The Quantified Scientist:

Citizen Neuroscience and Neurotechnology

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The human body and mind continuously interact with the environment, which triggers them to go through various changes. These changes occur at different time scales; relatively short-term changes occur throughout the day, for instance due to the circadian rhythm and through interactions with the environment. Slightly longer timescales changes occur throughout the year, for instance due to the seasons, pathogens and changes in lifestyle. At much longer timescales changes occur due to ageing and chronic medical conditions. However, most of what we know of these changes comes from longitudinal studies with relatively few timepoints or with a strong focus on a specific data modality. To obtain a better understanding of the changes occurring at these different timescales and to study how different data modalities interact, we initiated a longitudinal N=1 study pilot study in 2017 with very dense and deep phenotyping, dubbed "The Quantified Scientist" (the subject of this study is one of the authors, R.t.H.), Measurements include daily sleep recordings with wearable EEG (n>500), weekly sleep recordings with full polysomnography (n~100), weekly brain scans with structural and functional MRI (n>125), regular microbiome samples (n>250). Additionally, continuous measurements are collected using consumer wearables and twice-daily questionnaires and physiological measurements are collected in the morning and evening. The initial questions we hope to answer with this study is how sleep, the brain and the gut interact.

This study represents an extreme example of the *Quantified Self* (QS) movement. This movement consists of self-tracking enthusiasts that collect data on one or more aspects of their life, often with the goal of better understanding or improving parts of their lives. An overlapping community with an even stronger emphasis on the modulation and typically enhancement of brain function is the biohacker/neurohacker movement. Neurohackers adapt neurotechnologies from academic research, and often aim to rebuild or further develop these for everyday use (Wexler, 2017). Both quantified selfers and neurohackers can be considered citizen neuroscientists: they systematically apply neurotechnologies, monitor brain-related data, and quantitatively or qualitatively assess their effects on brain function. These group of individuals are often at the forefront of implementing new neurotechnologies, and are therefore among the first to encounter the upsides and downsides of these new technologies.

In their target article, MacDuffie et al. (2021) investigated attitudes toward different ethical challenges that come with the use of neurotechnology in two groups of stakeholders, namely members of the neural device industry and members of the general public. The authors report some consistency, but also some differences between the groups in their attitudes toward ethical principles related to neurotechnology.

We argue that citizen neuroscientists such as quantified selfers and neurohackers constitute a third group of stakeholders with a highly relevant viewpoint on the ethics of neurotechnologies, as they have extensive user experience as early adopters and often considerable expertise in neurotechnological devices, however they do not have the financial conflicts interests that representatives of neural device industry might have. Additionally, citizen neuroscientists typically have a much deeper understanding and more systematic approach to these technologies than the general public. Accordingly, they may provide a potentially insightful combination of being highly knowledgeable about the technology at hand and being directly affected by it as users.

On a YouTube channel accompanying the *Quantified Scientist* project (https://www.youtube.com/TheQuantifiedScientist), one of the authors (R.t.H.) tests consumer devices for

their accuracy (e.g. sleep-tracking capabilities, heart rate measurements and step counting). The subscribers of this channel consist of individuals interested in tracking different aspects of their life using consumer products like smartwatches and neural devices, including people from the QS movement. As a response to the target article by MacDuffie et al. (2021), a brief survey was done among the channel subscribers, asking some of the same questions as the target article. In total, n=338 subscribers answered, most of whom used one or two electronic tracking devices, n=86 used three or more such devices, and n=17 used also neurotechnological devices to directly measure brain activity via EEG (see Figure 1; for the full survey results see https://www.robterhorst.com).

While a strict comparison between the results of target article by MacDuffie et al. (2021) and the survey among channel subscribers is difficult given the probable differences between the survey modalities, the data nevertheless suggest that there might be interesting differences between citizen neuroscientists and both industry representatives and the general public that should be assessed in a more systematic study. Whereas the evaluation of the topics of *Privacy* and *Responsibility* appears to be similar in citizen neuroscientists and the general public, in particular for the topics *Control* and *Enhancement* they appear to deviate from the general public in their evaluation, going even beyond the evaluation of neural device industry representatives. Interestingly, this effect appears to be even stronger for respondents who use proper neurotechnology such as EEG. This observation is also in line with the evaluation of our case study of the The Quantified Scientist project (i.e., R.t.H.), who similarly to many members of the QS community sees some potential for self-improvement in self-tracking practices. This perspective renders some ethical topics areas (including *Enhancement* and *Control*) more relevant in comparison to the general public.

