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Research Report

Mentalizing with the future: Electrical stimulation of the right TPJ increases sustainable decision-making

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ABSTRACT

While many people acknowledge the urgency to drastically change our consumption patterns to mitigate climate change, most people fail to live sustainably. We hypothesized that a lack of sustainability stems from insufficient intergenerational mentalizing (i.e., taking the perspective of people in the future). To causally test our hypothesis, we applied high-definition transcranial direct current stimulation (HD-tDCS) to the temporo-parietal junction (TPJ). We tested participants twice (receiving stimulation at the TPJ or the vertex as control), while they engaged in a behavioral economic paradigm measuring sustainable decision-making, even if sustainability was costly. Indeed, excitatory anodal HD-tDCS increased sustainable decision-making, while inhibitory cathodal HD-tDCS had no effect. These finding cannot be explained by changes in participants' fairness norms or their estimation of how other people would behave. Shedding light on the neural basis of sustainability, our results could inspire targeted interventions tackling the TPJ and give neuroscientific support to theories on how to construct public campaigns addressing sustainability issues.

Intergenerational sustainability is one of humankind's most pressing challenges and global climate change threatens the welfare of billions of people around the globe (FAO et al., 2018; OECD, 2015). While any lasting way of achieving intergenerational sustainability will require a broad range of political, societal, and industrial measures to avert harm from future generations, one very promising lever to combat climate change is to change individual human behavior. At first glance, this seems like low-hanging fruit: Most people acknowledge the urgency to act (European Commission, 2014;

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Jones & Saad, 2018), and individual and household decisions and consumption account for up to 40%–70% of greenhouse gas emissions (Hertwich & Peters, 2009; Vandenbergh et al., 2008). Too often, however, people fail to behave sustainably towards future generations even when they have the means to do so (Gifford, 2014; Hauser et al., 2014; Jacquet et al., 2013) and identifying mechanisms to encourage sustainable decision-making could be vital to mitigate climate change.

While it is known that whether and how people engage in sustainable behavior is massively influenced by social aspects (Pearson & Schuldt, 2018), intergenerational sustainability is different from normal social encounters with fellow members of one's own generation, for example because consequences of one's behavior are temporally distant and future generations cannot reciprocate (Hauser et al., 2014; Weber, 2017), leading some to even define the next generation as outgroup (Meleady & Crisp, 2017). Thus, we here propose that intergenerational sustainability requires a special set of sociocognitive processes that goes beyond what we know about the processes involved in social interactions with people in the present. Specifically, a failure to engage in *intergenerational mentalizing* (i.e., thinking about the needs, values, and mental states of others in the future) could result in a reduced proclivity for sustainable decision-making. The reasoning behind this thought is simple: If we do not mentally engage with the beneficiaries of sustainable actions, why should we accept to pay a cost for their sake?

Note that this intergenerational mentalizing is not the same as pro-environmental attitudes, which are often vague, general beliefs about the environment, like whether the environment is being exploited by humans (Dunlap et al., 2000). Rather, intergenerational mentalizing refers to concrete thoughts about individuals in the future, and therefore has a strong cognitive component. While mentalizing with other people in the present already is a challenge in and of itself, intergenerational mentalizing is probably further impaired by the temporal aspect of sustainability: Not only do people have to form a mental representation about the needs of total strangers (and then restrict their own consumption to benefit them), these strangers are not only physically but also temporally removed – they might not even have been born.

Importantly, while it seems theoretically plausible that intergenerational mentalizing causally influences sustainable decision-making, it has not yet been shown empirically, and too often, the importance and peculiarities of cognitive factors influencing human decision-making are ignored by policy makers discussing climate change (Clayton et al., 2015; Fehr-Duda & Fehr, 2016). Thus, we here wanted to test whether increasing intergenerational mentalizing leads to more sustainable decisions, measured in a decision-making experiment with real, monetary consequences for both the decision-makers as well as the next generation. In order to be able to draw causal inferences, we here use a well-established, non-invasive brain stimulation technique, high-definition transcranial direct current stimulation (HD-tDCS) and applied it on the right temporo-parietal junction (TPJ). The TPJ has been linked to mentalizing within the current generation (Costa et al., 2008; Jeurissen et al., 2014; Van Overwalle, 2009; Young et al., 2010), and there is ample evidence that applying tDCS to the TPJ modulates mentalizing (Donaldson et al., 2018; Mai et al., 2016; Santiesteban et al., 2012; Sellaro et al., 2016). We applied both excitatory anodal stimulation and inhibitory cathodal stimulation, comparing both to an active control site (vertex).

