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Free will strikes back: Steady-state movement-related cortical potentials are modulated by cognitive control

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ABSTRACT

In psychology and neuroscience, opposition to free will has asserted that any degree of perceived self-control or choice is a mere epiphenomenon which provides no meaningful influence on action. The present research tested the validity of this conclusion by designing a paradigm in which the potential effect of self-monitoring on motor output could be investigated. Using a repetitive finger tapping task that evokes automatic patterns in participants tapping responses, we have obtained evidence that (1) participants may voluntarily reduce the predictability of their tapping patterns (2) by exercising cognitive control that (3) modulates response-locked steady-state movement-related potentials over primary and supplementary motor areas. These findings challenge the most radical accounts of the nonexistence of free will and instead provide support for a more balanced model of human behaviour in which cognitive control may constrain automatic response tendencies in response preparation and action execution.

1. Introduction

Although humans typically experience and report a sense of control and responsibility over their actions [i.e. they report to have free will (Baumeister & Monroe, 2014)] the question whether humans have free will has long disputed among philosophers (Lavazza & Inglese, 2015), for one, because free will seems to be incompatible with the concept of determinism (Van Inwagen, 1975). More recently, questions concerning the existence of free will have expanded to the fields of psychology (Baumeister, 2008) and cognitive neuroscience (Brass et al., 2019), whereby initial findings by Libet (1999) have led to strong claims about the inexistence of free will. Such claims have now become the norm in popular science communication [e.g. Harris (2012), Lamme (2010), Swaab and Kunen (2015), but see Kolk (2012) for a dissenting voice]. Despite the conviction with which these conclusions have been presented, the limited number of studies and paradigms with which free will has been investigated and their associated methodological problems prohibit any definite conclusions. In the current study we present a new experimental paradigm in which the influence of free will on behaviour and the neural mechanisms supporting response preparation may be investigated. Different from the majority of previous neuroscientific investigations in this field of study, our findings are compatible with the existence of free will and its effects on

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behaviour via neural mechanisms that have hitherto been implicated in preconscious response preparation.

The current literature on free will, can be summarised along two main perspectives, when excluding mind-matter dualism as a viable option. The most radical and dominant position is to treat experiences of willed action as cosmetic additions a top a brain which largely operates subconsciously and generates actions automatically (Hopfinger & Ries, 2005; Kim & Lee, 2011; Schneider & Chein, 2003), that is reflexively or impulsively without a possibility for conscious intervention (Burns & Bechara, 2007; Hallett, 2007; Wegner, 2004). According to the alternative position that is mainly reflecting behavioural and philosophical arguments, free will can be seen as a relative phenomenon, rather than an all-or-none case (Baumeister, 2008; Deecke & Kornhuber, 2003; Dennett, 2004). In this alternative view, free will exists as the opposite of full automation and thus relatively more free will is exerted when decisions are informed by conscious and explicit information processing, including the weighing of options and suppression of automated or innate impulses.

A famous, but disputed argument for the former position stems from experiments relating the timing of self-reported intention formation to the timing of response-locked potentials, traditionally called readiness potentials (RP) preceding the button press (Haggard & Eimer, 1999; Kornhuber & Deecke, 1965; Libet, 1999), single cell activation in the Supplementary Motor Area (SMA) (Fried et al., 2011) and cortical activity measured with fMRI (Bode et al., 2011; Soon et al., 2008). The traditional and newer works converge on the observation that various measures of brain activity can predict action choices prior to participants' self-timed awareness of will and intention. There is no shortage of critical discussion on how timing was assigned to the relevant neural and mental events in these studies (Banks & Isham, 2009; Guggisberg & Mottaz, 2013; Hoy, 1982; Matsuhashi & Hallett, 2008; Rigoni et al., 2010; Van De Grind, 2002). Yet, even if we accepted the measurements of timing as valid, it is not at all certain, that this early activation causally precedes what the participants experience as their own will to act (Brass et al., 2019; Schlegel et al., 2013; Schmidt et al., 2016; Verbaarschot et al., 2015). It has been suggested on the basis of several findings that instead the RP is part of an ongoing oscillation which reflects changes in the brains' sensitivity and reactivity to the outside and inside world (Schmidt et al., 2016). Not mutually exclusive with this is another assertion, that the RP and similar (Fried et al., 2011; Soon et al., 2008) preparatory activity, rather than reflecting preconscious decisions are correlates of the processing that leads to a decision (Brass et al., 2019; Furstenberg, Deouell, et al., 2015). The latter view suggests that external and internal biasing signals (e.g. primes, preferences etc.) and stochastic noise in the motor system add up until one option to act crosses a threshold and becomes a definitive decision (Furstenberg, Breska, et al., 2015; Furstenberg, Deouell, et al., 2015). Moreover, this preparatory processing might not actually be unconscious and the self-report paradigms likely probe consciousness of only the final step of decision making (Guggisberg & Mottaz, 2013).

Another argument against free, or in his words, "conscious" will is handed out by Wegner (2004). Rather than settling for unstable arguments based on timing, he discusses examples where the presence or absence of will is misattributed. In a similar vein, and likewise circumventing the problem of timing, Hallett (2007) argues for a model in which action and perception/attribution of will happen in parallel. Errors of attribution demonstrate that the brain uses heuristics to classify behaviour into willed or automatic, but does not prove that these categories are a wrong dichotomy and that free will is an illusion. On the contrary, the very existence of this attribution process suggest that the distinction is behaviourally relevant. The latter is, ironically, acknowledged by those arguing against free will, in that wrongly identifying an action as deliberate and willed can, for example, promote the punishment of agents that are actually not accountable (Atiq, 2013). By framing, however, all agents as ultimately not accountable, radical opposition to free will oddly denies the possibility of two-sided errors in this attribution process. Note furthermore, that many examples of erred self-attribution are pathological (Fisher, 2000; Karp et al., 1996; Obeso et al., 1981; Pirio Richardson et al., 2006), or artificially created in the lab (Wegner & Wheatley, 1999). It is thus not clear how frequent such errors are in natural settings. Importantly, reducing "free will" to the conscious perception of otherwise generated behaviours (Hallett, 2007; Wegner, 2004) implies a non-hierarchical, parallel arrangement between behaviour and self-attribution, which leads to two problems. Firstly, this alleges that the hierarchies known from the cognitive- and motor control literature (Eccles, 1981; James, 1878; Kahneman, 2003; Koechlin et al., 1999; Mutha et al., 2008; Petty & Cacioppo, 1986) stand in no relation to the process of self-monitoring (of which self-attribution of agency is a token). Second, the Cartesian theatre that Dennett (1993) warns against, is restored as a viable option by positing a passive, aimless observer in the brain.

