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SHORT COMMUNICATION

Digital phenotyping and the COVID-19 pandemic: Capturing behavioral change in patients with psychiatric disorders

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Abstract
The COVID-19 pandemic has led to unprecedented societal changes limiting us in our mobility and our ability to connect with others in person. These unusual but widespread changes provide a unique opportunity for studies using digital phenotyping tools. Digital phenotyping tools, such as mobile passive monitoring platforms (MPM), provide a new perspective on human behavior and hold promise to improve human behavioral research. However, there is currently little evidence that these tools can reliably detect changes in behavior. Considering the Considering the COVID-19 pandemic as a high impact common environmental factor we studied potential impact on behavior of participants using our mobile passive monitoring platform BEHAPP that was ambulatory tracking them during the COVID-19 pandemic. We pooled data from three MPM studies involving Schizophrenia (SZ), Major Depressive Disorder (MDD) and Bipolar Disorder (BD) patients ($N = 12$). We compared the data collected on weekdays during three weeks prior and three weeks subsequent to the start of the quarantine. We hypothesized an increase in communication and a decrease in mobility. We observed a significant increase in the total time spent on communication applications (median 179 and 243 min per week respectively, $p = 0.005$), and a significant decrease in the number of unique places visited (median 6 and 3 visits per week respectively, $p = 0.007$), while the total time spent at home did not change significantly (median 64 and 77 h per week, respectively, $p = 0.594$). The data provides a proof of principle that digital phenotyping tools can identify changes in human behavior incited by a common external environmental factor.

1. Introduction

Social distancing- and public lockdown measures, aimed at controlling the COVID-19 pandemic have significantly limited our mobility in general and, more specifically, our ability to meet other people. Arguably, the pandemic and the ensuing policies to contain its spread can be considered as a unique sociological experiment in which one shared environmental factor has incited widespread behavioral changes in the entire population.

These unusual circumstances provide a unique opportunity to examine upcoming behavioral research tools in the field of digital phenotyping. Digital phenotyping is defined as the “moment-by-moment quantification of the individual-level human behavioral phenotype in situ using data from personal digital devices” (Torous et al., 2016, p. 2). One specific strategy of digital phenotyping is mobile passive monitoring (MPM), whereby data is collected through the smartphone without requiring any active input from the owner (excepting informed consent and installation). MPM generates objective behavioral data collected in real life settings, and is therefore thought to hold promise for improvement of behavioral research in general (Insel, 2017). However, empirical evidence to corroborate the claim that MPM can reliably detect behavioral changes is scarce (Moreno et al., 2020).

In this study we exploited the fact that the COVID-19 pandemic and ensuing containment policies can be expected to have exerted a substantial impact on behavior. These circumstances allowed us to examine the ability of MPM to detect changes in social behaviors at the group level. To this end, we used MPM data collected in ongoing studies of individuals with a psychiatric diagnosis, prior and subsequent to the introduction of social distancing and lockdown measures in the Netherlands (from here on referred to as ‘quarantine measures’). We hypothesized that the introduction of quarantine measures on March 12th 2020 would lead to a decrease in mobility and an increase in mobile communication, and that these changes would be reliably captured by MPM data collected by individual smartphones.

2. Experimental procedures

2.1. Study design

The study was conducted using BEHAPP, an MPM platform through which we aim to investigate and classify communication and exploration patterns in humans using objective data gathering techniques (https://behapp.org). After informed consent and installation, BEHAPP passively collects data via the smartphone of participants. The data collected relates to various aspects of behavior, including patterns of mobility, communication and diurnal rhythm. Compared to traditional methods, the potential novelty of MPM is the objective nature of the data as well as their unprecedented resolution, and that they can be prospectively collected in a natural “real-life” setting of participants.

Similar to policies in other countries throughout the world, the Dutch quarantine strategy was aimed at clearing the public space in order to prevent spread of the SARS-CoV-2 coronavirus (Coronaviridae Study Group of the International Committee on Taxonomy of Viruses, 2020). The strategy, which came into effect on March 12, 2020, is based on measures such as, but not limited to: 1) the mandatory closure of the hospitality, sports and educational sectors; 2) a ban on gatherings of groups 3) a mandatory halt of activities for professions which require close proximity to others (e.g. hairdressers and driving instructors); and 4) voluntary, but strongly recommended, stay and work from home orders (Ministry of General Affairs, the Netherlands, 2020a, 2020b).

