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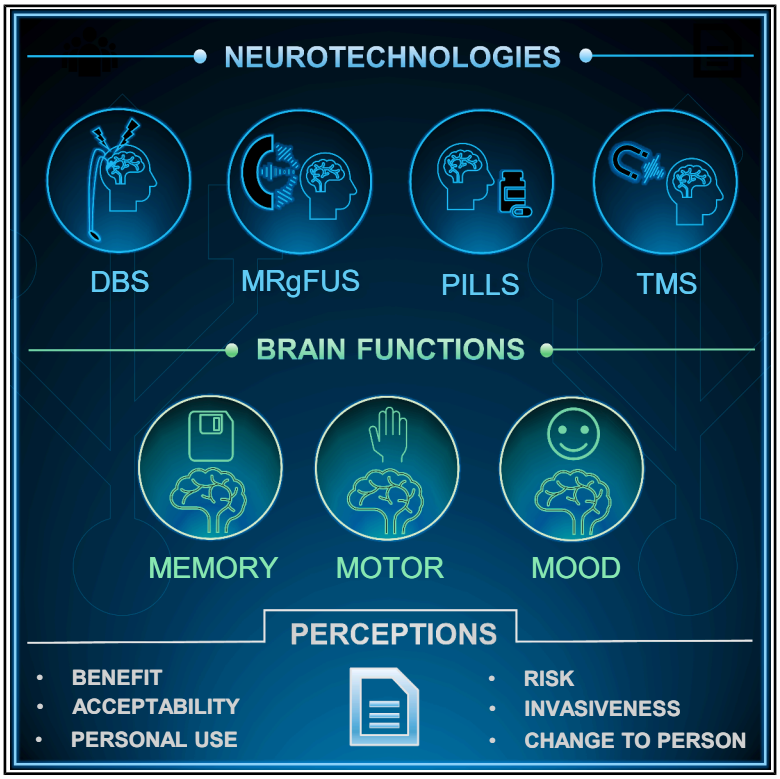
Article

Public perceptions of neurotechnologies used to target mood, memory, and motor symptoms

Graphical abstract



Highlights

- Public is open to neurotechnologies for severe neurological symptoms
- Devices that require surgery, like DBS, are seen as riskier than non-surgical options
- Neurotechnologies for motor symptoms were favored over those for mood
- Developers should consider user perception to improve uptake of neurotechnologies

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In brief

Furrer et al. conducted a US-based survey on the perception of neurotechnologies for treating mood, memory, and motor symptoms. Deep brain stimulation (DBS) was seen as the most invasive and risky, leading to the greatest perceived change to the person and being the least likely to be used, while non-surgical options such as pills were viewed as more acceptable. Treatments targeting motor symptoms were also rated as more beneficial and acceptable than those for mood or memory.

2 Explore
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Article

Public perceptions of neurotechnologies used to target mood, memory, and motor symptoms

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THE BIGGER PICTURE Developers and physicians should integrate public and patient perspectives to ensure that device development is responsive to the needs and concerns of potential end users. By tracking public and patient attitudes over time and addressing concerns, developers can refine neurotechnologies to meet user needs and improve uptake. Understanding how the public and patients perceive and define invasiveness across technologies is crucial, as they vary along with perceptions of risk and likelihood of usage. Given the significant investment in device development, incorporating user perspectives early helps ensure that products align with societal needs and are implemented ethically.

SUMMARY

Public attitudes toward four neurotechnologies for treating three types of brain disorders (mood, motor, and memory) vary on a range of metrics, such as perceived risk, invasiveness, and likelihood of use. In a survey of 1,052 US participants, deep brain stimulation (DBS) was seen as the most invasive and risky among the surveyed methods, involving the greatest perceived change to the person and the least likely to be used personally. Non-surgical options like transcranial magnetic stimulation (TMS) and pills were viewed as more acceptable. Devices targeting motor symptoms were rated as more beneficial and acceptable than those for mood or memory. These findings highlight barriers to adoption and the need to address public perceptions, ensure patients are informed, and promote ethical implementation of these technologies.

INTRODUCTION

Recent decades have seen the emergence of medical neurotechnologies aimed at offering treatments for a wide spectrum of brain-based conditions that affect people's mood, memory, or motor functions across a variety of methods, including ablation, electromagnetic stimulation, and pharmacological neuromodulation.[1] There is a growing commercial interest in neural implants (e.g., Neuralink) and increasingly promising research on these medical treatments, with market projections estimating the industry growing to $17 billion annually. Therefore, it is important to understand the public's perception of such technologies,[2–7] which can vary depending on how these technologies are portrayed in the media.[8,9] Furthermore, given that the early history of some of these neurotechnologies is clouded by ethical controversy, it is unclear whether there is significant public interest in engaging with these treatments regardless of how effective they become.[10–14] It is vital that the next generation of technological devices for treating brain-based conditions incorporate the views of the public to avoid repeating past transgressions and to ensure ethically sound innovation.