What is truly helpful, however, about Wegner's and Hallett's approach to reasoning about "free will", is that their conclusion concerning the parallel organization of conscious will and action preparation may be difficult to investigate within traditional timing paradigms and thus their arguments invite novel approaches. In the timing paradigms, the focus is on a single (albeit averaged across trials), simple movement. This set-up does not allow to integrate the role of cognitive control in what we call free will as it lays the focus solely on how W ("will" or time point of self-conscious intention to act) and M ("motor response" or time point of action) relate to neural activity [the terminology can be traced back to Libet (1999)]. Given that modern proponents of free will see it as the relative absence of automation (Baumeister, 2008; Deecke & Kornhuber, 2003; Dennett, 2004) the situation is thus somewhat reminiscent of denying a key witness access to the "court room". In the present study we take therefore a different approach to inquire the existence of, and functional mechanisms underlying free will. More precisely our approach builds on the longstanding idea in psychology and neuroscience that human behaviour may be well captured by metaphor of the "horse and the rider" whereby cognitive control (the rider) constrains and regulates automatic processes (the horse) in driving behaviour. Such "dual process" models of human behaviour are abundant in social psychology (Kahneman, 2003; Petty & Cacioppo, 1986) clinical psychology (Wiers et al., 2013) and cognitive neuroscience (Satpute & Lieberman, 2006) and can be traced back to the beginnings of the discipline (James, 1878). The idea of a "horse" and a "rider" is also implied in our current understanding of how the motor system is set up. The evolutionary capacity for goal-directed behaviour in humans (Koechlin et al., 1999) may circumvent simple stimulus–response associations by adjusting their gain (Mutha et al., 2008; Nashner, 1976; van Elk et al., 2012). Importantly, the presence of a hierarchy in the motor system offers means to define and distinguish automatic from deliberate behaviour in a scientifically testable manner, whereby automation is assigned to the lowest (uncontrolled) level in the hierarchy.

To test the validity of Hallett's parallel process hypothesis (Hallett, 2007) we designed a task in which we could observe the effects of self-monitoring on the organization of participants' motor output: a repetitive four-finger-tapping task (FFTT), in which automatic response patterns easily surface, but in which automatic response tendencies may also be suppressed and regulated through cognitive control. More precisely, participants in our task were asked to tap to the beat of a 90 beats/minute computer generated metronome using four fingers: the index and middle fingers of both hands. In an unrestrained response condition (URC) they could tap spontaneously, as long as they used all fingers in the task. Following previous research on bimanual rhythmic coordination (Brakke et al., 2007) we expected that participants would be inclined to produce simple alternating (e.g. left/right), automated button press patterns. In the cognitive control condition (CCC), participants were instructed to perform the same tapping task but to actively monitor their behaviour and avoid repetitions and patterns in their responses. Self-monitoring with the aim to avoid repetitions in the CCC was expected to invoke cognitive control and delegate control over behavioural output to higher levels of the motor hierarchy, thus demonstrating free will as defined by Baumeister (2008) and Dennett (2004), i.e. behaviour that is set apart from full automation.

We first tested in a larger sample (pilot study) if the task instructions indeed influenced participants' responses in the FFTT, i.e. whether response patterns were indeed less predictable in the CCC than in the URC. In a subsequent EEG experiment we investigated the steady-state movement-related potentials (ssMRP) in the FFTT. The term steady-state refers to the repeating pattern of sinusoidal brain potentials that are evoked by a series of repetitive events, for instance the presentation of a train of consecutive visual or auditory stimuli (Mast & Victor, 1991; Plourde & Boylan, 1991), In the case of the ssMRP, the events that drive the steady-state potential are a series of movements or button presses, that are usually executed in synchrony with a (computer generated) metronome. In comparison with the extensive RP literature on single discrete voluntary movements, only limited evidence has been collected on ssMRP (Gerloff et al., 1997, 1998; Kopp et al., 2000; Nazarpour et al., 2009; Osman et al., 2006) and these latter studies show noticeable differences in electroencephalographic activation over time, probably as a result of variations between studies in the frequency of movements, the involved effectors, movement kinematics, and the trigger-event that is used (e.g. EMG onset or button-press) for calculating response-locked averages. What appears to be reliable, however, is that source localizations of ssMRP consistently identify the SMA and the lateral sensorimotor cortices (Gerloff et al., 1997, 1998; Ikeda et al., 1993), which are the exact same sources that have been localised to underlie the RP in the Libet paradigm (Shibasaki & Hallett, 2006; Toro et al., 1993). In the present study we make use of this apparent overlap in source activity by testing if the motor activation that has been argued to precede conscious free will (Libet 1999) can itself be modulated by voluntary control processes. Such a finding would be consistent with the "horse and rider" metaphor of free will wherein RP may reflect a balance between automatic and controlled processing. As a manipulation check and confirmation that participants were indeed using cognitive control to influence their finger tapping we also compared the frontal midline theta power between the condition blocks and investigated correlations between the theta power and the predictability of participants' response patterns. Previous research has established frontal midline theta as a reliable indicator of executive attentional processes (Cavanagh & Frank, 2014; Mitchell et al., 2008; Tsujimoto et al., 2006) and the recruitment of cognitive control (Nigbur et al., 2011; Sauseng et al., 2007) supporting a range of functional processes that are relevant in the CCC condition such as the inhibition of task-irrelevant activity (Raghavachari et al., 2001), stimulus–response coupling and behavioural adaptation (van de Vijver et al., 2018; Womelsdorf et al., 2010), action monitoring (Schmiedt et al., 2005) and error and conflict detection (Tzur & Berger, 2007).

2. Methods

2.1. Participants

Twenty participants (8 ♀, age 23.4 ± 3.1 years, 60 % social science undergraduate students) participated in this study. The participants were recruited via personal invitation in the local cafeteria of the social science faculty of the Radboud University Nijmegen or via SONA, an online research participant system. Participants signed up for partial course credit or for a gift coupon equivalent to 25 Euros. Only right-handed participants were allowed to participate. Nineteen participants were absolutely right handed according to the Edinburgh Handedness Inventory (EHI) (Oldfield, 1971). One participant indicated ambidexterity, scoring just below the cutoff for right-handedness. Furthermore, all participants read and signed an informed consent form prior to initiation of the experiment.