To assess intergenerationally sustainable decision-making in a well-controlled laboratory setting, we used an intergenerational social dilemma game with an environmental framing, i.e., a fishing game, inspired by similar designs by others (Hauser et al., 2014; Jacquet et al., 2013). Such designs have a long history in behavioral economics and the study of social behavior (for an overview regarding inter-generational paradigms and neuroscience, see Aoki et al., 2020; for a general overview, see van Dijk & De Dreu, 2021). In the game at hand, four participants form a generation. Here, another asset of tDCS for studying group processes becomes apparent: Because it can easily be applied to multiple people at once, we could test 8 participants at a time. This enabled us to study interactions in groups while still retaining participants' anonymity, so that no participant would know with whom they would be interacting (modelling real-world sustainable decision-making, where cooperation among strangers around the globe is required to benefit the future generation; Hauser et al., 2014; Jacquet et al., 2013). Each participant can extract a maximum of 20 fish from a common pool (see Fig. 1A for a graphical representation). Participants receive a monetary reward for each extracted fish and their decisions have direct effects on the next people to come to the lab. Because these future participants are completely unknown to the participants and any negative effects on their payoff will happen with considerable temporal delay (when the original participants have long left the lab), we can use behavior towards the next group as proxy for behavior towards the next generation. As in everyday life, if participants want to behave sustainably towards a future generation, they have to restrict themselves: If the collective extraction exceeds an *inter-generational sustainability threshold* of 36 fish, the next generation in the laboratory will not receive the full payoff from their extraction in the fishing game; their payoff will be reduced by 80% (see Fig. 1A). This inter-generational sustainability threshold of 36 fish on a group level results in an individual inter-generational sustainability threshold of nine, i.e., on average, every participant can extract nine fish whilst still behaving sustainably towards the next generation.

Because of this individual inter-generational sustainability threshold, there are two ways of measuring sustainability of a participant's action. First, we might take the raw number of fish they extracted. However, this loses an important categorization: For example, if a participant changes their extraction from 11 to 17 fish, this looks like a much stronger change than changing from, say, 9 to 10. However, in the former case, both decisions were unsustainable, while in the latter case, the participant decided to move from a sustainable decision to an unsustainable one. It might therefore be more informative to dichotomize participants' decisions into sustainable and unsustainable, and use the number of sustainable decisions as dependent variable. While we favor this second approach, we here report both indices for completeness.

In everyday life, some sustainable decisions are costlier than others, with the most environmentally harmful behaviors arguably being especially tempting for many people (e.g.,

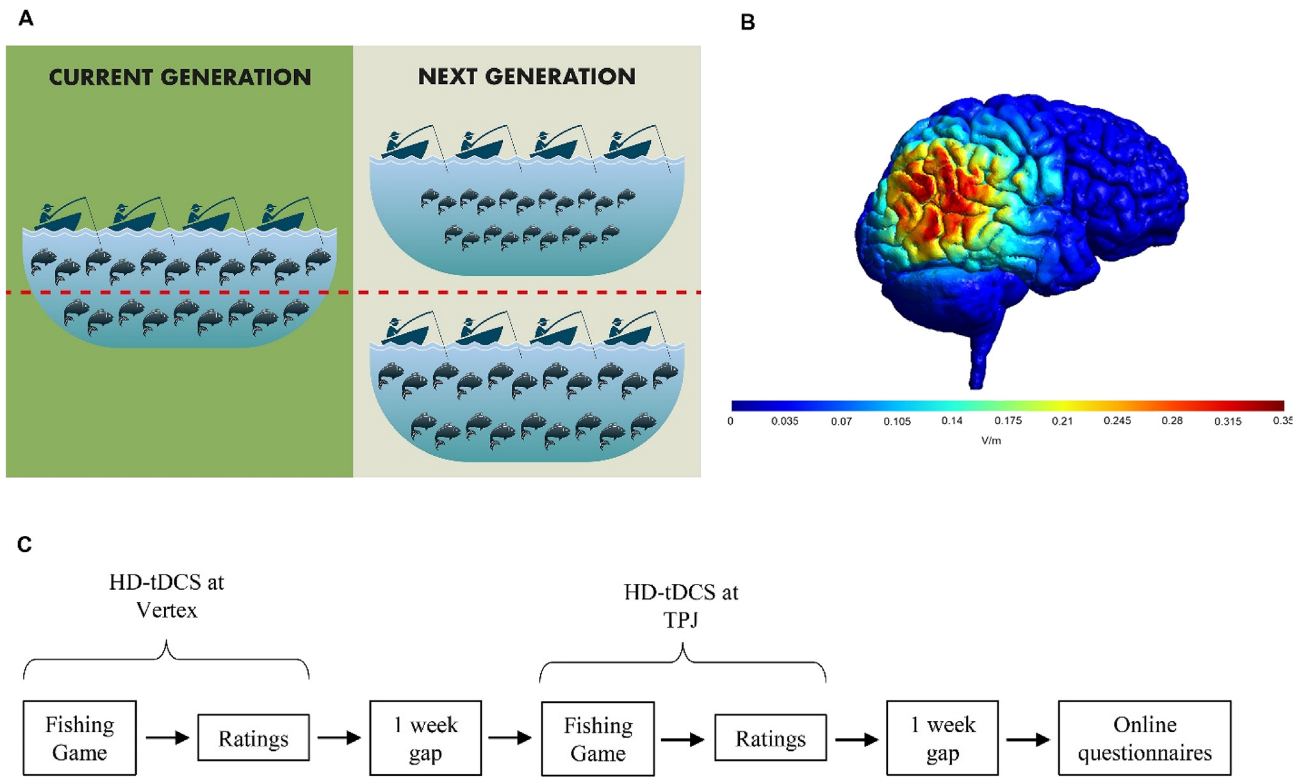

Fig. 1 – Experimental setup and design. Panel A depicts the fishing game: If the four participants forming the current generation (on the left) exceed the inter-generational sustainability threshold (dashed line) and extract more than 36 fish (9 fish each) the next group's payoff was reduced by 80% (depicted by smaller, less valuable fish; top right). If a group stayed within the threshold's bounds, the next generation got the full payoff (bottom right). Additionally, if the four players exceed the intra-generational sustainability threshold (not depicted) of 68 fish (17 fish each), their own payoff is reduced by 80%. Panel B shows the results of a simulation of the electric fields in the right TPJ. The electric field strength was .32 V/m, see Methods for details. Panel C shows the design of the study. Note that the order of stimulation site was counterbalanced. Stimulation was ongoing while participants engaged in the fishing game, the fairness rating, and the estimation of the other player's extraction.