To test the hypothesis of behavioral changes caused by quarantine measures, we compared MPM data collected on weekdays during three weeks prior and three weeks subsequent to the start of

Table 1 Demographic data of participating subjects. In order to preserve the privacy of the participants we report on age brackets and omit cohort data from the overview.

Demographic data			
Subject ID	Diagnosis	Sex	Age bracket
1	MDD	M	20-29
2	SZ	M	30-39
3	BD	F	20-29
4	SZ	M	30-39
5	MDD	F	40-49
6	MDD	F	50-59
7	MDD	F	50-59
8	MDD	M	50-59
9	MDD	F	50-59
10	MDD	F	40-49
11	MDD	M	40-49
12	MDD	F	50-59
13	MDD	F	60-69

the quarantine. We chose, *a-posteriori*, to report on the four outer most weeks excluding the two weeks in between as we observed this transitional period to introduce too much noise in the behavioral patterns of our subjects. Some participants already changed their behavior in an early stadium, while others needed more time to adjust. For similar reasons we chose to focus on weekdays only. In typical circumstances, weekday and weekend states show strong differences which, when combined, lead to diminished signal strength. Thus, all outcome measures were calculated from weekdays before and after March 12, 2020. Outcomes from weeks 9 and 10 (24-02-2020-06-03-2020) and weeks 13 and 14 (23-03-2020-03-04-2020) were combined as 'pre-quarantine' and post-quarantine' states, respectively.

2.2. Participants

We pooled data from three ongoing MPM studies in the Netherlands: NESDA, The Netherlands Study of Depression and Anxiety, a cohort study on depression and anxiety disorders (Penninx et al., 2008); SMARD, a study on Smartphone based Monitoring and cognition Modification Against Recurrence of Depression; and HAMLETT, (Handling Antipsychotic Medication Long-term Evaluation of Targeted Treatment, Begemann et al., 2020), a trial which compares different antipsychotic treatment strategies (continuation, dose-reduction and discontinuation) in patients with schizophrenia-spectrum disorders. From these three studies, we identified 13 individuals (Table 1) with BEHAPP data available for the exact time frame spanning the four target weeks (weeks 9, 10, 13 and 14). All subjects were enrolled in the respective studies based on a lifetime diagnosis; ten subjects with remitted Major Depressive Disorder (MDD), two with Schizophrenia (SZ) and one with Bipolar Disorder (BD). All patients consented to sharing their data as part of ongoing MPM studies and the application of MPM as a data collection technique was approved by ethics committees. Furthermore, permission was granted by all three studies for this exploratory study in the context of the COVID-19 pandemic.

2.3. Measurements

Mobile communication was measured by 1) the total time spent using communication apps (in minutes); and mobility was measured by 2) the total time spent at home (in hours); and 3) the total number of unique places that were visited.

For the time spent on communication apps (e.g. WhatsApp or Facebook Messenger), BEHAPP registers app usage logs which includes the name of the app and duration of use per event. The total time spent using communication apps is calculated by filtering the log for all instances with apps belonging to the communication category and subsequently summing the usage duration values. The categorization scheme is based on general app categories as specified in the Google Play Store (Google Play Store Team, 2020).

Outcome 2) and 3) are derived from patterns of mobility and are derived from pre-processed geolocation data. Our pre-processing procedure, known as 'stay point detection', is based on previous work by Zheng et al. (2009). In short, this procedure converts raw geolocation data into a list of stay points, which form a chronological overview of places where participants were stationary, including the time spent stationary at each point. Here, we defined a stay point as any location with a radius of 350 m, where participants remained for at least 30 min. Additionally, by clustering stay points and determining where the majority of nightly hours are spent both the unique number of places and the home location of the participant can be derived (Jongs et al., 2020). Thus, we calculated 2) the total time spent at home by summing the time spent for all stay points which belonged to the 'home' category, and 3) the total number of unique places visited by counting the number of unique stay points in the geolocation data.

2.4. Statistics

For our quantitative outcome measures, the Wilcoxon signed-rank test was applied as a non-parametric statistical hypothesis test used to compare two repeated measurements on similar individuals (namely, before and after the start of the quarantine measures). We compensated for multiple testing (three tests) by applying the Bonferroni correction with $p < 0.017$.

