene could be linked to active social network size assessed via smartphone tracking. The findings are intriguing as the neuropeptide oxytocin is known to play a role in diverse social functions (Insel, 2010; Quintana et al., 2021), but due to the small sample in Sariyska et al. it is of importance to examine replication studies. Another article by DeBoever et al. (2020) should be mentioned at this point as they used the term "digital phenotyping" in their genetics article in the title, but after inspection of this work the scientists did not use the kind of digital data discussed in the present work. Finally, we mention interesting new work which linked gaze recorded via the smartphone to mental fatigue (Tseng, Valliappan, Ramachandran, Choudhury, & Navalpakkam, 2021).

5 | CONCLUSION

As one can see from the few highlighted works, the research field aiming to predict neurobiology of humans from digital footprints finds itself in the early stages. With the tremendous rise of psychiatric and neurodegenerative disorders across the world, not only sensing psychological constructs, but also the underlying neurobiology from ubiquitously available digital data is of utmost importance to understand human mental conditions.

Because of the global transformation into digital societies, given that we count at the moment more than 3.5 billion smartphone users carrying their phones often 24/7 and also considering that the world currently sees about 4 billion social media users, there is an abundance of digital data waiting to be studied. In the context of human neuroscientific research, this digital data may yield powerful new insights when combined with clinical data on molecular genetics, epigenetics, hormones, structural and functional MRI and EEG (see a more detailed overview in Montag and Elhai (2019)). Ultimately, a structured research approach not only relying on neuroscientific and self-report data, but also including digital footprints as an additional data layer, will likely bring human neuroscience to a better understanding of the human mind (see Figure 2). One day, indeed it might be possible to infer neurobiology of a person to a high degree of precision from studying digital traces, such as left from human smartphone interactions. These patterns of digital markers giving insights into the neurobiology of a person might be best termed digital biomarkers (Dagum, 2018, 2019).

ACKNOWLEDGMENT

Open access funding enabled and organized by Projekt DEAL.

CONFLICT OF INTEREST

The authors report no conflicts of interest with this article. However, for reasons of transparency the authors report the following.

Dr. Montag mentions that he has received (to Ulm University and earlier University of Bonn) grants from agencies such as the German Research Foundation (DFG). Dr. Montag has performed grant reviews for several agencies; has edited journal sections and articles; has given academic lectures in clinical or scientific venues or companies; and has generated books or book chapters for publishers of mental health texts. For some of these activities he received royalties, but not from gaming or social media companies. Dr. Montag mentions that he is part of a discussion circle (Digitalität und Verantwortung: https://about.fb.com/de/news/h/gespraechskreis-digitalitaet-und-verantwortung/) debating ethical questions linked to social media, digitalization and society/democracy at Facebook. In this context, he receives no salary for his activities. Finally, he mentions that he currently functions as independent scientist on the scientific advisory board of the Nymphenburg group. This activity is financially compensated. At the moment, he also receives funding for a research project on digital phenotyping by Mindstrong Health, Mountain View, CA.

Dr. Elhai notes that he receives royalties for several books published on posttraumatic stress disorder (PTSD); is a paid, full-time faculty member at University of Toledo; is a paid, visiting scientist at Tianjin Normal University; occasionally serves as a paid, expert witness on PTSD legal cases; and receives grant research funding from the U.S. National Institutes of Health.

Dr. Dagum is the founder of Mindstrong Health, a company developing digital phenotyping for mental healthcare delivery. He served as its Chief Executive Officer from its founding in 2013 through October 2019 and was granted five U.S. patents on digital phenotyping/digital biomarkers. Dr. Dagum is also the co-founder and CEO of Applied Cognition whose mission is to prevent and treat age and illness related declines in cognitive function using the first wearable device that continuously and remotely monitors brain health using a unique cognitive biomarker. Dr. Dagum owns stock in Mindstrong Health and in Applied Cognition.

AUTHOR CONTRIBUTIONS

Christian Montag wrote the first draft of this review article. This article was critically revised by both Paul Dagum and Jon D. Elhai.

PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1002/hbe2.272.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

ORCID

Christian Montag https://orcid.org/0000-0001-8112-0837

REFERENCES

Anderson, S. F., & Maxwell, S. E. (2017). Addressing the "replication crisis": using original studies to design replication studies with appropriate statistical power. *Multivariate Behavioral Research*, *52*(3), 305–324. https://doi.org/10.1080/00273171.2017.1289361

Arnett, J. J. (2008). The neglected 95%: Why American psychology needs to become less American. *American Psychologist*, *63*(7), 602–614. https://doi.org/10.1037/0003-066X.63.7.602

Azucar, D., Marengo, D., & Settanni, M. (2018). Predicting the Big 5 personality traits from digital footprints on social media: A meta-analysis. *Personality and Individual Differences*, *124*, 150–159. https://doi.org/10.1016/j.paid.2017.12.018