flying or eating meat). It could be that different types of decisions are differentially affected by changes in intergenerational mentalizing. For example, maybe heightened intergenerational mentalizing leads to enough concern to endure small costs for the benefits of strangers in the future, but no to enough concern to bypass a large reward. To explore this, we varied the value of fish: One fish was worth either 1 CHF (≈1$) or .10 CHF.

There is some evidence that information about the state of a resource (i.e., warnings) might lead to more sustainability, even though there are significant interindividual differences when it comes to reacting to warnings (Baumgartner et al., 2021). In the experiment at hand, participants did not receive any instant feedback on the consequences of their behavior – which is similar to most decision-making situations in everyday life, where people do not immediately receive a feedback either, but maximum effects on global warming occur about ten years after CO_2-offset (Ricke & Caldeira, 2014).

We also wanted to ensure that stimulation of the right TPJ did not put participants in a state in which they understood the game less well or paid less attention, resulting in behaviors that did not reflect their true behavioral preferences. To control for this, the design includes another sustainability threshold: the *intra-generational sustainability threshold* of 68 fish (i.e., on average 17 fish per participant). If the collective extraction of the current generation exceeded the intra-generational sustainability threshold, the participants lost 80% of the payoff from their extraction in the fishing game, making threshold-adherence personally relevant to the participants. Because of this significant potential personal loss, it would not be rational for participants to exceed this threshold, and we thus expected no effects of tDCS regarding this threshold.

Because there can be substantial variance in factors influencing sustainable decision-making, like pro-environmental attitudes (Baumgartner et al., 2019) and mentalizing abilities (Bukowski & Samson, 2017), the most important comparison (TPJ versus vertex as active control) was a within-participant-comparison, maximizing our power (see Fig. 1B for a simulation of the stimulation site and Fig. 1C for a graphical depiction of the experimental design).

Because HD-tDCS is known to elicit quite painful skin sensations (Garnett & den Ouden, 2015), we wanted to ensure that potential effects were not actually due to different levels of perceived pain. We therefore administered a numeric rating scale for pain, a standard scale for measuring adult pain

(Hawker et al., 2011), with meaningful verbal anchors and adapted descriptions of participants' experience. Additionally, we also administered a Likert-scale measuring the (un) pleasantness of the stimulation to capture unpleasant sensations other than pain, which are also known to occur (Fertonani et al., 2015).

Because we did not expect stimulation of the TPJ to alter general attention or understanding of the rules of the task, we did not expect to see any changes in adherence to the intragenerational threshold. However, because of previous literature suggesting a causal role of the right TPJ in mentalizing and because we assumed that intergenerational mentalizing is important for sustainable decision making, we hypothesized that increasing activity of the right TPJ by anodal HD-tDCS leads to more sustainable decisions (compared to vertex stimulation), while diminishing activity of the right TPJ by cathodal HD-tDCS leads to less sustainable decisions (compared to vertex stimulation).

1. Materials and Methods

1.1. *Study design*

We recruited 72 participants, all students at the University of Bern. Those with history of mental or neurological disorders were not admitted to the experiment, as were students of psychology or economics who might have been familiar with similar experimental designs and thus might have behaved different from naïve subjects. All participants gave written informed consent, and the experiment was approved by the local ethics committee and conducted in accordance to the declaration of Helsinki. 9 participants answered incorrectly to the comprehension check after the experiment; 3 participants reported that the stimulation induced strong pain that made them make mistakes in the game and 1 participant did not receive the full-length-stimulation due to a technical error. These participants were excluded from all analyses, so that our final sample comprised 59 participants (25 females; mean age 20.75, SD: 2.89). The exclusion criteria were defined before data analysis. The sample size was determined using a power analysis for a general linear model using the R packages pwr (Champely, 2020). Assuming a u of 3, a conventional power of 80%, and a significance level of .05, the required sample size was 73. Due to the necessary exclusions, our final sample size is slightly smaller. Still, our sample size is similar to typical studies in the field (Donaldson et al., 2018; Mai et al., 2016; Santiesteban et al., 2012) reporting medium effect sizes. No part of the study procedures or analyses was preregistered prior to the research being conducted.