2.2. EEG set-up and placement

EEG was collected using a BrainAmp amplifier (BrainProducts GmbH, Munich, Germany) at a 500 Hz sampling frequency from 60 Ag/AgCl active electrodes (Fp2, AF7, AF8, F7, F5, F3, F1, Fz, F2, F4, F6, F8, FT7, FC5, FC3, FC1, FC2, FC4, FC6, FT8, T7, C5, C3, C1, Cz, C2, C4, C6, T8, TP7, CP5, CP3, CP1, CPz, CP2, CP4, CP6, TP8, TP1, P7, P5, P3, P1, Pz, P2, P4, P6, P8, PO7, PO3, PO4, PO8, O1, Oz, O2, PO9, PO10) at placements based on the international 10–20 recording system ("American Electroencephalographic Society Guidelines for Standard Electrode Position Nomenclature," 1991). The electrodes were mounted in an elastic cap (ActiCap, BrainProducts GmbH, Munich, Germany) and filled with Electrocap (ECI) Electrode gel (MedCat B.V., Erica, the Netherlands). The EEG signal was referenced to left mastoid and stored on disk for offline processing. Recorded EEG data were analysed in BrainVision Analyser 2.0 (BrainProducts GmbH, Munich, Germany). The ground was placed on the left clavicle. Vertical and horizontal eye movements were recorded by two additional bipolar channels placed above and below the right eye and on the outer canthi of each eye. The impedance of each electrode was kept below 5 kΩ at all times.

The EEG-cap was fitted by measuring head circumference right above the nasion and inion. Electrode Cz was placed in the middle between nasion and inion and in the middle between the tips of both ears. After fitting the cap, all electrode positions were gently scratched by use of a blunt needle and excessive hair was pushed away. Ground, reference and EOG electrode positions were abraded by use of a scrub gel and attached to the skin by means of a sticker electrode. This procedure took about 45 min per participant.

2.3. Procedure

The experiment consisted of two conditions. In both, participants had to press four buttons on a button-box (see Fig. 1) with each button assigned to one of the index and middle fingers of each hand. Each button could be pressed only once at a time and pressing was required to be in line with the pace of a computer-generated rhythmic sound - a beep presented at a rate of 1.5 Hz via a loudspeaker. The pace of the computer metronome was determined via pilot testing of different presentation frequencies. The goal was to have a tapping frequency at which response monitoring was feasible but challenging, and at which automatic response tendencies would still occur.

The conditions differed as follows: In the Cognitive Control Condition (CCC), participants were asked to monitor their responses throughout the condition block and control their finger tapping to actively avoid patterns and repetitions in their responses. In the Unrestrained Response Condition (URC), participants could press any button they liked, as long as they used all four fingers during the task. Each condition was practiced once before the start of the experiment in two consecutive blocks of 50 button-presses, once for the CCC condition and once the URC condition. The conditions were each tested twice in a counter-balanced order, resulting in four experimental blocks (CCC-URC-CCC-URC or URC-CCC-URC-CCC) consisting of 450 button-presses each. After the practice blocks (for each CCC and URC) and the first two experimental blocks participants were offered a break and asked to indicate their readiness to continue with the experiment. The instructions for each condition were briefed to the participants verbally before the experiment and in written form on a computer screen prior to each block. During the practice phase the experimenter also directly provided feedback to the participants and if necessary instructed them to keep the pace of the pace-maker sound.

The overall duration of the full experiment was around 90 min (15 min practice phase (including the time needed for instructions and explanations), 25–30 min for the testing phase, +45 min for attaching the electrodes).

2.4. Behavioural variables

Latency differences between the metronome-generated signals and behavioural responses were collected. Their averages and standard deviations were calculated for each subject and condition.

RNG values (RNG and RNG2) were calculated from response pairs [grouped by RGCalc, an algorithm provided by Towse and Neil (1998)] to measure the predictability of response patterns per condition. RNG(2) values measure predictability by first establishing the frequency with which each response pair is observed (here for a given subject and condition), summarizing the overall predictability of that subject's sequence of responses with a value between 0 and 1 (higher value = higher predictability). Since the set of possible combinations is limited across participants and conditions by the rules of the experiment (see above) we expected that a difference between conditions (URC > CCC) should arise only if participants successfully complied with the instructions. This means that we expected smaller RNG(2) values, i.e. less predictable responses in the CCC, if participants were successful in randomizing their response patterns as instructed. RNG values were first proposed by Evans (1978), and a subsequent RNG2 variant was introduced by Neuringer (1986). Neuringer's variation defines response pairs by pairing together responses separated by one (e.g. the first and third

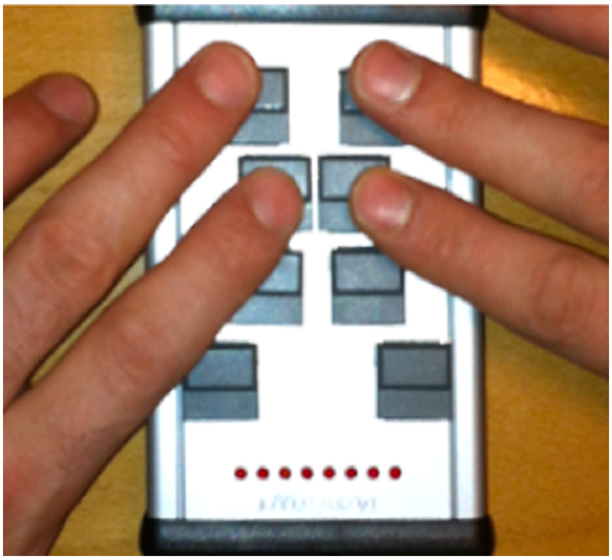

Fig. 1. *Photograph showing the Button-Box and Finger Setting of the Participants' Left and Right Index and Middle Fingers in the Four Finger Tapping Task.* *Note.* The image shows the positions of the left and the right index and middle finger that were used to operate the four (top) buttons.

response of a sequence form the first pair used in the analysis). This allows for the detection of more complex regularities. Both variants are calculated here using RGCalc (Towse & Neil, 1998).

2.5. EEG post-processing and variables

The offline EEG signal was re-referenced to the right mastoid (TP1). Subsequently, segments containing excessive muscle activity were marked manually and omitted from further analyses. Ocular correction was applied (Gratton et al., 1983) using the right horizontal EOG and the top vertical EOG as reference electrodes. The data were segmented into multi-movement epochs encompassing five button presses by selecting segments of ± 1765 ms around each button press. This was done in order to capture the ongoing oscillations accompanying the button presses. A whole-interval baseline was used for baseline-correction, as in Gerloff et al. (1997). Because source localization with ERPs is not possible with the use of this baseline-correction procedure, current source density (CSD) transformation was applied (cf. Perrin et al. 1989) to allow an approximation of source activation. CSD transformation provides the topography of current sources and sinks on the scalp with sensitivity for both tangential and radial sources (Cui et al., 1999).

Multi-movement epochs were averaged per participant and per condition. ERPs were calculated from 900 responses (2 blocks × 450 trials). The average analysable number of segments left per participant after omission of artefacts consisted of 1469.8 ± 194 trials (M ± SD). Due to relatively more noise in the CSD-transformed averages compared to raw ERPs, CSD-transformed ERPs were filtered between 0.5 and 30 Hz for all electrodes.