Balerna, M., & Ghosh, A. (2018). The details of past actions on a smartphone touchscreen are reflected by intrinsic sensorimotor dynamics. *Npj Digital Medicine*, *1*(1), 1–5. https://doi.org/10.1038/s41746-017-0011-3

Cao, Y., Gao, J., & Zhou, T. (2019). Orderliness of campus lifestyle predicts academic performance: A case study in Chinese University. In H. Baumeister & C. Montag (Eds.), *Digital phenotyping and mobile sensing: New developments in psychoinformatics* (pp. 125–137). Springer International Publishing. https://doi.org/10.1007/978-3-030-31620-4_8

Cobb, M. (2020). *The idea of the brain: The past and future of neuroscience*. Hachette.

Dagum, P. (2018). Digital biomarkers of cognitive function. *Npj Digital Medicine*, *1*(1), 1–3. https://doi.org/10.1038/s41746-018-0018-4

Dagum, P. (2019). Digital brain biomarkers of human cognition and mood. In H. Baumeister & C. Montag (Eds.), *Digital phenotyping and mobile sensing: New developments in psychoinformatics* (pp. 93–107). Springer International Publishing. https://doi.org/10.1007/978-3-030-31620-4_6

DeBoever, C., Tanigawa, Y., Aguirre, M., McInnes, G., Lavertu, A., & Rivas, M. A. (2020). Assessing digital phenotyping to enhance genetic studies of human diseases. *The American Journal of Human Genetics*, *106*(5), 611–622. https://doi.org/10.1016/j.ajhg.2020.03.007

Duckrow, R. B., Ceolini, E., Zaveri, H. P., Brooks, C., & Ghosh, A. (2021). Artificial neural network trained on smartphone behavior can trace epileptiform activity in epilepsy. *IScience*, *24*(6), 102538. https://doi.org/10.1016/j.isci.2021.102538

Elhai, J. D., & Montag, C. (2020). The compatibility of theoretical frameworks with machine learning analyses in psychological research. *Current Opinion in Psychology*, *36*, 83–88. https://doi.org/10.1016/j.copsyc.2020.05.002

Gosling, S. D., Sandy, C. J., John, O. P., & Potter, J. (2010). Wired but not WEIRD: The promise of the Internet in reaching more diverse samples. *The Behavioral and Brain Sciences*, *33*(2–3), 94–95. https://doi.org/10.1017/S0140525X10000300

Helmstaedter, M. (2015). The mutual inspirations of machine learning and neuroscience. *Neuron*, *86*(1), 25–28. https://doi.org/10.1016/j.neuron.2015.03.031

Henrich, J., Heine, S. J., & Norenzayan, A. (2010). Most people are not WEIRD. *Nature*, *466*(7302), 29–29. https://doi.org/10.1038/466029a

Huckins, J. F., da Silva, A. W., Wang, R., Wang, W., Hedlund, E. L., Murphy, E. I., Lopez, R. B., Rogers, C., Holtzheimer, P. E., Kelley, W. M., Heatherton, T. F., Wagner, D. D., Haxby, J. V., & Campbell, A. T. (2019). Fusing mobile phone sensing and brain imaging to assess depression in college students. *Frontiers in Neuroscience*, *13*, 248. https://doi.org/10.3389/fnins.2019.00248

Insel, T. R. (2010). The challenge of translation in social neuroscience: A review of oxytocin, vasopressin, and affiliative behavior. *Neuron*, *65*(6), 768–779. https://doi.org/10.1016/j.neuron.2010.03.005

Insel, T. R. (2017). Digital phenotyping: Technology for a new science of behavior. *JAMA*, *318*(13), 1215–1216. https://doi.org/10.1001/jama.2017.11295

Loken, E., & Gelman, A. (2017). Measurement error and the replication crisis. *Science*, *355*(6325), 584–585. https://doi.org/10.1126/science.aal3618

Marengo, D., & Montag, C. (2020). Digital phenotyping of big five personality via Facebook data mining: A meta-analysis. *Digital Psychology*, *1*(1), 52–64. https://doi.org/10.24989/dp.v1i1.1823

Markett, S., Montag, C., & Reuter, M. (2018). Network neuroscience and personality. *Personality Neuroscience*, *1*, E14. https://doi.org/10.1017/pen.2018.12

Markett, S., Wudarczyk, O. A., Biswal, B. B., Jawinski, P., & Montag, C. (2018). Affective network neuroscience. *Frontiers in Neuroscience*, *12*, 895. https://doi.org/10.3389/fnins.2018.00895