Participants were pseudorandomly allocated to one of two groups (controlling for gender). One group received anodal stimulation (29 participants, 12f), the other cathodal stimulation (30 participants, 13f), see Fig. 1C for a graphical depiction of the procedure. Per experimental session, 8 participants were present in the same room, but without visual contact to any of the other participants. Participants were asked not to talk to their fellow participants and to switch off their phones. In the first session, participants received general information regarding the experiment and safety of HD-tDCS and provided informed consent. The HD-tDCS-electrodes were then installed on the participants' heads (see below for details), they received the instructions for the fishing game and had to answer four questions about the game to ensure they correctly understood the rules. During the instruction, they had a calculator available to help with understanding. The stimulation was then started and after a waiting period of 5 min the fishing game started. Directly afterwards, participants were asked to state which behavior in the game they would deem fair and to guess how many fish the other participants in their group extracted (see below). Participants were also asked to state how many fish each participant could have extracted on average while still acting sustainably (see below). Stimulation was then stopped.

One week after the first session, participants showed up to an almost identical second session, except that the second session also included feedback on participants' payoff, the decisions of their group, and consequences for the next group (see below). For the second session, the same eight participants showed up as for the first session and participants played in the same group of four people, but without knowing with whom exactly they would play. Per stimulation group, half of the participants received stimulation at the TPJ in week 1 and stimulation of the vertex in week 2; half received the reversed order. One week after the second session, participants received a link to three online questionnaires (see below) via email and were asked to fill them out online. This delayed assessment was implemented so that participants' responses could not be affected by tDCS.

1.2. *Application of HD-tDCS*

We here employed a well-established non-invasive neuromodulation technique, high-definition tDCS (HD-tDCS; Datta et al., 2009), which has been shown to influence a range of cognitive and social functions (Donaldson et al., 2017; Martin et al., 2018; Nikolin et al., 2015).

Our stimulation parameters and electrode position follow previous studies on social cognition and the TPJ (Donaldson et al., 2017, 2018). The electrodes were placed following the 10-20-EEG-system: In the TPJ condition, the electrode was placed at P6, the return electrodes at C6, CP8, P2, PO8. As control condition, we chose a vertex stimulation, with the electrode positioned over Cz, the return electrodes at C1, C2, FCZ, CPZ. In both cases, the intensity of stimulation was 2 mA (mA) for a maximum of 20 min delivered with a neuroConn DC-Stimulator MC (software version 1.6.0, neuroConn, Ilmenau, Germany). In the anodal condition, the central electrode served as anode and the return electrodes as cathode, in the cathodal condition, this was reversed. To confirm that the TPJ condition indeed tackled the TPJ and, in contrast, that the vertex condition did not, a computer simulation was conducted (using SimNIBS 2.1.1, www.simnibs.de), see Fig. 1B. In the right TPJ condition, the electric field strength reached on the right TPJ was .32 V/m (V/m), in the vertex condition, the electric field strength reached on the right TPJ was .004 V/m. Since previous modelling results proposed that an electric field strength of .13 V/m is sufficient to modulate neural functioning (Reato et al., 2010), the simulation results indicate that the right TPJ condition, but not the vertex condition, influenced the right TPJ. Previous research suggests that the earliest effect on cortical excitability induced by both anodal and cathodal tDCS are visible after 5 min of stimulation (Nitsche, et al., 2003; Nitsche, et al., 2003). Thus, we implemented a 5-min waiting period between onset of HD-tDCS and start of the fishing game.

1.3. Assessment of sustainable decision-making

To assess the sustainability of participants' decision making, they engaged in a computerized fishing game (implemented using z-tree, Fischbacher, 2007) with real, monetary consequences for both their own generation as well as the subsequent group (generation) in the laboratory. Participants took on the role of a fisher who can extract between 0 and 20 fish from a common pool shared with three other participants. A fish was worth either 1 CHF or .10 CHF (varying the temptation participants face); participants were informed about the current value before every decision. Participants were informed that two trials would be selected by a random mechanism at the end of the experiment and the amount of money corresponding to their extraction would be paid to them in cash (in addition to a flat fee of 55 CHF). If the four participants collectively extracted more than 36 fish (the inter-generational sustainability threshold), the payoff in that trial was reduced by 80% for the next group of four (i.e., generation) to come to the lab. Similarly, if the participants collectively extracted more than 68 fish (the intra-generational sustainability threshold) in any given trial, their payoff from that trial was reduced by 80%. This was implemented as control, to ensure that the application of HD-tDCS at the TPJ did not render participants in a state where they did not understand the consequences of their actions in the game. Specifically, we expected that the higher intra-generational sustainability threshold (with its potentially large negative consequences for one's own payoff) would not be exceeded more often after tDCS at the TPJ than on the vertex.

Participants were asked to complete eight trials in a pseudo-randomized order with four trials per exchange rate (i.e., one extracted fish is either worth 1 CHF or .10 CHF). All trials were independent of each other. Each trial consisted of one decision screen (see Fig. S2): Participants saw which exchange rate applied and were reminded about the inter- and intra-generational sustainability thresholds. They saw the question “How many fish do you want to extract” at the bottom of the screen, and a visual scale with the numbers from 0 to 20. They made their decision by clicking on the appropriate number, which was highlighted shortly afterwards. Participants of the same generation made their decisions at the same time and in the same room, but anonymously and without visual contact. Additionally, they were instructed not to speak to each other. The groups were stable over all trials and participants were informed about this. Before the experiment, participants were informed that they would receive their payment with no other person present and from a person who could not infer their decisions from their payoff. This was done to eliminate reputation effects towards the experimenter or other participants. Additionally, feedback on the collective extraction of their other group members, their payoff, and the consequences of their behavior for the next generation was only provided once at the very end of the second experimental session, so that it could not influence participants’ decision.