After obtaining the grand averages, a grand average pooled over conditions was calculated to determine the timing and distribution of peak activity in the ssMRP associated with finger tapping during the multi-movement epoch. The pooled grand average revealed ssMRP activations over the left and right primary motor cortices and medial supplementary motor area, as well as activations over the left and right temporoparietal area (see Fig. 5B). Considering that our hypotheses for the ssMRP focussed on the primary and supplementary motor areas, statistical analyses were only directed at these regions, and not at the temporoparietal activations. Furthermore it was observed that ssMRP over primary and supplementary motor areas were highly synchronous as can be observed in Fig. 2. Consequently ssMRP signals from electrodes overlaying these regions were averaged for statistical analysis (see results section for the exact electrode labels). Windows of 100 ms surrounding the maximum of each peak were used to export the amplitude of ssMRP peaks per condition for statistical analysis of condition differences.

In addition to ssMRP, averaged multi-movement epochs were analysed for theta power (Jensen & Tesche, 2002) by frequency extraction between 4 and 7 Hz and subsequently averaged per condition and participant.

2.6. Statistical analysis

Average response latencies, RNG values, ssMRP peak amplitudes and frontal midline theta power per condition and per participant, were tested for condition differences using Wilcoxon Signed Rank paired tests (GraphPad Prism). Since smaller samples (as used here) are affected more seriously by deviations from a normal distribution [see Central Limit Theorem (Pólya, 1920)], the use of non-parametric tests was deemed a more cautious approach. Correlations between condition differences in frontal midline theta power and ssMRP peak amplitudes were performed in IBM SPSS v25.

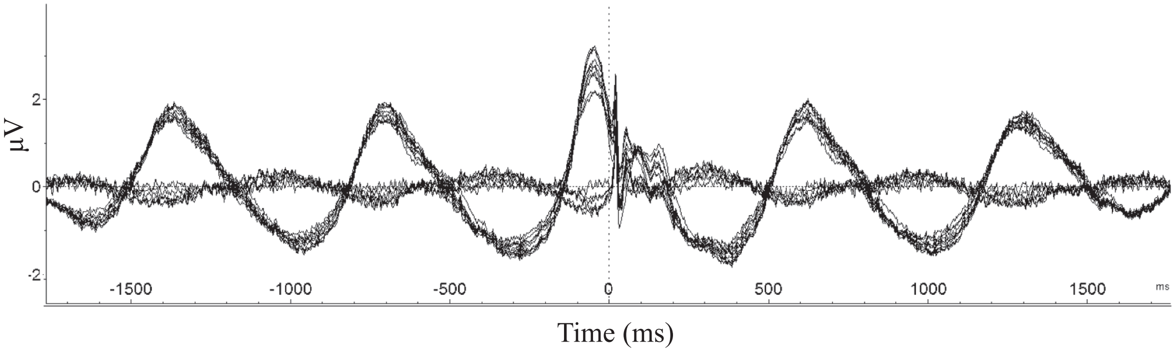

Fig. 2. *Steady-State Movement-Related Potentials. Note.* Steady-state movement-related potentials as measured over primary and supplementary motor areas (FC1-FC4, C1-C4, Fz, Cz) and temporoparietal electrodes (TP7, TP8, P7, T8, CP6, CP7). The group of lines with the stronger oscillatory pattern reflect the electrodes over the primary motor and supplementary motor areas. The group of lines with the smaller oscillatory pattern reflect the temporoparietal electrodes (effects on temporoparietal electrodes were not analysed and only displayed for completeness).

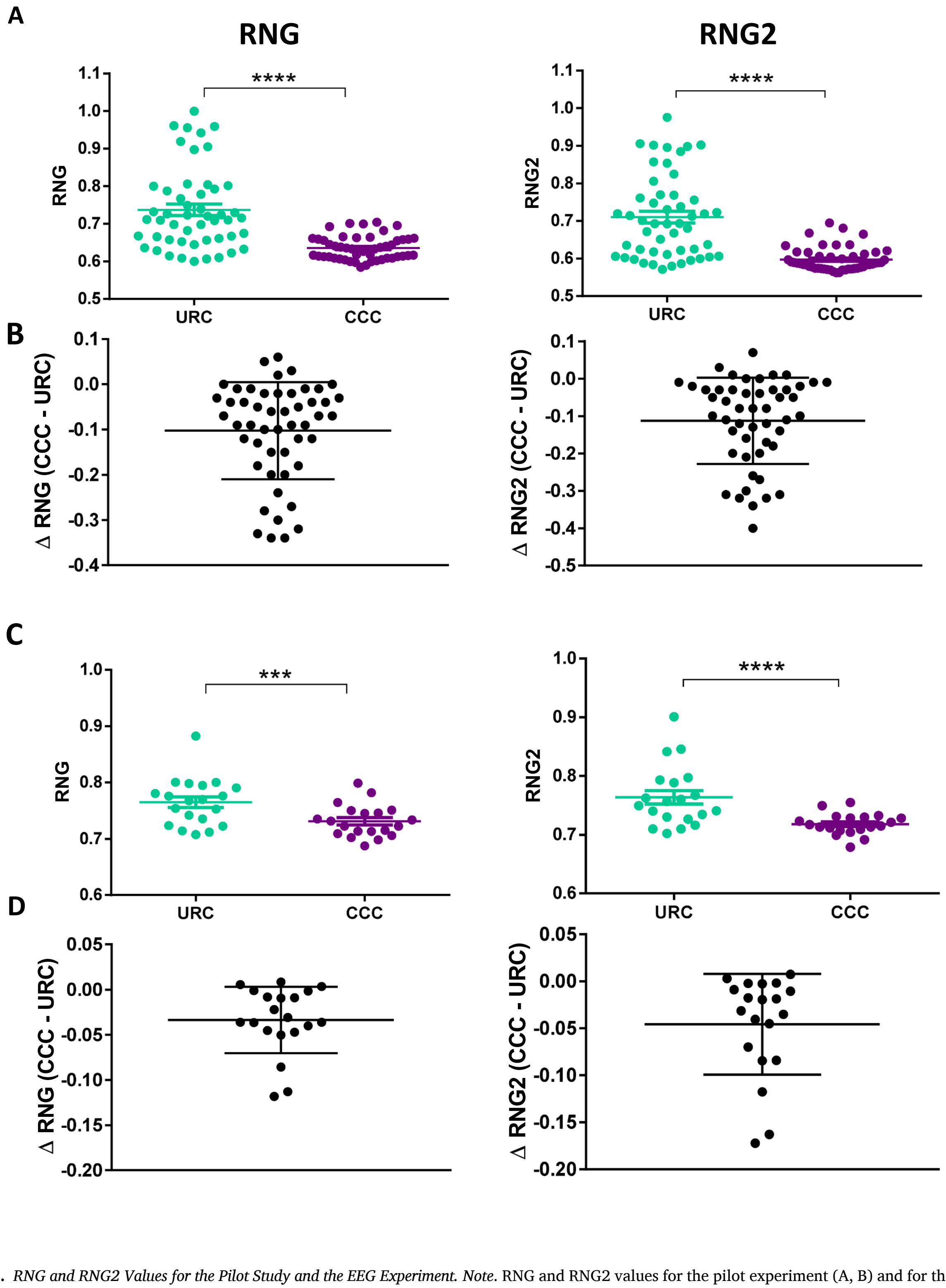

Fig. 3. *RNG and RNG2 Values for the Pilot Study and the EEG Experiment. Note.* RNG and RNG2 values for the pilot experiment (A, B) and for the EEG experiment (C, D). The coloured graphs (A, C) present mean RNG and RNG2 values per condition and dots show the data points of individual participants. The black graphs (B, D) show the RNG and RNG2 condition effect (CCC-URC) with dots representing the condition difference per individual participant. Wide horizontal lines reflect the means of the distribution and whiskers represent standard errors (A, C) or the standard deviation (B, D). *** $p < 0.001$, **** $p < 0.0001$.