Markowetz, A., Błaszkiewicz, K., Montag, C., Switala, C., & Schlaepfer, T. E. (2014). Psycho-informatics: Big data shaping modern psychometrics. *Medical Hypotheses*, *82*(4), 405–411. https://doi.org/10.1016/j.mehy.2013.11.030

Miller, G. (2012). The smartphone psychology manifesto. *Perspectives on Psychological Science*, *7*(3), 221–237. https://doi.org/10.1177/1745691612441215

Montag, C., & Becker, B. (2019). Psychological and neuroscientific advances to understand internet use disorder. *e-Neuroforum*, *25*(2), 99–107. https://doi.org/10.1515/nf-2018-0026

Montag, C., & Diefenbach, S. (2018). Towards homo digitalis: Important research issues for psychology and the neurosciences at the dawn of the internet of things and the digital society. *Sustainability*, *10*(2), 415. https://doi.org/10.3390/su10020415

Montag, C., Duke, É., & Markowetz, A. (2016). *Toward psychoinformatics: computer science meets psychology* [review article]. Computational and Mathematical Methods in Medicine. Hindawi. https://doi.org/10.1155/2016/2983685

Montag, C., & Elhai, J. D. (2019). A new agenda for personality psychology in the digital age? *Personality and Individual Differences*, *147*, 128–134. https://doi.org/10.1016/j.paid.2019.03.045

Montag, C., & Elhai, J. D. (2020). Digital phenotyping—A case for cognitive functions and dementia? *Digital Psychology*, *1*(1), 44–51. https://doi.org/10.24989/dp.v1i1.1810

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. *Behavioural Brain Research*, *329*, 221–228. https://doi.org/10.1016/j.bbr.2017.04.035

Montag, C., Sindermann, C., & Baumeister, H. (2020). Digital phenotyping in psychological and medical sciences: A reflection about necessary prerequisites to reduce harm and increase benefits. *Current Opinion in Psychology*, *36*, 19–24. https://doi.org/10.1016/j.copsyc.2020.03.013

Moradi, E., Pepe, A., Gaser, C., Huttunen, H., & Tohka, J. (2015). Machine learning framework for early MRI-based Alzheimer's conversion prediction in MCI subjects. *NeuroImage*, *104*, 398–412. https://doi.org/10.1016/j.neuroimage.2014.10.002

Obuchi, M., Huckins, J. F., Wang, W., da Silva, A., Rogers, C., Murphy, E., Hedlund, E., Holtzheimer, P., Mirjafari, S., & Campbell, A. (2020). Predicting brain functional connectivity using Mobile sensing. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, *4*(1), 23:1–23:22. https://doi.org/10.1145/3381001

Open Science Collaboration. (2015). Estimating the reproducibility of psychological science. *Science*, *349*(6251), aac4716. https://doi.org/10.1126/science.aac4716

Peltonen, E., Sharmila, P., Opoku Asare, K., Visuri, A., Lagerspetz, E., & Ferreira, D. (2020). When phones get personal: Predicting Big Five personality traits from application usage. *Pervasive and Mobile Computing*, *69*, 101269. https://doi.org/10.1016/j.pmcj.2020.101269

Quintana, D. S., Lischke, A., Grace, S., Scheele, D., Ma, Y., & Becker, B. (2021). Advances in the field of intranasal oxytocin research: Lessons learned and future directions for clinical research. *Molecular Psychiatry*, *26*(1), 80–91. https://doi.org/10.1038/s41380-020-00864-7

Reichert, M., Braun, U., Gan, G., Reinhard, I., Giurgiu, M., Ma, R., Zang, Z., Hennig, O., Koch, E. D., Wieland, L., Schweiger, J., Inta, D., Hoell, A., Akdeniz, C., Zipf, A., Ebner-Priemer, U. W., Tost, H., & Meyer-Lindenberg, A. (2020b). A neural mechanism for affective well-being: Subgenual cingulate cortex mediates real-life effects of nonexercise activity on energy. *Science Advances*, *6*(45), eaaz8934. https://doi.org/10.1126/sciadv.aaz8934

Reichert, M., Braun, U., Lautenbach, S., Zipf, A., Ebner-Priemer, U., Tost, H., & Meyer-Lindenberg, A. (2020a). Studying the impact of built environments on human mental health in everyday life: Methodological developments, state-of-the-art and technological frontiers. *Current Opinion in Psychology*, *32*, 158–164. https://doi.org/10.1016/j.copsyc.2019.08.026

Salvatore, C., Cerasa, A., Castiglioni, I., Gallivanone, F., Augimeri, A., Lopez, M., Arabia, G., Morelli, M., Gilardi, M. C., & Quattrone, A. (2014). Machine learning on brain MRI data for differential diagnosis of Parkinson's disease and progressive supranuclear palsy. *Journal of Neuroscience Methods*, *222*, 230–237. https://doi.org/10.1016/j.jneumeth.2013.11.016