1.4. Fairness ratings

To make sure that any effect of HD-tDCS was not due to changes in perceived fairness, participants were asked to rate which extraction they see as fair while still under the influence of HD-tDCS. For this, they were reminded of the two types of decision screens (with one fish worth 1 CHF resp. .10 CHF) and were asked to judge which amount of extracted fish they see as fair (on a scale from 0 to 20, as in the actual fishing game). This was done after the fishing game to prevent this question from priming a certain behavior during the actual decision-making.

1.5. Estimation of others’ extraction

Similarly, we wanted to make sure that a potential change in sustainable behavior did not merely occur because stimulation of the TPJ lead the participants to change their estimations of what the other players might do and they adjusted their behavior accordingly. Thus, participants were also asked to estimate how many fish the other players in their group extracted on average (separated for the two exchange rates).

1.6. Inter-generational threshold comprehension check

To ensure that a potential effect was not due to changes in task understanding, participants were asked to report the average amount of fish each player could extract so that the group would not exceed the intergenerational sustainability threshold. This additional comprehension check was implemented to ensure that participants did not accidently behave unsustainably while believing they were actually behaving sustainably (or vice versa).

1.7. Questionnaires

To make sure that our results were not influenced by stable differences between the anodal and cathodal group (e.g., pro-social preferences or environmental attitudes), participants were asked to fill in three online questionnaires one week after their last experimental session. To assess environmental attitudes and personal values (including biospheric values, i.e., concern for nature, and altruistic/egoistic values), we used the New Environmental Paradigm (Dunlap et al., 2000) and the Schwartz Value Scale (Steg et al., 2014). To measure participants’ pro-social preferences, we used the Honesty–Humility Scale from the Hexaco (Ashton & Lee, 2009). 51 participants filled in the questionnaires.

To ensure that results were not influenced by different levels of pain and discomfort that participants might experience, we administered a numeric rating scale for pain, a standard scale for measuring pain (Hawker et al., 2011), with meaningful verbal anchors. Additionally, we administered a 7-point Likert-scale measuring the (un)pleasantness of the stimulation (ranging from “very pleasant” to “very unpleasant”) to capture unpleasant sensations other than pain, which are also known to occur (Fertonani et al., 2015). Both the pain and discomfort scale were administered while HD-tDCS was ongoing.

1.8. Statistical analyses

To analyze our data, we ran mixed-effects models, which can account for both fixed effects and random effects. If not specified differently, a maximal random-effects structure was used and models include a per-participant random adjustment to the fixed intercept as well as per-participant random adjustments for the experimental factors varying within-participants (stimulation site and exchange rate). In a first step, we always ran analysis without interactions (most notably without stimulation site x stimulation type) and included interactions in additional steps. It lies in the nature of a within-design that the order of conditions or the time could influence participants. Thus, we included week and order of stimulation as covariates for all analyses. All estimates (B) are unstandardized.

We first tested for an interaction between stimulation type (anodal/cathodal) and stimulation site, which would indicate that the stimulation has differential effects in the anodal and cathodal group. Where appropriate, we supplemented this with post-hoc tests to establish where an effect stemmed from. Finally, we corroborated our results by including relevant covariates and additional control measures, please refer to the results section for details. Any effect was regarded as statistically significant if $p < .05$ (two-tailed). Analyses were conducted using the statistic software R (R Core Team, 2016), mixed-effects models were calculated using the R-package lme4 (Bates et al., 2015; Kuznetsova et al., 2017). Conditional and marginal coefficients of determination (R^2c resp. R^2m, indicating the full variance explained resp. The variance explained by the fixed factors) were calculated using the package MuMIn (Barton, 2018), following the method proposed by Nakagawa & Schielzeth (2013), and reported alongside the full models in the supplementary material.

2. Results

2.1. Intra-generational sustainability threshold

As described above, we did not expect HD-tDCS to change participants understanding of the task or their general attention and therefore did not expect any changes with regards to the intra-generational sustainability threshold. In order to statistically test this assumption, we ran a model with stimulation type and stimulation site as fixed effects and the number of decisions exceeding the intra-generation threshold as dependent variable. In a next step, we added the interaction between stimulation type and stimulation site to the model. Exceeding of the intra-generation threshold was rare (on average, less than one decision per participant exceeded the threshold, regardless of stimulation type or stimulation site) and as expected, there were no significant main effects ($B = -.06$, $SE = .08$, $p = .425$ and $B = .12$, $SE = .14$, $p = .383$, for effects of stimulation site and stimulation type, respectively), nor was there a significant interaction ($B = .09$, $SE = .15$, $p = .580$, see table S1 for the full results). Thus, the stimulation did not result in behavior that would indicate that participants stopped paying attention to the rules of the fishing game.

2.2. Sustainable decision-making (inter-generational sustainability threshold)

Next, we wanted to test whether stimulation of the TPJ could alter sustainable decision-making. As in real life, our participants were not very sustainable. Indeed, in the control (vertex) condition, only 37% (anodal group) and 42% (cathodal group) of decisions did not exceed the individual intergenerational sustainability threshold.