3. Results

3.1. Pilot study

3.1.1. Response latencies and RNG

Response latencies of button presses did not differ between conditions (Wilcoxon Signed Rank sum $= 771$, $P = 0.1795$). In the URC condition, response pairs were more predictable than in the CCC condition as reflected in both the RNG index (0.7 ± 0.02 versus 0.6 ± 0.004, M ± SE of RNG for URC versus CCC; Wilcoxon Signed Rank sum $= -1145$, $p < 0.0001$) and the RNG2 index (0.7 ± 0.02 versus 0.6 ± 0.004, M ± SE of RNG2 for URC versus CCC; Wilcoxon Signed Rank sum $= -1171$, $p < 0.0001$). These result are summarised in Fig. 3A and 3B.

3.2. Main experiment

3.2.1. Response latencies and RNG

Of 35,654 recorded responses to pacing stimuli only 346 were missing (~1%). Latencies to button press did not differ between conditions (Wilcoxon Signed Rank sum $= -82$, $p = 0.1327$), but displayed a trend for higher variation in the CCC (100.8 ± 6.5 versus 89 ± 4.9, M ± SE for latency SD; Wilcoxon Signed Rank sum $= 102$, $p = 0.0583$). In the URC condition response pairs were more predictable as reflected in the RNG index (0.8 ± 0.01 versus 0.7 ± 0.01, M ± SE of RNG for URC versus CCC; Wilcoxon Signed Rank sum $= -184$, $p = 0.0002$) and the RNG2 index (0.8 ± 0.01 versus 0.7 ± 0.004, M ± SE of RNG2 for URC versus CCC; Wilcoxon Signed Rank sum $= -192$, $p < 0.0001$). See Fig. 2B for an overview of RNG(2) results.

3.2.2. Theta power

Theta frequency band power (4–7 Hz) was averaged over multi-movement epochs. Visual inspection of the averaged spectrogram across conditions (Fig. 4A) suggested that the strongest activation was found over the mediofrontal grid (electrodes F1, F2 and Fz). The difference in theta power between conditions (CCC – URC) was also significantly higher for the mediofrontal average compared to the global average (0.6 ± 0.3 versus 0.2 ± 0.1, M ± SE for difference theta power CCC – URC, Wilcoxon Signed Rank sum $= -120$, $p = 0.024$, Fig. 4B) confirming our expectation, that the strongest condition contrast would be found over the grid with the highest overall activation. Theta power averaged over the mediofrontal grid was significantly higher in the CCC than the URC (10.3 ± 0.9 versus 9.7 ± 0.9, M ± SE μV; Wilcoxon Signed Rank sum $= 118$, $p = 0.0266$, Fig. 4C).

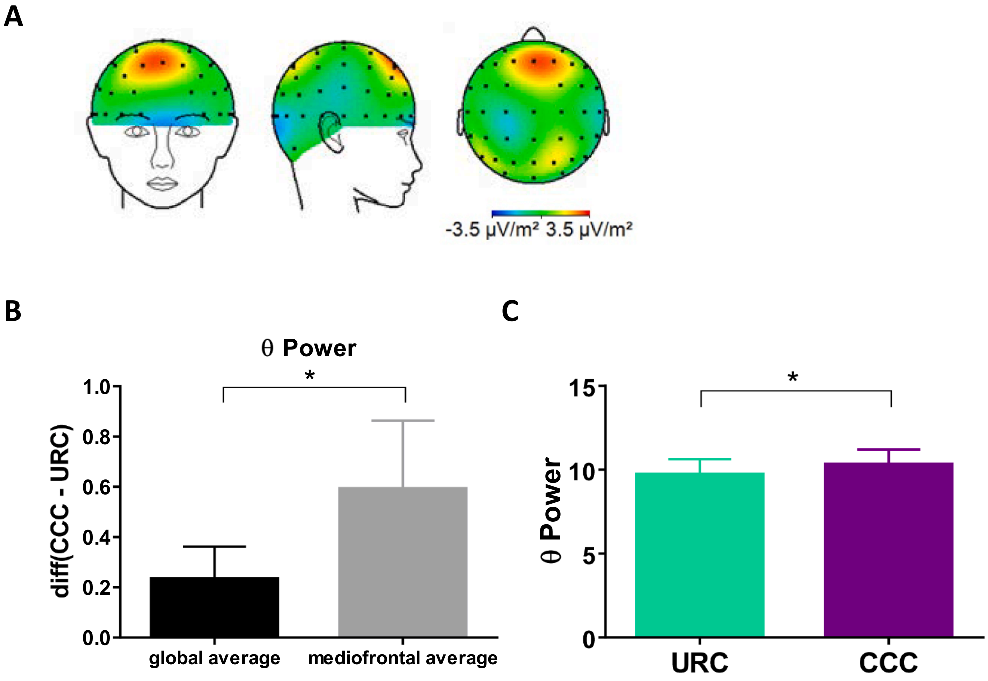

Fig. 4. *Frontal Midline Theta Power. Note.* (A) Scalp topography of frontal midline theta power averaged across conditions. (B) Means and standard errors of the difference in theta power between conditions, for all electrodes (global theta power) and mediofrontal electrodes. (C) Averaged frontal midline theta power per condition. * $p < 0.05$.