Neurotechnologies vary widely with respect to their mode of treatment delivery; deep brain stimulation (DBS) requires one or more electrodes to be implanted into specific brain regions for electrical stimulation, transcranial magnetic stimulation (TMS) induces intracranial effects from the application of a magnetic field on a patient's scalp, MRI-guided focused ultrasound (MRgFUS) produces subcortical lesions without the use of an open surgical approach (also referred to as "incisionless surgery"), and pharmacological regimens (i.e., pills), require

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Table 1. Sample demographics

Sample size (*n*)	1,052
Age	
mean (σ)	45.5 (σ = 16.1)
Gender	
Female	514 (49.1%)
Male	507 (48.5%)
Trans female/trans woman	3 (0.28)
Trans male/trans man	7 (0.7%)
Genderqueer/gender non-conforming	12 (1.1%)
Other[a]	25 (2.4%)
Race	
American Indian, Native American, Alaska Native	11 (1%)
Asian	65 (6%)
Black or African American	135 (12.5%)
Native Hawaiian, Pacific Islander	3 (0.3%)
Other[b]	8 (0.7%)
White	825 (76.1%)
Ethnicity	
Not Hispanic or Latino	992 (91.5%)
Hispanic or Latino	57 (5.3%)
Education level	
Bachelor's degree or higher	551 (52.6%)
Household income	
$0–$49,999	444 (42.4%)
≥$50,000–109,999	399 (36.8%)
≥$110,000	205 (18.9%)

Participants could select multiple races. Missing values across demographics ranged from 35 to 38.

[a]Other gender in sample 1 included the following self-reported identities: genderfluid, non-binary, transmasculine, and trans non-binary.

[b]Other race/ethnicity included the following self-reported races (counts): Middle Eastern (2), Jewish (2), Mediterranean (1), Indigenous American (1), Hebrew (1), French/Indian/Black/White (1).

ingesting medications orally to diffusely target an array of mechanisms in the brain.[2,15] Public perceptions of these technologies may vary, given the differences in treatment delivery methods and their associated risks, which, in turn, may influence how receptive members of the public are to a specific technology.

When it comes to medical neurotechnologies, there has been a particular focus in the academic literature on DBS, which may be in part due to increasing investment in expanding the capacity of these devices to both record brain activity and stimulate the brain as well as the neuroethical debate around whether, and to what degree, DBS may impact a patient's personality and related characteristics.[16–22] There have been numerous evaluations of psychosocial impacts of DBS devices for psychiatric and movement disorders over the past 10–15 years[17–50] There have also been some qualitative studies of TMS treatments during this time[51–54]; however, only recently has there been a focused examination of MRgFUS.[55] Previous investigations of neurotechnologies have tended to fall into silos with respect to the disorders or symptomatology being studied; namely, researchers focused on motor (i.e., "doing") symptoms[24,28,32,34,35,44,46,50,56–59] or those involving mood/psychiatric (i.e., "feeling")[15,27,33,37,41,47,53,55,60–62] or memory/cognition (i.e., "thinking").[36,63–65] However, research simultaneously examining varying forms of neuromodulation as well as how the type of disorder being treated may influence views on each of these technologies is lacking. Finally, much of the previous work has been limited to examining the perspectives of patients and clinicians, and the studies that did explore the public's attitudes around some of these neuromodulatory interventions were conducted using either surveys or assessments of social media.[30,42,54,60,66–68]

In this work, we aim to address several of the meaningful gaps in the literature, as identified above. First, our study employs an experimental approach by randomly assigning participants to evaluate four technologies based on one of three symptoms/functions they are targeting (i.e., mood, memory, and motor). This allows us to comparatively examine how public attitudes toward neurotechnologies might shift based on the symptoms presented, which expands on previous work that was limited to observational studies (i.e., surveys or media analyses). We also include a range of both neurotechnologies (i.e., DBS, MRgFUS, TMS, and pills) and symptomatology (i.e., mood, memory, and motor) to address the need for work that spans the siloed research on this topic. Our study utilized a within-subjects design for the four neurotechnologies and a between-subjects design for the symptoms. This approach allowed us to capture nuanced preferences for technologies through direct comparisons while isolating symptom-specific perceptions and examining potential interactions between treatments and symptoms without introducing confounds from simultaneous symptom evaluation. This design provides an understanding of how people evaluate these treatments in contexts where multiple treatment options might be considered simultaneously. We focused on describing symptoms rather than defining disorders (e.g., Alzheimer's disease, major depressive disorder, and Parkinson's disease) to make it easier for participants to understand the effects rather than the causes, minimizing bias from varying familiarity and ensuring a more consistent understanding across the sample. The outcomes investigated in this study provide insights into the complex public attitudes related to risks, benefits, invasiveness, acceptability, perceived changes to the patient, and the likelihood of personal use across this range of neurotechnologies. These findings help identify barriers to the uptake of these technologies, aid clinicians in addressing public perceptions surrounding these technologies, and inform the responsible development and use of these and future neurotechnologies.