Humans have always strived for self-improvement and a rapidly increasing variety of behavioral, biological and physical strategies for neuroenhancement exists (Dresler et al., 2019). While purely passive QS practices using neurotechnologies for self-knowledge and personalized healthcare/science (Heyen, 2020) arguably are less risky than many pharmacological or invasive self-improvement strategies, there are

concerns about the personal and societal effects of excessive self-tracking (Baron et al., 2017; Baker 2020) that have to be taken serious. Beyond the consumer market and basic research, wearable neurotechnology has a strong potential in clinical settings, however improvements in data quality are needed for many existing wearables (Pardamean et al., 2020; Rentz et al., 2021). Citizen neuroscience can play a valuable role in respective feasibility and validation studies: if performed carefully, citizen science can generate high-quality data (Parrish et al., 2019), and large sample sizes through crowdsourcing studies using wearable technologies outside the laboratory have been demonstrated successfully also for the neuroscience field (Dikker et al., 2021).

In conclusion, citizen neuroscientist communities are a yet understudied group of stakeholders. Their members can contribute relevant ethical considerations from a uniquely affected and informed perspectives, and can further play a role in the development and validation of neurotechnologies for application beyond consumer market and basic research, such as clinical settings.

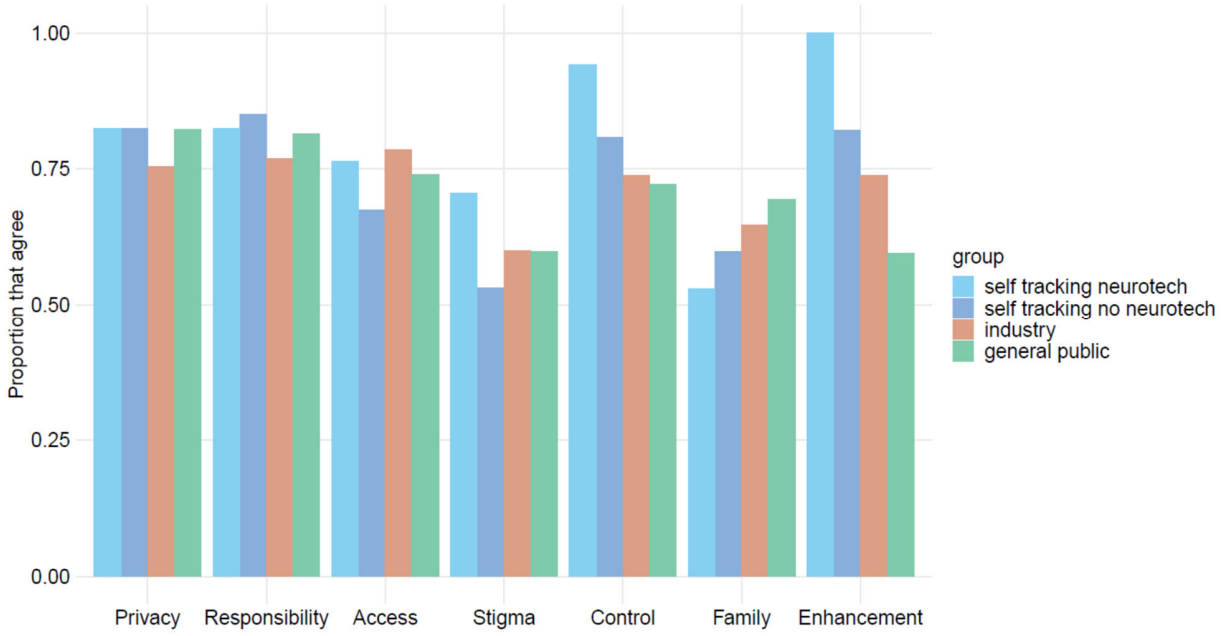

Figure 1: Rated importance of different topics relevant for the use of neurotechnology in different groups of stakeholders. The first two bars in each category are based on answers provided by subscribers of the YouTube channel *The Quantified Scientist*; a channel that covers the topic of self-tracking. The first bar reflects the answers of people that own a neurotechnological device to directly measure brain activity via EEG, and the second bar reflects the answers of people that are actively using other types of technology to track aspects of their behavior and biology. The third and fourth bars are based on the uncorrected proportions of Supplementary Table 1 of MacDuffie et al. (2021).

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