In a first step, we used the raw number of extracted fish as dependent variable and stimulation type, stimulation site, and their interaction as fixed effects. Because anodal and cathodal stimulation were hypothesized to have opposing effects, we would expect a statistically significant interaction. However, while descriptively present (see Fig. S1), the interaction did not reach statistical significance ($B = .84$, $SE = .60$, $p = .165$). A separate model without the interaction showed that there were also no main effects for stimulation site or stimulation type (see table S2).

As discussed earlier, this could be because this index is relatively «noisy», i.e., changing values do not necessarily reflect changes in sustainability. For example, a change from 12 to 13 fish would cancel out a change from 10 to 9 fish – but arguably, the latter is a more important change, as it reflects a change towards sustainability, while in the former example, both decisions were already unsustainable. Thus, we ran the same models as before, but with this more informative index (the number of sustainable decisions as dependent variable). Indeed, while there were no main effects of stimulation type ($B = -.07$, $SE = .39$, $p = .852$) or stimulation site ($B = .22$, $SE = .16$, $p = .172$), we found a statistically significant interaction of stimulation type and stimulation site ($B = -.64$, $SE = .31$, $p = .042$, see table S3), indicating that in the anodal and cathodal group, stimulation of the TPJ had differential effects on sustainable behavior (see Fig. 2 for summary statistics). When adding exchange rate to the model, this, also, was a significant predictor ($B = -.52$, $SE = .18$, $p = .006$, see table S4). However, the interaction between stimulation site and stimulation group was not affected by the exchange rate, as apparent from the absence of a significant three-way interaction with exchange rate ($B = .23$, $SE = .39$, $p = .547$, see table S4). Similarly, the result remained stable against the inclusion of gender, age, relevant personality measures, or rating of participants' pain and unpleasantness during the stimulation, see tables S5 and S6.

In the analysis reported above, a statistically significant effect of week of testing emerged, i.e., participants were slightly more sustainable in the second week. Because we have counterbalanced our design (half of the participants received stimulation of the vertex in the first week and stimulation of the TPJ in the second week; for the other half this was reversed) and because we have accounted for both week (week 1/week 2) and order of stimulation (Vertex first/TPJ first) in our statistical models, we do not believe that this poses an issue for our results.

We also checked whether HD-tDCS at the TPJ affected choice consistency. To this end, we calculated the standard

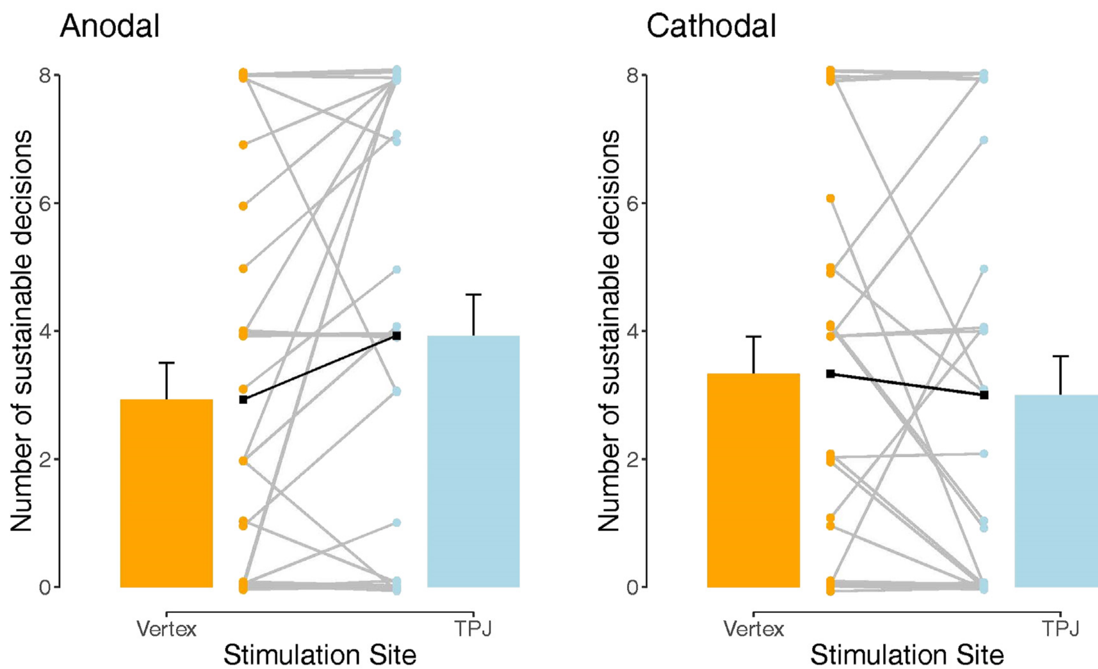

Fig. 2 – Number of sustainable decisions per combination of stimulation site and stimulation. The colored bars and the black lines represent the mean per group, error bars represent the standard error. Each grey line represents one participant and how their behavior changed between vertex and TPJ stimulation. In the anodal group, the mean (standard error) number of sustainable decisions was 2.93 (.57) for vertex stimulation and 3.93 (.64) for TPJ stimulation; in the cathodal group, this was 3.33 (.58) for vertex stimulation and 3.00 (.61) for TPJ stimulation.

deviation of the extraction for each participant and compared whether there were any differences in the standard deviation depending on stimulation type and stimulation site. No statistically significant effects emerged, neither for stimulation type, $F(1,57) = .00$, $p = .992$, stimulation site, $F(1,57) = 1.56$, $p = .217$, nor for their interaction, $F(1,57) = 1.89$, $p = .175$.