RESULTS

We present our study participants' demographic information in Table 1. Of the 1,145 participants who began the survey by selecting "I give my consent to participate in this survey," 61 participants were removed because they failed either the initial bot check or the attention check used in the survey. Of the remaining participants, 1,052 completed the main outcome measures. Participants were almost evenly split with respect to gender

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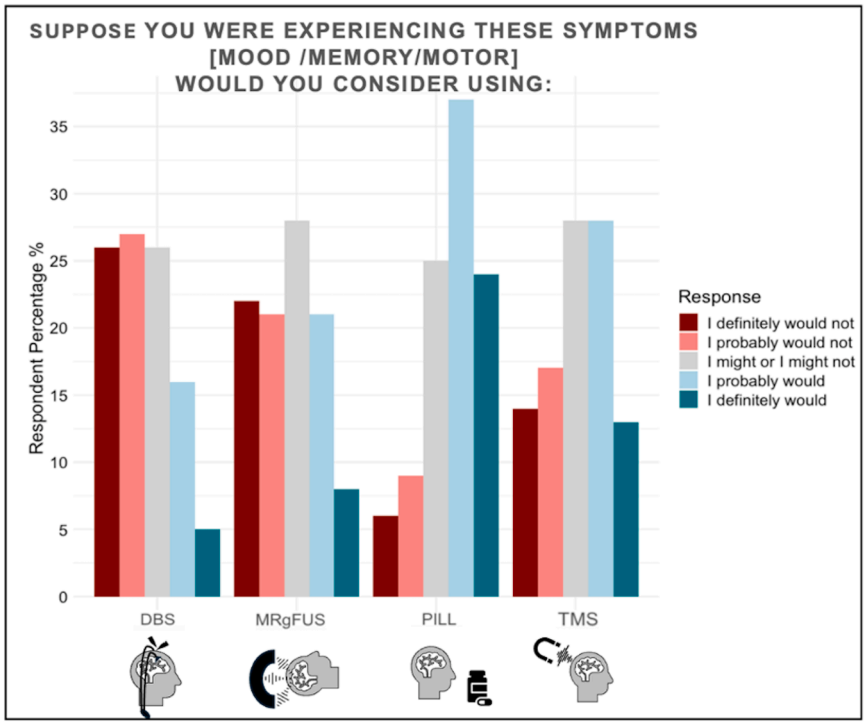

Figure 1. Likelihood of using four neurotechnologies (averaged across symptom types)

Participants rated their likelihood of using each of the four neurotechnologies on the *x* axis on a 5-point Likert scale. The *y* axis represents the percentage of participants who selected each answer for each neurotechnology. These results represent participants' reported likelihood of using each technology averaged over the three potential symptoms (mood, memory, and motor). Significant variation in reported likelihood to use these neurotechnologies is observed based on symptoms, which is further examined in Figure 2.

(*n* females = 514, *n* males = 507), were predominantly White (76%), with an average age of 45.5 years. Descriptive statistics on the outcome measure that asks participants' familiarity are first reported in the results, and participant likelihood to use each technology based on the symptoms presented is shown in Figure 1. Then, we present the results of the statistical analyses using repeated measures analysis of variance (ANOVA). The first set of results, "Perceptions across different neurotechnologies," focuses on differences in attitudes between the neurotechnologies irrespective of the symptoms (i.e., averaging across symptoms). The second set of results, "Perceptions across different symptoms," focuses on differences in attitudes between the symptoms irrespective of the neurotechnologies (i.e., averaging across technologies). The third set of results, "interaction effects of neurotechnologies and symptoms," focuses on differences in attitudes as a result of the interactions between symptoms and neurotechnologies. In Figure 1, we report participants' ratings of how likely they would be to consider each neurotechnology (averaged across the three symptom groups). Participants' familiarity ratings for each technology were as follows, in decreasing mean order: pills (mean = 3.66, standard deviation [σ] = 1.31), DBS (mean = 1.63, σ = 0.89), TMS (mean = 1.46, σ = 0.84), and MRgFU (mean = 1.46, σ = 16.1).