3. Results

Prior to the analysis we carried out two quality control steps: First we examined general data loss, retaining only participants with at least four out of five days of data on a weekly basis. One patient (SZ) exceeded this threshold and was therefore excluded from the sample. Consequently, data from $N = 12$ were included in the analyses of the communication outcome measure. Secondly, we verified the resolution of location data, retaining nine participants with sufficient location data available to extract the two location data bound outcome measures ($N = 9$). The median age was 49; 38% male and 62% female.

Results from our primary outcomes are depicted in Fig. 1a-c. When comparing behavior post to prior to the start of quarantine, there was a statistically significant increase in the total time spent using communication apps (median 179 and 243 min per week respectively, $p = 0.005$) as well as the total number of unique places visited (median 6 and 3 per week respectively, $p = 0.007$). The time spent at home was not significantly different (median 64 and 77 h per week, respectively, $p = 0.594$).

The significant decline in the unique number of places that were visited prompted further (post-hoc) investigation into the underlying geolocation data. Fig. 2 depicts an aggregated overview of all unique stay points in relation to the home location of each participant for both timeframes. The figure illustrates how the distances traveled from home de-

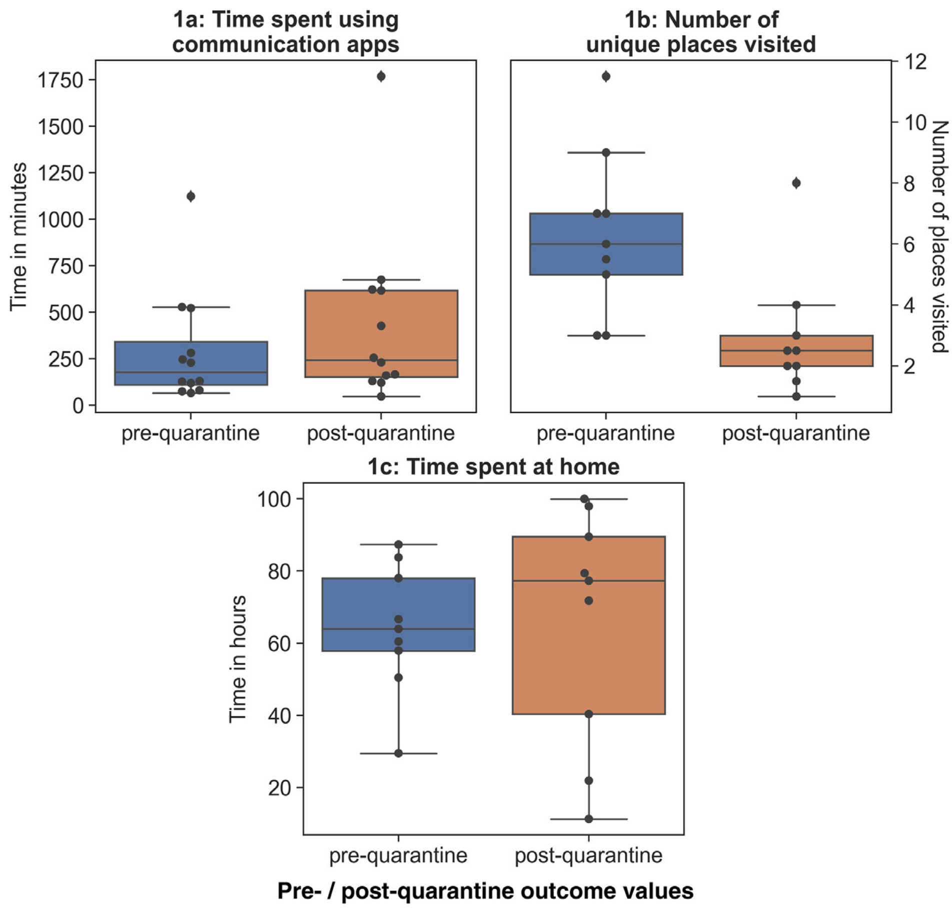

Fig. 1 a-c: Overview of outcome measures before and after the introduction of quarantine measures on March 12, 2020. 1a: Time spent using communication apps in minutes per week, 1b: The number of unique places visited per week, 1c: The total time spent at home in hours per week.