Additionally, we ran an analysis with sustainability as binary dependent variable on a trial-by-trial basis (i.e., whether a participant exceeded the inter-generational sustainability threshold in any one given decision). Because standard logistic regressions cannot be used for repeated measures, we here used a generalized estimation equation model (Lumley, 2019; Ristl, 2019). Again, the interaction between stimulation site and stimulation group was statistically significant, corroborating our results ($B = .705$, SE = .27, $p = .033$; for the complete results see table S7).

Having established the robustness of our effect, we next wanted to test whether the significant interaction is driven equally by both groups, or largely driven by either the anodal or cathodal stimulation. We tested this by running post-hoc analyses, separating the data for anodal and cathodal stimulation.

While we did not find a significant effect in the cathodal group ($B = -.22$, SE = .20, $p = .28$, see table S8), our data do support our hypothesis regarding the anodal group: There was a significant effect of stimulation site in the anodal group ($B = .57$, SE = .23, $p = .019$, see table S8), indicating that excitation of the TPJ increased sustainable decision-making. Again, this effect was not influenced by the exchange rate, as apparent from the absence of a significant interaction of stimulation site and exchange rate ($B = -.10$, SE = .26, $p = .698$, see table S9).

To further understand our findings, we next wanted to see whether the increase of sustainable decisions in the anodal group was because participants changed their opinion about which behavior is fair. We therefore tested whether they changed their fairness ratings depending on the stimulation site. There was, however, no effect of stimulation site on fairness ratings ($B = -.01$, SE = .33, $p = .98$, see table S10 and Fig. S3).

Similarly, when binarizing the fairness ratings into 0–9 (sustainable) and 10–20 (unsustainable) (sustainable/unsustainable) and comparing the distributions, a χ^2-test also yielded no difference between stimulation at TPJ and at vertex ($\chi^2 = 0$, $p = 1$ for both .10 CHF and 1 CHF). Indeed, most people already thought that a fair decision is a sustainable one, regardless of stimulation site: 69% of subjects (both under TPJ and vertex stimulation) reported that fair equals sustainable when one fish was worth 1 CHF; 79% and 76% (for TPJ and vertex, respectively) when one fish was worth .10 CHF.

Next, we wondered whether it might be possible that the behavioral change under anodal stimulation was not due to changed intergenerational mentalizing, but due to altered mentalizing with one's own generation. For example, could it be that under anodal stimulation of the TPJ, more people expected the other group members to behave sustainable and then followed their lead?

Our data confirm that this is not the case: The estimation of the other players' extraction did not differ between anodal stimulation at the TPJ and at vertex ($B = -.49$, SE = .32, $p = .138$, see table S10).

When binarizing the estimations into 0–9 (sustainable) and 10–20 (unsustainable) and comparing the distributions, a χ^2-test also yielded no difference between TPJ and vertex ($\chi^2 = 0$, $p = 1$ for .10CHF and $\chi^2 = .11$, $p = .75$ for 1CHF).

Thus, the change in sustainable behavior cannot be explained by a changed perception about what is fair. Similarly, the behavior cannot be the consequences of altered estimations about what one's own generation will do, indicating that it might indeed be concern about the future that is the driving force and that participants did not merely think their fellow participants behaved differently and followed their behavior.

3. Discussion

The experiment at hand provides causal evidence that excitatory anodal stimulation of the right TPJ leads to an increase in sustainable decisions in an intergenerational dilemma. The results remained stable after the inclusion of relevant covariates, such as order of stimulation (TPJ/vertex versus vertex/TPJ), week of testing (first appointment versus second appointment), pain and unpleasantness elicited by the stimulation, and personality measures. Our findings are in line with the hypothesis that a failure to engage in intergenerational mentalizing is one of the driving forces behind widespread inaction in the face of potentially catastrophic environmental problems. Due to their unique nature, intergenerational dilemmas are particularly challenging for humans, especially because of the absence of reciprocity and the large temporal gap until consequences of one's behavior will arise (Hauser et al., 2014; Weber, 2017). While the TPJ and corresponding mentalizing processes are known to be involved in decision-making in social dilemmas with the current generation (Morishima et al., 2012; Soutschek et al., 2016; Strombach et al., 2015), we here show that functioning of the TPJ causally influences behavior in intergenerational dilemmas. Additionally, not only give our data insight into the neuroscientific basis of sustainable decision-making, they also hint at an underlying cognitive mechanism: intergenerational mentalizing.

While the enhancing effects of the excitatory anodal stimulation are in line with our hypothesis, the expected decrease of sustainable decisions under inhibitory cathodal stimulation was not statistically significant (albeit descriptively present). This could have two reasons. First, the absence of a statistically significant cathodal effect could be due to a floor effect, as the baseline was already quite unsustainable. Indeed, only one third of participants had more than 50% sustainable decisions under cathodal vertex stimulation (and an equal number of participants made not a single sustainable decision at all). While this made it more difficult to further impair sustainable decision-making by applying brain stimulation, it is probably also a good portrayal of life outside the laboratory, where unsustainable behavior is very frequent. Second, it has been shown that in cognitive tasks, an improvement following anodal stimulation is more common than a decline following cathodal stimulation (Jacobson et al., 2012).