Perceptions across different neurotechnologies

Benefit, acceptability, and personal use

The results of the repeated measures ANOVAs are reported in the following format: F statistic (between-group degrees of freedom, within-group degrees of freedom) = F value, p = p value, and ηp^2 = partial eta-squared effect size. Please refer to the methods for exact definitions and question framings presented to participants. Analyses revealed a significant main effect of neurotechnology on perceived benefit ($F(2.92, 1049) = 83.24$, $p < 0.001$, $\eta p^2 = 0.07$), acceptability ($F(2.88, 1049) = 318.53$, $p < 0.001$, $\eta p^2 = 0.23$), and personal use ($F(2.90, 1049) = 336.53$, $p < 0.001$, $\eta p^2 = 0.24$). See Figures 2A–2C for plots. Post hoc tests revealed that pills were rated as most beneficial (mean = 3.33, σ = 0.92), followed by DBS (mean = 3.03, σ = 0.96) and then TMS (mean = 2.88, σ = 1.01) and MRgFUS (mean = 2.88, σ = 1.06). All post hoc comparisons for perceived benefit were significant ($p < 0.001$) except for TMS and MRgFUS (p = 1.00). Post hoc tests revealed that, for acceptability and personal use, pills were rated as most acceptable (mean = 3.75, σ = 1.01) and most likely to be used by participants (mean = 3.65, σ = 1.11), followed by TMS (acceptability: mean = 3.22, σ = 1.07; personal use: mean = 3.08, σ = 1.23), then MRgFUS (acceptability: mean = 2.84, σ = 1.13; personal use: mean = 2.71, σ = 1.24), and finally DBS (acceptability: mean = 2.72, σ = 1.03; personal use: mean = 2.47, σ = 1.18). All post hoc comparisons were significant ($p < 0.005$).

Risk, invasiveness, and change to person

The results of the ANOVAs revealed a significant main effect of neurotechnology on risk ($F(2.91, 1049) = 570.80$, $p < 0.001$, $\eta p^2 = 0.35$), invasiveness ($F(2.92, 1049) = 1027.31$, $p < 0.001$, $\eta p^2 = 0.50$), and change to person ($F(2.93, 1049) = 164.62$, $p < 0.001$, $\eta p^2 = 0.14$). See Figures 2D–2F for plots. Post hoc tests revealed that, for risk and change to person, participants perceived DBS as the riskiest (mean = 3.83, σ = 1.04) and leading to the greatest change to the person (mean = 2.69, σ = 1.13), followed by MRgFUS (risk: mean = 3.39, σ = 1.19; change to person: mean = 2.52, σ = 1.12), pills (risk: mean = 2.54, σ = 0.89; change to person: mean = 2.26, σ = 1.04), and TMS (risk: mean = 2.40, σ = 1.09; change to person: mean = 2.02, σ = 1.04). All post hoc comparisons were significant ($p < 0.002$). Post hoc tests for invasiveness revealed that participants perceived DBS as the most invasive (mean = 4.16, σ = 1.04), followed by MRgFUS (mean = 3.18, σ = 1.31), TMS (mean = 2.13, σ = 1.15), and lastly pills (mean = 1.94, σ = 1.00). All post hoc comparisons between the four neurotechnologies were significant ($p < 0.001$).

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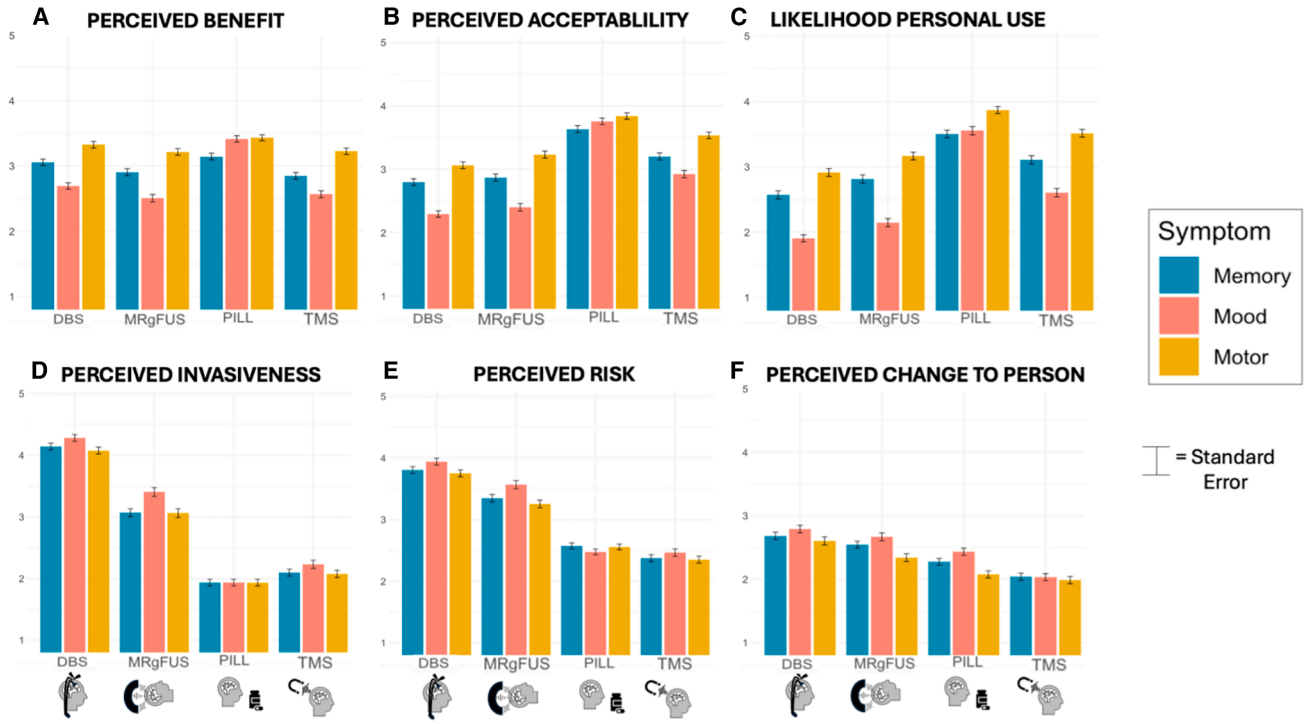