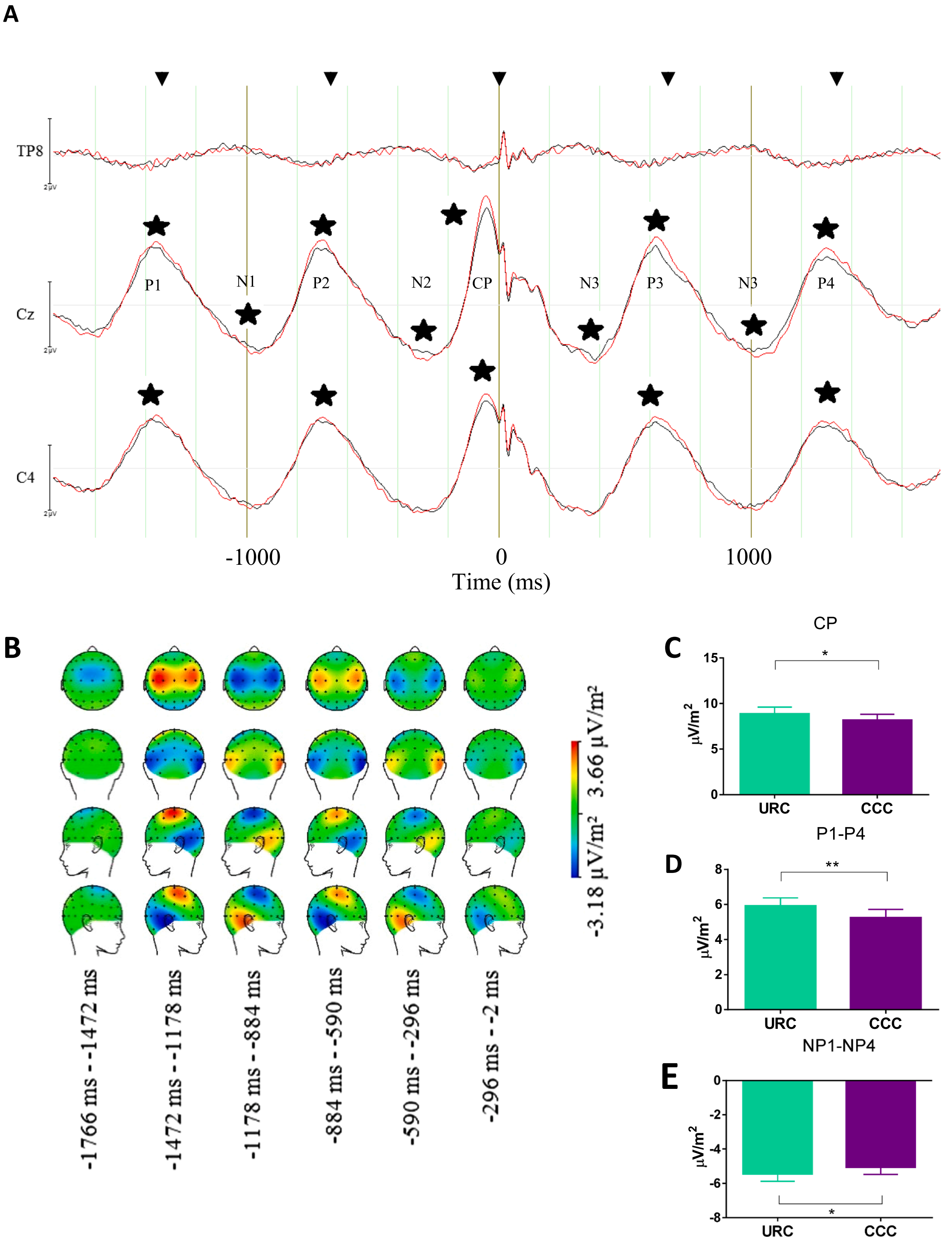

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Fig. 5. *Steady-State Movement-Related Potentials. Note.* (A) Steady-state movement-related potentials waveforms for the CCC (black lines) and URC (red lines) across the multi-movement epoch (-1766 ms – +1766 ms) response-locked to the central button press for three representative electrode leads across the primary motor cortex (C4), SMA (Cz) and the right temporoparietal region (TP8). Temporoparietal activations were not analysed but displayed for completeness. Downward arrow heads indicate the average time of the beep to which button presses had to be synchronised. Star symbols indicate peaks for which a significant difference was found between conditions. (B) CSD-transformed scalp topographies of the positive and negative ssMRP peaks for the left hand side of the multi-movement epoch. (C-E) Mean amplitude and standard errors of the CSD-transformed ssMRP central peak (CP), positive peaks (P—*P*4), and negative peaks (NP1-NP4) for the URC and the CCC conditions. * $p < 0.05$, ** $p < 0.01$.

3.2.3. *Steady-state movement-related cortical potentials*

Visual inspection of the local maxima and minima and ssMRP waveforms (Fig. 5A and Fig. 5B) across conditions indicated a sequence of peaks over the mediofrontal and centrolateral electrodes (FC1-FC4, C1-C4, Fz, Cz) that were found to be highly synchronous in their activation over time (see Fig. 2). Consequently, ssMRP peak activity was analysed for the entire set of mediofrontal and centrolateral electrodes. The averaged (FC1-FC4, C1-C4, Fz, Cz) activity was analysed separately for the central peak (CP) of the multi-movement epochs and for the average non-central responses (P1-P4 for the positive ssMRP peaks, NP1-NP4 for the negative ssMRP peaks). CP amplitude differed significantly between conditions, with larger peaks observed in the URC condition than in the CCC condition (8.9 ± 0.7 versus 8.2 ± 0.6, M ± SE μV; Wilcoxon Signed Rank sum = -124, p = 0.0188, Fig. 5C). The averaged positive (P1-P4) non-central component was also larger in the URC than in the CCC condition (5.9 ± 0.5 versus 5.2 ± 0.5, M ± SE μV; Wilcoxon Signed Rank = -160, p = 0.0016, Fig. 5D). The average negative component (NP1-NP4) was more negative in the URC than in the CCC condition (-5.4 ± 0.4 versus −5.0 ± 0.4, M ± SE μV; Wilcoxon Signed Rank = 130, *p* = 0.0136, Fig. 5E).

3.2.4. *Correlations between response-locked potentials and theta power*

Condition differences in mediofrontal (Fz, F1, F2) theta power (CCC – URC) correlated negatively with condition differences (CCC – URC) in response-locked peak amplitudes (CP) averaged across the mediofrontal and centrolateral electrodes (FC1-FC4, C1-C4, Fz, Cz; r = -0.522, p = 0.018). This correlation remained significant after controlling for outliers (r = -0.512, p = 0.025, Fig. 6A) which was done after visual inspection suggested that the observed effect might depend on one observation (confirmed as an outlier based on the 2.68 standard score threshold). Condition differences (CCC – URC) in the amplitude of non-central positive peaks (P1-P4) were also negatively correlated with condition differences (CCC – URC) in theta power (r = -0.631, p = 0.003, Fig. 6B), while the amplitude difference scores (CCC – URC) of negative peaks (N1-N4) were not significantly correlated with theta power (CCC – URC) difference scores (p = 0.254).