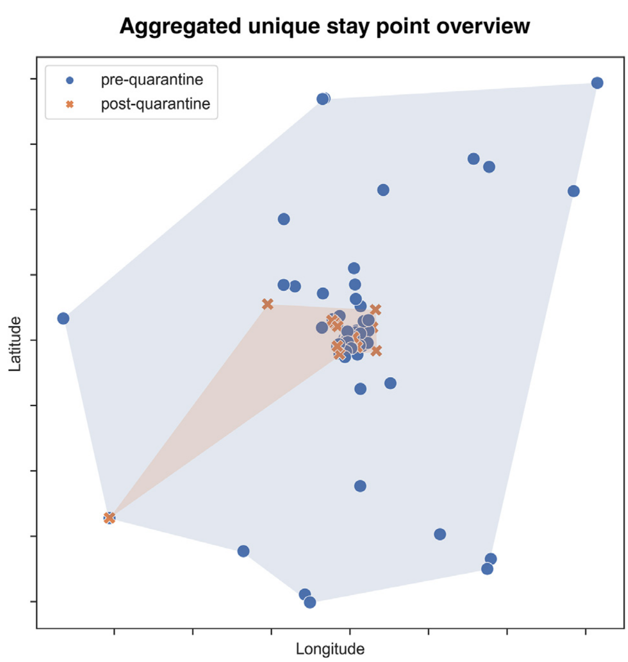

Fig. 2 Aggregated unique stay point overview. In order to preserve the privacy of participants, latitude and longitude information including scale are omitted from the figure and all unique stay points are centered around a mid point of 0.0.

crease sharply with less overall density at the center meaning that patients spent less time outside of their homes during the first weeks of quarantine.

4. Discussion

This study reports on the ability of mobile passive monitoring, a novel digital phenotyping strategy, to reliably measure behavioral changes in groups of individuals. To this end, we considered the COVID-19 pandemic as a unique sociological experiment in which the behavior of the entire population is influenced by a common environmental factor. We expected that the initiation of the quarantine would induce a decrease in movement patterns as well as an increase in communicative behaviors. Our observations were consistent with these expectations, indicating that MPM can reliably detect such behavioral changes, even in a relatively small sample set as used in the current analysis.

In accordance with our expectations, we observed a significant increase in the total time spent on communication applications and a significant decrease in the number of unique places visited, while the total time spent at home did not change significantly as examined before and after the quarantine. The decrease in unique places visited suggests that patients were less likely to explore new places outside of the home during quarantine, as was expected. Total time spent at home increased, but the difference was not significant. Although we expected *a priori* to also see an increase in this measure, it is important to note that time spent at home prior to the pandemic was already quite elevated in this cohort of mentally affected subjects, leaving limited room for further increase. Indeed, observations reported in other studies indicate that this population is inclined to spend more time at home compared to individuals without psychiatric illness (Schuch et al., 2017; Stubbs et al., 2016).

Our exploratory study was limited in sample size due to the unplanned nature of our analyses, and because the specific time-frame of our study reduced the number of subjects from the ongoing studies with data available during that exact time frame. We have addressed this by limiting the number of tests (three) based on *a priori* formulated hypotheses and the application of conservative correction for multiple testing. The inclusion of healthy control subjects would have allowed us to compare the impact of the pandemic on those with and those without psychiatric illness, but these data were simply not available within the selected time frame. However, the fact that our observations were obtained in a group of individuals with psychiatric illness does not diminish the conclusion of this study.

In conclusion, we provide a proof of principle that the MPM class of digital phenotyping tools can reliably identify relevant changes in human behavior when incited by a common external environmental factor.

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Contributors

RRJ, MCR, MJK and JASV conceptualized and designed the study. RRJ and MCR performed the data analysis. IH, NI, AT, BWJHP, HGR and IECS were involved in the implementation, execution and/or patient recruitment of the clinical studies. MJK and JASV are the founders of the BEHAPP mobile passive monitoring service. RRJ built and maintained the BEHAPP mobile passive monitoring service. RRJ and JASV wrote the first version of the manuscript. All authors reviewed the manuscript prior to submission and their feedback was implemented to the final version of the manuscript.

Conflict of Interest

Authors declare no conflicts of interest.

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