Importantly, our data show an increase in sustainable decisions under anodal stimulation of the TPJ, but no such change was observed in participants' rating of which behavior would have been fair. Thus, our findings indicate that people already knew which behavior was fair and we did not change participants' belief about how one *should* behave. Rather, by stimulating their mentalizing system, we led them to actually change their intergenerational *behavior*.

Similarly, our results cannot be explained by altered mentalizing with the current generation that leads to a change in participants' estimation about how the other members of their generation behave. Thus, participants did not just expect their fellow participants to behave sustainably and then followed their lead, but rather chose to do so on their own accord.

Note that this does not mean that anodal HD-tDCS at the TPJ has no effect of mentalizing with and behavior towards one's own generation at all. However, we deliberately designed our experiment in such a way that participants' behavior towards the next generation cannot be confounded by their behavior towards the current generation (because participants cannot act prosocially towards their own generation). This further corroborates the point that a change in *intergenerational* mentalizing and corresponding sustainable behavior towards the next generation drives the behavioral effect and that it is not altered perception of the own generation that is causing it.

While we have carefully controlled for potential confounds, some important limitations should be noted. First, the size of our effects is small by convention. This indicates that mentalizing with future generations is only one aspect of intergenerational sustainability, and other factors (and potential moderators) should be investigated in subsequent research.

Next, like in any experimental design, one might wonder whether our intergenerational resource dilemma is an adequate representation of the complex reality of sustainable behavior. Although our design certainly captures important aspects of sustainability (temporal delay between decision and consequence; uncertainty about behavior of others; victims of climate change are unknown, unidirectionality), we would encourage future studies to use different measures of sustainability. For example, one might try to encourage mentalizing with future generations in the field and directly measure participants day-to-day sustainability (e.g., electricity or water use). Additionally, one might question whether in real life, there is a larger social bond between generations than between anonymous groups in the lab, for example because the next generation is partly made up of people's own offspring and people may want to preserve resources for the future. While this is possible, there is evidence that having children does not actually increase sustainability (Thomas et al., 2018), and the majority of the next generation still consists of strangers.

There is ample evidence that stimulation of the TPJ alters mentalizing (Donaldson et al., 2017; Mai et al., 2016; Santiesteban et al., 2012; Sellaro et al., 2016; Soutschek et al., 2016). However, it remains possible that our stimulation changed other cognitive functions as well, and we did not explicitly measure changes in mentalizing. Thus, it might be wise to include a direct measure of mentalizing in future studies to analyze whether effects of tDCS on sustainability are really mediated through mentalizing. Similarly, it might be fruitful to collect data on how participants view the next generation, to assess whether increased mentalizing changes their perception.

While it would be naïve to assume that voluntary behavioral change can solve climate change in the absence of meaningful economic and political actions, our results can still help to motivate the general public to do their share for climate change mitigation: Because activity in the right TPJ seems to be causally involved in sustainable decision-making, enhancing functioning of the right TPJ (and correspondingly, intergenerational mentalizing) could be one fruitful way to encourage sustainable behavior. From a neuroscientific point of view, this might be achieved through trainings targeting the TPJ, either directly or via training mentalizing. For example, it is known that neurofeedback can alter structure and functioning of the brain (Ghaziri et al., 2013; Pineda et al., 2014), even though its large-scale application would raise some logistical challenges. Alternatively, behavioral trainings or meditation (with some types of meditation already being employed in schools) have been shown to improve mentalizing and change socio-affective circuits in the brain, including the TPJ (Böckler et al., 2017; Mascaro et al., 2013; Valk et al., 2017).

Our results give neuroscientific support to theories on how policy makers and environmental NGOs can effectively communicate their message (in a way that promotes intergenerational mentalizing). For example, one might try to «give climate change a face», by giving maximally concrete examples of who will suffer from a lack of sustainable actions. This idea could also profit from the psychological effect that identifiable victims receive more help than unidentifiable ones (Lee & Feeley, 2016). Similarly, public campaigns might be particularly effective if they make it maximally clear that decisions today have direct effects on individuals in the future (as opposed to a vague "next generation"), thereby encouraging intergenerational mentalizing with those individuals as well. So far, however, the much-needed change towards more sustainable decision-making has not happened, neither on an individual level, nor in cooperate behavior, nor through political action. We hope that our results, evidencing the causal role of the right TPJ for intergenerational sustainability, can help to achieve more sustainability by inspiring the development of new, neuroscientifically informed interventions to enhance the functioning of the right TPJ and corresponding mentalizing processes.

CRediT author statement

Benedikt P. Langenbach: Conceptualization; Methodology; Investigation; Formal analysis; Writing - Original Draft

Branislav Savic: Conceptualization; Methodology; Investigation; Writing - Review & Editing

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Data and material availability

We report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study.

All data and study materials necessary to replicate the analyses described in this paper are available from https://osf.io/mwz32/. Legal copyright restrictions prevent public archiving of the various instruments described in the Questionnaires section (see Section 1), which can be obtained from the copyright holders in the cited references.

Declaration of competing interest

The authors declare no competing interests.

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Supplementary data

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