4. Discussion

In psychology and neuroscience, opposition to free will has asserted that any degree of perceived self-control or choice is a mere epiphenomenon which provides no meaningful influence on action (Hallett, 2007; Wegner, 2004). The present research tested the validity of this conclusion by designing a paradigm in which the potential effect of self-monitoring on motor output could be investigated, following dual process models that have argued for the impact of cognitive control on automatic behavioural tendencies (Wiers et al., 2013). Thereby, the present study investigated a more balanced hypothesis [as implied by e.g. Dennett (2004), Baumeister (2008), Deecke and Kornhuber (2003)] stating that voluntary executive mechanisms may constrain automatic response tendencies and influence preparatory motor activity preceding and accompanying action execution. Using a repetitive finger tapping task (FFTT) that evokes automatic patterns in participants tapping responses, we have obtained evidence that (1) participants may voluntary reduce the predictability of their tapping patterns and (2) do so by exercising cognitive control that modulates the response-

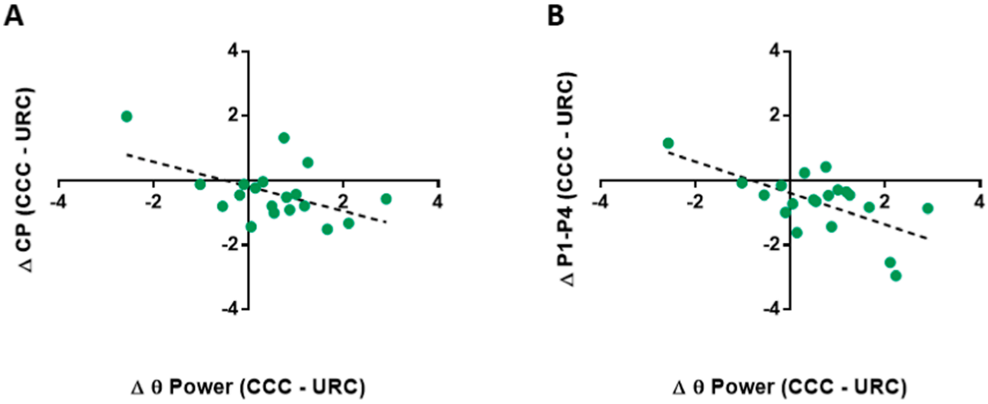

Fig. 6. *Correlations Between Condition Differences in Frontal Midline Theta Power and ssMRP Peak Amplitudes. Note.* Correlations between condition differences in frontal midline theta power (Fz, F1, F2) and ssMRP peak amplitudes (FC1-FC4, C1-C4, Fz, Cz) for (A) the CP component and (B) the *P*1-*P*4 peaks in the multi-movement epoch.

locked cortical potentials preceding and following the tapping response. These findings challenge the most radical accounts of the nonexistence of free will and instead provide support for a more balanced model of human behaviour in which cognitive control may constrain automatic response tendencies in response preparation and action execution.

In accordance with the idea that the concept of free will is not merely an illusion of control (Wegner, 2004) or an epiphenomenon accompanying behavioural decisions (Hallett, 2007) that originate in automatic motor processes, participants in our study were able to voluntary influence the response selection process and the sequence of tapping responses in the FFTT. RNG and RNG2 values in our pilot study and the subsequent experiment were found to be significantly reduced in the CCC relative to the URC indicating that participants managed to effectively reduce the number of repetitions in the FFTT so that the sequence of their button presses became more random and less predictable (Fig. 3). Under the assumption that predictable response patterns result from falling back on automation, this result by itself supports the notion that distinguishing automatic and volitional behaviour is meaningful. The stronger frontal midline theta power in the CCC than in the URC furthermore confirmed our prediction that participants would exert cognitive control to constrain automatic response selection and support a more controlled behavioural strategy in the CCC.

In line with previous studies investigating steady-state movement-related cortical potentials (ssMRP) in repetitive motor tasks (Gerloff et al., 1997, 1998), the FFTT generated a prominent and consistent pattern of negative and positive ssMRP components over lateral primary motor cortex and medial supplementary motor regions. The topography of the lateral components and their maxima over the C3 and C4 locations clearly point to underlying neural sources in the Rolandic sensorimotor cortices controlling hand and fingers movements (Praamstra et al., 1999; van Schie et al., 2004, 2008). The maximum of the medial ssMRP component was found just anterior to the vertex, suggesting a source in the supplementary motor area (Nguyen et al., 2014), in line with previous research that has found the SMA to be involved in the planning and execution of bimanual motor sequences (Gerloff & Andres, 2002; Lee & Quessy, 2003; Serrien et al., 2002). Both lateral and medial components were analysed together, as they synchronously oscillated between positive and negative peaks during the execution of the FFTT. The positive ssMRP component was found to peak just prior to the registration of the tapping response, whereas a negative ssMRP component was found to be activated during the transportation phase in which the finger was lifted up and brought down towards the button. Previous foundational work on the relationship between movement parameters such as velocity, speed, force and distance (Cooper et al., 1989; Kirsch et al., 2010; O'Suilleabhain et al., 1999; Slobounov & Ray, 1998) has revealed that movement preparation and execution are accompanied by negative event-related potentials over the vertex and centrolateral brain regions supporting motor control, whereas the absence of movement is associated with a relative positivity at these locations. The timing of the positive peaks in our multi-movement epoch appears to converge with the latency of button presses during which movement speed and muscle force were at a minimum. Conversely, the timing of the negative peaks in our ssMRP suggests that movement kinematics and force development were maximal in between the button presses when participants raised and lowered their fingers. Hence, the timing of positive and negative peaks in the ssMRP appears to match with the observed kinematics of finger tapping.

The amplitude of the positive peaks preceding the button presses and the negative peaks during movement execution were found to be suppressed in the CCC condition relative to the URC condition. These findings suggest that participants' attempt to prevent automatic repetitions in the sequence of their responses influenced electrocortical motor activity associated with movement preparation and execution. Since in electrophysiology, signal amplitude is the function of synchronised currents sharing polarity and orientation (Buzsáki et al., 2012), the general amplitude reduction we observed here across positive and negative peaks might therefore reflect the inhibition of spontaneous response tendencies in the CCC relative to the URC. Comparable findings have been reported for RP by Dreher et al. (1999) and Praamstra et al. (1995) who found that preparation of free (unconstrained) single movements and movement sequences were accompanied by stronger medial RP amplitudes than fixed (prior instructed) single movements and movement sequences. This finding confirms the view that the aim to voluntarily control action (sequences) is associated with a suppression of motor activation, relative to conditions in which participants spontaneously generate actions without much further thought. Related as well, is a finding by De Jong et al., (1995) who reported that the possibility of having to revert to a different response (e.g. in response to a change signal to generate a foot response instead of a manual response) may attenuate participants' LRP activation for the initial action. This finding corroborates the idea that the possibility of having to flexibly change responses on the fly (as is the case in the CCC) may constrain motor preparation.