Figure 2. Perceptions of four neurotechnologies by symptom type

Shown are perceived benefit (A), acceptability (B), likelihood of personal use (C), perceived invasiveness (D), risk (E), and change to person (F) by neurotechnology and symptom.

Perceptions across different symptoms

Benefit, acceptability, and personal use

The results of the ANOVAs revealed a significant main effect of symptoms on benefit ($F(2, 1049) = 47.34$, $p < 0.001$, $\eta p^2 = 0.08$), acceptability ($F(2, 1049) = 55.54$, $p < 0.001$, $\eta p^2 = 0.10$), and personal use ($F(2, 1049) = 86.09$, $p < 0.001$, $\eta p^2 = 0.14$). Post hoc tests revealed that the average effect of neurotechnology was rated as most beneficial for motor symptoms (mean = 3.30, $\sigma = 0.93$), followed by memory symptoms (mean = 2.99, $\sigma = 0.96$) and finally mood symptoms (mean = 2.80, $\sigma = 1.05$). Similarly, neurotechnology was rated as most acceptable for motor symptoms (mean = 3.42, $\sigma = 1.05$), followed by memory symptoms (mean = 3.13, $\sigma = 1.08$) and mood symptoms (mean = 2.85, $\sigma = 1.19$). For personal use, neurotechnology was also rated as most likely to be used for motor symptoms (mean = 3.37, $\sigma = 1.16$), followed by memory symptoms (mean = 3.00, $\sigma = 1.20$) and mood symptoms (mean = 2.56, $\sigma = 1.32$). All post hoc comparisons between the three symptoms were significant ($p < 0.001$).

Risk, invasiveness, and change to person

The results of the ANOVAs revealed a significant main effect of symptoms on risk ($F(2, 1049) = 3.53$, $p = 0.03$, $\eta p^2 = 0.01$), invasiveness ($F(2, 1049) = 7.04$, $p < 0.001$, $\eta p^2 = 0.01$), and change to person ($F(2, 1049) = 6.31$, $p = 0.002$, $\eta p^2 = 0.01$). Post hoc tests revealed that the average effect of neurotechnology was rated as significantly riskier ($p = 0.03$, mean = 3.11, $\sigma = 1.27$), more invasive ($p < 0.002$, mean = 2.96, $\sigma = 1.50$), and leading to a greater change to person ($p = 0.001$, mean = 2.48, $\sigma = 1.13$) for mood symptoms compared to motor symptoms (risk: mean = 2.98, $\sigma = 1.19$; invasiveness: mean = 2.78, $\sigma = 1.43$; change to person: mean = 2.25, $\sigma = 1.15$). Post hoc differences between mood and memory symptoms were significant for invasiveness ($p = 0.009$, mood: mean = 2.96, $\sigma = 1.50$; memory: mean = 2.81, $\sigma = 1.39$) but not for risk ($p = 0.27$, mood: mean = 3.11, $\sigma = 1.27$; memory: mean = 3.02, $\sigma = 1.18$) or change to person ($p = 0.45$, mood: mean = 2.48, $\sigma = 1.13$; memory: mean = 2.39, $\sigma = 1.04$). There were no significant post hoc differences between motor and memory symptoms for risk ($p = 1.00$), invasiveness ($p = 1.00$) or change to person ($p = 0.11$).

Interaction effects of neurotechnologies and symptoms

The results of the ANOVAs showed significant interaction effects for benefit ($F(5.85, 1049) = 20.92$, $p < 0.001$, $\eta p^2 = 0.04$), acceptability ($F(5.76, 1049) = 16.82$, $p = 0.001$, $\eta p^2 = 0.03$), personal use ($F(5.80, 1049) = 16.30$, $p = 0.001$, $\eta p^2 = 0.03$), risk ($F(5.82, 1049) = 3.11$, $p = 0.005$, $\eta p^2 = 0.01$), invasiveness ($F(5.84, 1049) = 2.12$, $p = 0.05$, $\eta p^2 = 0.004$), and change to person ($F(5.86, 1049) = 3.42$, $p = 0.003$, $\eta p^2 = 0.01$). To further investigate the interaction effects, we conducted a series of post hoc tests with Bonferroni corrections (correcting for 66 total estimates). Due to space limitations, we report the results that speak to the primary findings in the manuscript, and the full list of results for each post hoc test can be found in Tables S1–S6.