Sariyska, R., Rathner, E.-M., Baumeister, H., & Montag, C. (2018). Feasibility of linking molecular genetic markers to real-world social network size tracked on smartphones. *Frontiers in Neuroscience*, *12*, 945. https://doi.org/10.3389/fnins.2018.00945

Schwartz, J., Ordaz, S. J., Kircanski, K., Ho, T. C., Davis, E. G., Camacho, M. C., & Gotlib, I. H. (2019). Resting-state functional connectivity and inflexibility of daily emotions in major depression. *Journal of Affective Disorders*, *249*, 26–34. https://doi.org/10.1016/j.jad.2019.01.040

Tost, H., Reichert, M., Braun, U., Reinhard, I., Peters, R., Lautenbach, S., Hoell, A., Schwarz, E., Ebner-Priemer, U., Zipf, A., & Meyer-Lindenberg, A. (2019). Neural correlates of individual differences in affective benefit of real-life urban green space exposure. *Nature Neuroscience*, *22*(9), 1389–1393. https://doi.org/10.1038/s41593-019-0451-y

Tseng, V. W.-S., Valliappan, N., Ramachandran, V., Choudhury, T., & Navalpakkam, V. (2021). Digital biomarker of mental fatigue. *Npj Digital Medicine*, *4*(1), 47. https://doi.org/10.1038/s41746-021-00415-6

Twose, J., Licitra, G., McConchie, H., Lam, K. H., & Killestein, J. (2020). Early-warning signals for disease activity in patients diagnosed with multiple sclerosis based on keystroke dynamics. *Chaos: An Interdisciplinary Journal of Nonlinear Science*, *30*(11), 113133. https://doi.org/10.1063/5.0022031

Webb, C. A., Israel, E. S., Belleau, E., Appleman, L., Forbes, E. E., & Pizzagalli, D. A. (2020). Mind-wandering in adolescents predicts worse affect and is linked to aberrant default mode network–salience network connectivity. *Journal of the American Academy of Child & Adolescent Psychiatry*, *60*(3), 377–387. https://doi.org/10.1016/j.jaac.2020.03.010

Westbrook, A., Ghosh, A., van den Bosch, R., Määttä, J. I., Hofmans, L., & Cools, R. (2021). Striatal dopamine synthesis capacity reflects smartphone social activity. *IScience*, *24*(5), 102497. https://doi.org/10.1016/j.isci.2021.102497

Yao, Y.-W., Liu, L., Ma, S.-S., Shi, X.-H., Zhou, N., Zhang, J.-T., & Potenza, M. N. (2017). Functional and structural neural alterations in Internet gaming disorder: A systematic review and meta-analysis. *Neuroscience & Biobehavioral Reviews*, *83*, 313–324. https://doi.org/10.1016/j.neubiorev.2017.10.029

AUTHOR BIOGRAPHIES

Christian Montag is Professor for Molecular Psychology at Ulm University (Ulm, Germany). He studied psychology at University of Giessen (Giessen, Germany) and then worked on his PhD and habilitation dissertation at University of Bonn (Bonn, Germany). Christian Montag is interested in Personality Neuroscience. Here, he also combines molecular genetics with brain imaging techniques such as structural/functional MRI to better understand individual differences in human nature. Adding to this he conducts research in the fields of Neuroeconomics, Technological Use Disorders, and Psychoinformatics. In the realm of Psychoinformatics he applies mobile sensing and digital phenotyping principles to predict psychological traits and states.

Jon D. Elhai is Professor of Psychology and Psychiatry at the University of Toledo. His primary area of research is in posttraumatic stress disorder (PTSD), studying the disorder's underlying dimensions, and relations with cognitive coping processes and externalizing behaviors. He also has a program of research on cyberpsychology and behavioral addictions, examining problematic internet, and smartphone use.

Paul Dagum, MD, PhD is an entrepreneur, physician, and computer scientist. He is currently the CEO and Co-Founder of Applied Cognition, a healthcare innovation company to prevent and treat disease-related declines in cognitive function. Dr. Dagum is the founder of Mindstrong and was its CEO through November 2019. He has an outstanding record of bringing product, technology, and business model innovation to healthcare, cybersecurity, and supply chain through four successful venture-backed companies. Dr. Dagum's early research in dynamic Bayesian networks is in use today in many modern-day applications. He further created the first digital biomarkers of brain function from human-computer interactions and built a digital care delivery model for mental health built on a foundation of continuous measurement and AI-informed telehealth services.

How to cite this article: Montag, C., Elhai, J. D., & Dagum, P. (2021). Show me your smartphone… and then I will show you your brain structure and brain function. *Human Behavior and Emerging Technologies*, *3*(5), 891–897. https://doi.org/10.1002/hbe2.272