Following the theoretical position on free will that cognitive control may play an important role in constraining automatic response tendencies and regulating behaviour, we hypothesised that frontal midline theta power – an electrophysiological correlate of executive attentional processes and cognitive control (Boran et al., 2019; Cavanagh & Frank, 2014; Mitchell et al., 2008; Nigbur et al., 2011; Sauseng et al., 2007; Tsujimoto et al., 2006) – would be larger in the CCC than in the URC, which was indeed the case. This finding confirms that participants employed more cognitive control in attempting to prevent repetitions and response patterns in the FFTT. In further support of the hypothesised involvement of cognitive control in response selection, the relative increase in frontal midline theta in the CCC was found to be associated with the relative attenuation of the amplitude of positive peaks in the ssMRP that preceded button presses in the FFTT. In contrast, no significant correlations were obtained between condition differences in frontal midline theta power and the amplitude of negative peaks. This suggests that cognitive control was mainly concerned with the actual goal of each movement (the button press) and less so with the action means, i.e. the vertical transport of the fingers, in line with goal directed models of action control (van Elk et al., 2014; van Schie & Bekkering, 2007). Note, however, that further research is necessary to further investigate the causal influence of frontal midline theta on movement-related cortical potentials associated with response selection and movement execution. More specifically, the FFTT could be combined with TMS, TDCS or neuro-feedback training that aims to enhance or suppress frontal midline theta (Enriquez-Geppert et al., 2014; Miller et al., 2015; Noda et al., 2013), to investigate the causal effect of cognitive control in the CCC.

For the negative peaks accompanying the transportation phase preceding the button-press, we found a stronger negativity, i.e.

more activation, in the URC condition than in the CCC condition. This finding suggests that movement execution in the URC was more pronounced than in the CCC, or vice versa, that execution in the CCC condition was relatively constrained or suppressed as compared to the URC. Future studies using the same paradigm may employ motion tracking to investigate if instructions to prevent repetitions in the FFTT indeed influence movement kinematics as is suggested by the present ssMRP findings. In accordance with this idea studies have found cognitive load manipulations to affect movement kinematics such as lower velocity in walking speed (Kannape et al., 2014) and the reduced velocity of arm movements with increased end-point variability in an upper extremity precision task (Srinivasan et al., 2015).

One potential weakness of the present findings is that the condition specific modulations of activation over the medial and lateralised motor cortices may reflect attenuations in motor activation associated with action execution rather than action preparation. Although this does not alter the fact that participants were able to voluntary influence their response selection (i.e. the sequence of tapping responses in the FFTT) and modulate their ssMRP by exercising cognitive control, which in itself provide strong arguments for the reality of free will, this limitation may constrain our conclusions with regards to the function of the RP and the suggestion that the RP is impervious to conscious will. It should be noted however that both the lateralised (LRP) and the medial activation that make up the RP are closely associated with motor output and do not terminate when the response preparation interval ends and motor execution begins (Ball et al., 1999; Eimer & Coles, 2003; Kristeva et al., 2003; Urbano et al., 1998). In other words, the functional properties of these motor structures may be investigated both prior to response execution and during response execution and discoveries made during either phase may thus be consequential for our understanding of the RP. Furthermore, it should be noticed that the previously discussed findings of Dreher et al. (1999) and Praamstra et al. (1995) on the RP confirm that instructions to constrain spontaneous (automatic) response selection (by preparing the execution of a memorised action sequence or movement rather than preventing recurring response patterns) were found to directly modulate the RP (also see Tauge et al., 1995). These findings corroborate the present conclusion that motor activation preceding and accompanying the execution of voluntary actions may be modulated voluntarily. Nonetheless, it may be fruitful for future ssMRP studies with the FFTT to use brisk movements (sudden flexion of the fingers) which has the advantage that motor activation preceding movement onset may be more easily separated from motor activation accompanying movement execution (cf. Gerloff et al. 1997, 1998). Alternatively, isometric strain gauges could be used so that participants may execute discrete "button presses" without lifting their fingers (cf. Newman-Norlund et al. 2008). Furthermore, future studies could track movement kinematics and collect electromyograms to more precisely track time the course of movement execution. Another weakness of the current study is that our data does not seem to allow for any strong conclusions about the proximity or distality at which conscious will can influence behaviour. If anything, our data suggests that cognitive control exerts an effect prior to any button press. However, one should bear in mind that ssMRP reflect average activations across many trials and may include responses in which cognitive control did and did not exert an influence. Alternatively, there is a possibility that movements were not simply controlled at the level of individual button presses but at the level of movement sequences. Future work could investigate fluctuations in theta power over time to study the time course at which cognitive control is expressed and its potential influence on concurrent and consecutive action sequences.

With the caveat in mind that the EEG findings in our study may reflect ssMRP in association with action execution and action preparation, rather than merely action preparation, our findings demonstrate that neural activity from areas that support action preparation and movement execution can be modulated by cognitive control, thereby allowing volition to overcome automatic response selection. This approach opens up the possibility for a new line of empirical arguments in the future of studying free will. More specifically, we believe that a shift is necessary from paradigms that allow participants to choose the moment of their response ("when" paradigms), to paradigms that allow participants to choose the type of response ("what" paradigms) as the latter may allow for a more natural expression of volition/free will than the former which has been argued to depend on spontaneous impulses (Furstenberg, Breska, et al., 2015; Furstenberg, Deouell, et al., 2015). Furthermore, we believe that the dual process account of free will as presented here, suffices as a theoretical model to explain both voluntary response selection in "what" paradigms as well as automatic response tendencies that have been argued to drive actions in "when" paradigms.

5. Conclusion

Following the seminal research by Libet (1999) that initiated the neuroscience of free will and his finding that readiness potentials in primary and supplementary motor regions seem to precede the awareness of the intention to act (Fried et al. 2011; Haggard and Eimer 1999; Kornhuber and Deecke 1965; Libet 1999; Schlegel et al. 2013), the main narrative in neuroscience and psychology over the past two decades has been that the human experience of free will is merely an illusory epiphenomenon with little or no power to affect the neural mechanisms that drive behaviour [except perhaps the capacity for vetoing; (Asma, 2017)]. The results of the present study speak against the commonly accepted notion that neural activation from primary and supplementary motor cortices is impervious to volition and that automatic action tendencies cannot be controlled. Instead, our findings argue for a more balanced and neurophysiologically realistic (dual process) model of free will in which automatic response tendencies do exist but can be regulated through the expression of cognitive control. In order to advance our understanding of the psychological and neurophysiological mechanisms underlying our experience and capacity for free will we welcome future research to expand its horizon and include "what" paradigms in addition to "when" paradigms.

Declarations

Informed consent: All participants read and signed an informed consent form prior to the experiment.

Data availability statement: All data, stimuli and analysis scripts belonging to this research can be obtained by contacting the first author.

CRediT authorship contribution statement

Hein Thomas van Schie: Conceptualization, Methodology, Writing – review & editing, Visualization, Supervision. **Ivaylo Borislavov Iotchev:** Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Félix René Compen:** Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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