Benefit, acceptability, and personal use

As depicted in Figure 2, perceived benefit results for symptoms across technologies were similar, except for pills being

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perceived as significantly more beneficial for mood compared to memory symptoms ($p < 0.001$) but not significantly different for motor symptoms ($p = 1.00$). Pills were perceived as significantly more beneficial for treating mood symptoms compared to any of the other three neurotechnologies. The pattern of results for symptoms across technologies were similar, except for pills, for which there were no significant differences across symptoms ($p = 1.00$), because pills were perceived as particularly more acceptable to treat mood symptoms compared to the other neurotechnologies. As depicted in Figure 2, the patterns of results for symptoms across technologies were similar, except for pills being perceived as significantly more likely to be used for motor symptoms compared to mood ($p = 0.010$) and memory ($p < 0.001$). Pills were rated as being significantly more likely to be personally used to treat mood symptoms compared to the other neurotechnologies.

Risk, invasiveness, change to person

As depicted in Figure 2, the pattern of risk perceptions for symptoms across technologies were similar, with mood > memory > motor, except for pills, where there were no significant differences across symptoms ($p = 1.00$). The patterns of results for perceived invasiveness for symptoms across technologies were similar to risk perceptions, except for pills, where there were no significant differences across symptoms ($p = 1.00$). Perceptions of change to person for symptoms across technologies were similar for risk and invasiveness, except that there were no significant differences across symptoms for DBS and TMS ($p = 1.00$), but motor compared to mood symptoms were perceived as resulting in less change to the person for pills ($p < 0.001$) and MRgFUS ($p = 0.006$).

DISCUSSION

This study examined participants' perceptions of several forms of neuromodulation across three symptom profiles (mood, memory, and motor). Our findings contribute to the handful of prior analyses of public opinion surrounding the use of neurotechnologies to treat certain brain disorders.[30,42,54,60,66,68,69] Descriptive results indicate that the US public's willingness to use neurotechnologies to treat their severe mood, motor, or memory symptoms varies across neurotechnology modalities. Specifically, 21% of respondents report that they would "probably" or "definitely" use DBS, 29% for MRgFUS, 41% for TMS, and 61% for pills. Furthermore, on average, participants reported low familiarity with all neurotechnologies besides pills. These findings indicate potential openness to adopting neurotechnological interventions among the general population and suggest that greater exposure to and education about these potential treatments could increase acceptability. Although there were broad patterns that emerged (e.g., DBS and MRgFUS were seen as more invasive, risky, and causing more change to person than pills or TMS), there were notable nuances in participants' views on these neurotechnologies and their utility for different types of conditions.

DBS is an established intervention for treatment of severe movement disorders and has shown promise for some treatment-refractory psychiatric conditions.[70] However, despite DBS being perceived as more beneficial than MRgFUS and TMS, it was also rated as less acceptable and less likely to be used. DBS was also viewed by participants as the riskiest and most invasive neurotechnology. This suggests that, despite its efficacy and potential benefit, the public still has concerns about this treatment approach. This is consistent with some previous work showing that the public holds generally positive, but cautious, views of DBS.[30,60,68] When considered alongside MRgFUS, which produces a permanent lesion, DBS offers greater flexibility as a treatment option, with titratable stimulation parameters and the ability to be removed in the event of complications or lack of efficacy.[71] Therefore, from a clinical perspective, it may be surprising that participants rated DBS as more invasive and riskier than MRgFUS. However, participants' responses may be influenced by the implantation process, as DBS requires an "open surgical approach" for placement of the device as well as the ongoing presence of the device in the individual's body. Participants also viewed DBS as being significantly more likely to change someone as a person than the other technologies, which aligns with the ongoing debate within the neuroethics literature.[16,17,19–21,31,47,48] Concerns have been raised that media coverage of this debate may contribute to the public's views of acceptability toward DBS.[72]

Participants' views on pills stand in contrast to those of DBS, with this form of neuromodulation being rated as the most beneficial, acceptable, and likely to be used. This trend may be, at least in part, related to how common oral medications are in the US, particularly those used to modulate mood (e.g., antidepressants and anxiolytics).[73–75] Pills were also perceived as the least invasive neurotechnology despite qualitative findings noting the potential for medications to be perceived as invasive by related stakeholders, given their systemic effects on the body.[76] It is notable that, while pills were viewed as the least invasive, they were also viewed as riskier and as leading to greater change to person than TMS. Yet participants still felt that pills were more acceptable and were more open to using them than TMS. This aligns with previous work demonstrating that people hold generally positive views of TMS but may only be willing to consider it as a treatment option if medications are not effective.[60]

Across all four neurotechnologies, participants felt that these treatments were most beneficial and acceptable and were more likely to use them personally in the context of motor symptoms, followed by memory and mood symptoms. This is consistent with a previous media analysis examining DBS, which found that the use of DBS for movement disorders was viewed as a more effective treatment for movement disorders than psychiatric disorders (64% versus 9%).[42] We found that the use of these technologies to treat mood symptoms was viewed to carry the greatest levels of risk, invasiveness, and change to person. This distinction between acceptability of neuromodulation for brain-based conditions that manifest through physical symptoms versus psychological symptoms will be critical to understand in greater detail, including the range of reasons for which respondents hold these judgments. The reasons underlying these judgments may have important implications for potential adoption of these technologies in psychiatry and reduction of stigma for individuals who are already engaging with these interventions. The pattern of results on perceived acceptability most

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closely resembled the pattern of results for personal use, which suggests that perceived norms may play a role in the potential uptake of these technologies. Last, exploratory correlations were conducted between demographics (age, education, and income) and the six outcome measures across neurotechnologies (averaged across symptoms). Age showed weak but often statistically significant technology-specific associations (e.g., age was negatively correlated with perceived benefit across each technology), while income and education exhibited occasional weak effects. Full results are provided in Tables S7–S10.

Overall, our findings suggest that the public holds nuanced views of neuromodulation with respect to their level of risk, invasiveness, and potential to change who someone is as a person, which have important ethical implications for individuals who choose to engage with these interventions, particularly with respect to the informed consent process. These data highlight the importance of patient-clinician communication and shared decision-making. As clinicians counsel patients on their treatment options, they should focus not only on the potential risks and benefits of a procedure but also be sensitive to the level of perceived invasiveness and the patients' views on the potential for an intervention to impact who they are. These discussions can help increase patients' understanding of these technologies, thereby enhancing their autonomy and ensuring that they are making informed treatment decisions.

Current limitations and outlook

To examine the potential impact of different symptomatology on the public's views of these neurotechnologies, we were limited to selecting technologies for which there are applications across all the symptom domains (i.e., mood, motor, and memory). Based on previous work, there are some neuromodulation approaches (e.g., electroconvulsive therapy) that may have elicited different responses, given the stigma and long history of this technology in psychiatry, and we recognize that the absence of this technology from the experiment is a notable limitation.[77] In addition, we did not examine neuromodulation via digital tools or strategies that do not rely on technology, such as cognitive behavioral therapy. In the current study, we also opted for respondents to subjectively interpret the outcomes of interest (e.g., invasiveness and change to person). Given a lack of consensus on the definition of these constructs and the different types of invasiveness observed in the context of neuromodulation, we opted not to provide specific definitions.[76] Future researchers interested in additional nuances within these constructs could use these results as an intuitive baseline and examine how providing specific definitions might influence opinions. Future research should explore how different types of surgical procedures, as well as the terminology used to describe them, might further influence perceptions. For example, procedures like DBS with an open surgical approach versus MRgFUS, involving permanent lesions, could elicit different responses based on the procedural details provided. Finally, we note that participants were questioned about their interest in using these technologies in the absence of any information about the costs associated with each intervention. Given the substantial financial costs associated with many of these treatments, this is an important potential barrier to access and uptake that should be considered in future work.[78–80]

Conclusions

As rates of brain-based conditions continue to rise, members of the public may one day stand to benefit from some form of neuromodulation examined in the present study. Our results suggest that, despite viewing interventions as effective and potentially beneficial, the public views some forms of neuromodulation as invasive, risky, and able to change who they are as a person. These findings provide insights into the public's complex views on neuromodulation, which can be used to facilitate conversations about barriers to uptake, ethical safeguards on novel applications of neuromodulation, and alignment of technology development and use with the values of end users and society. This engagement will serve, we hope, to improve informed consent processes and maximize the available benefits of current and future neurotechnologies while minimizing the risks through careful collective deliberation.

METHODS

Overview

We designed a survey using the Qualtrics platform and employed a randomized experimental design to examine public attitudes toward the use of four neurotechnologies: DBS, TMS, pills, and MRgFUS. These technologies were presented to participants as potential treatments being offered to a person described as experiencing symptoms severely affecting one of three (randomly assigned) brain functions: mood, memory, or motor. This study was pre-registered (https://aspredicted.org/DYV_HXH).

Participants

Participants (n = 1052) were adult members of the US public and were recruited from Prolific (www.prolific.com), an online sampling firm, using the platform's nationally representative stratified sampling option using self-reported age, gender, and race demographics. All participants provided informed consent prior to participating in the experiment. All research activities were approved by the Harvard Medical School Institutional Review Board (IRB22-0986).

Procedure

All participants rated each neurotechnology (4 within-subjects groups: DBS, TMS, pills, and MRgFUS) based on a hypothetical person experiencing one of three symptoms (3 between-subjects groups: mood, memory, and motor).

Description of symptoms

Participants were randomly assigned to be presented with one of the three descriptions of the target's symptoms: "A person has been experiencing the following""

- Mood symptoms (e.g., feeling sad, irritable, empty), a loss of pleasure or interest in activities, for most of the day, every day. They experience poor concentration, feelings of excessive low self-worth, hopelessness about the

future, disrupted sleep, changes in appetite, and feeling tired.

- Memory symptoms (e.g., unable to recall memories, difficulty retaining new information), memory loss for most of the day, every day. They experience difficulty learning and recalling new information such as recent events, conversations, or people, and recalling important memories and personal information about themselves.
- Motor symptoms (e.g., slowed movement, muscle weakness), a loss of muscle control, for most of the day, every day. They experience tremors while their muscles are at rest, stiffness, trouble swallowing, unstable posture, difficulties with walking, and reduced control over their facial muscles.

Description of neurotechnologies

Following the description of the target person's symptoms, participants were presented with the following vignettes of the neurotechnologies: "Given the severity of their condition, they are presented with the following neurotechnology to help reduce symptoms":

- Deep brain stimulation (DBS), which involves surgically implanting electrodes into the brain to deliver electrical stimulation to a specific region of the brain.
- Transcranial magnetic stimulation (TMS), which involves placing a magnet against an area (outside) of the head to deliver magnetic stimulation to a specific region of the brain.
- Pills, which involve ingesting medication (taken by mouth) in the form of a pill to deliver chemicals to the brain.
- MRI-guided focused ultrasound (MRgFUS), which involves placing a cap on the outside of the head that delivers focused sound waves to create a precise lesion in a specific region of the brain.

Attitudes (outcome measures)

Following the between-subjects assignment to one of the three symptom conditions (mood, memory, or motor symptoms), all participants were asked to report their attitudes by responding to six outcome measures. Each outcome measure was reported for each of the four neurotechnologies: "Given this person's (mood/memory/motor) symptoms, to what extent do you think using (DBS/TMS/pills/MRgFUS) would be (beneficial/risky/invasive/acceptable)?" on 5-point Likert scales (range: 1 = not at all, 5 = extremely). Upon answering the four dependent variables mentioned above, participants answered two more questions for each of the neurotechnologies: "Given this person's (mood/memory/motor) symptoms, to what extent do you think using (DBS/TMS/pills/MRgFUS) would change who they are as a person?" on 5-point Likert scales (1 = not at all, 5 = a great deal), and finally, "Now, suppose YOU were experiencing these (mood /memory/motor) symptoms, would you consider (DBS/TMS/pills/MRgFUS)?" on 5-point Likert scales (range: 1 = I definitely would not, 5 = I definitely would). These measures represent an initial subset of questions presented to participants. Participants were also asked how familiar they were with each neurotechnology on a 5-point Likert scale (1 = not familiar at all, 5 extremely familiar). Additional questions about these neurotechnologies were asked at the end of the survey for a separate manuscript.

Statistical analyses

In order to compare how attitudes vary for each neurotechnology based on the targeted symptoms, we conducted a mixed-effects ANOVA on each of the six outcome measures: benefit, acceptability, personal use, risk, invasiveness, and change to person. Mauchly's test of sphericity indicated that the assumption of sphericity was violated ($p < 0.001$) for each outcome variable; therefore, we applied Huynh-Feldt sphericity corrections for each analysis. Significant main effects were followed up with Bonferroni-corrected post hoc comparisons.

RESOURCE AVAILABILITY

Lead contact

The lead contact is Rémy Furrer (rfurrer@mgh.harvard.edu).

Materials availability

Survey materials are currently part of ongoing research efforts. We are committed to transparency and will make these materials publicly available upon completion of the full set of studies. In the meantime, materials can be shared upon reasonable request for the purpose of verification or collaboration.

Data and code availability

All analyses were conducted in JASP. Data are currently part of ongoing research efforts. We are committed to transparency and will make these materials publicly available upon completion of the full set of studies. In the meantime, data can be shared upon reasonable request for the purpose of verification or collaboration.

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AUTHOR CONTRIBUTIONS

Conceptualization, R.A.F., A.R.M., I.S., P.Z., T.W., F.X.S., and G.L.-M.; methodology, R.A.F., A.R.M., I.S., P.Z., F.X.S., and G.L.-M.; formal analysis, R.A.F.; investigation, R.A.F., A.R.M., I.S., P.Z., F.X.S., and G.L.-M.; data curation, R.A.F.; writing – review & editing, R.A.F., A.R.M., I.S., P.Z., T.W., F.X.S., and G.L.-M.; visualization, R.A.F.; supervision, T.W., F.X.S., and G.L.-M.; funding acquisition, T.W., F.X.S., and G.L.-M.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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