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Title. Spontaneous EEG fluctuations determine the readiness potential: Is preconscious brain activation a preparation process to move?

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Abstract

It has been repeatedly shown that specific brain activity related to planning movement develops before the conscious intention to act. This empirical finding strongly challenges the notion of free will. Here we demonstrate that in the Libet experiment, spontaneous fluctuations of the slow electro-cortical potentials (SCPs) account for a significant fraction of the readiness potential. The individual potential shifts preceding self-initiated movement were classified as showing a negative or positive shift. The negative and positive potential shifts were analyzed in a self-initiated movement condition and in a no-movement condition. Comparing the potential shifts between both conditions, we observed no differences in the early part of the potential. This reveals that the apparently negative RP emerges through an unequal ratio of negative and positive potential shifts. These results suggest that ongoing negative shifts of the SCPs facilitate self-initiated movement but are not related to processes underlying preparation or decision to act.

Key words. Free will, Intention to move, Libet experiment, Slow Cortical Potential, Readiness Potential

Introduction

Following the discovery of the readiness potential (RP; Kornhuber and Deecke, 1965), a slow negative shift in the EEG which can be seen by averaging several epochs, Libet's famous experiment (Libet et al., 1983) has incited hot debates concerning the question of free will (Haggard, 2008). In many different replications of this experiment it was shown that the RP precedes the subjective intentions to act (Haggard and Eimer, 1999; Sirigui et al., 2004; Miller et al., 2011; Rigoni et al., 2011; Schurger et al., 2012; Schlegel et al., 2013). This pre-conscious brain activity, starting approximately 2 sec before movement onset and well before the conscious intention to act (see **Fig. 1a**), is often interpreted as an indicator that voluntary acts are preceded and determined by unconscious processes (Libet et al., 1983; Shibasaki and Hallett 2006). That is, a 'decision' to move has already been initiated by the brain before subjects report any conscious awareness of their decision.

However, this interpretation has been challenged by several recent studies: Trevena and Miller (2010) showed that negative potential shifts did not depend on the decision to move. A tone sound prompted participants to decide whether to move or not but no evidence was found for stronger negative potential shifts before a decision to move than before a decision not to move. Herrmann et al., (2008) made a similar argument by showing that RP-like preparatory activity emerges well before subjects had to respond to a visual stimulus, and this preceding activation did not differ between two alternative responses (left- or right-hand movement). They concluded that this activity does not determine the choice between two alternatives available but rather may reflect general preparation. In addition, the lack of causal relationship between the onset of preconscious brain activity and the time of conscious intention to act suggested that the RPs reflect processes independent of will and consciousness (Schlegel et al., 2013).

Since participants in the Libet experiment were instructed to perform a movement whenever an urge to act appears, it is unclear whether self-initiated movements were purely 'voluntary' acts or simple reactions to an internal stimulus (Bennett and Hacker, 2003; Kotchoubey, 2012). In the latter case, it might be argued that pre-conscious brain activity may reflect the general fluctuations of internal non-specific preparation instead of a decision process to move. A recent study added to these interpretations of the RP by employing a stochastic accumulator model for neural activity occurring before self-initiated movements (Schurger et al., 2012). The fluctuating time series average produced by their model was well fitted to the RP suggesting that the shape of the climbing RP only appears to build up steadily, but may rather reflect spontaneous fluctuations of neural activity.

In this study, we thus assume that if the average RP reflects the spontaneous fluctuation of neural activity instead of movement preparation, then the same components of the RP would be observed not only in a self-initiated movement condition, but also in a no-movement condition. To test this hypothesis, we split the slow electro-cortical potential (SCP) into ongoing negative and ongoing positive shifts. Participants performed either a self-initiated movement (W-Task; Libet et al., 1983), or a simple auditory stimulus occurring at random times (T-Task) for the no-movement condition.

Methods

Thirteen adults (five females; mean age, 37.8 years; range, 22-54 years) carried out the Libet-type self-initiated movement and auditory stimulus tasks. The experiment was approved by the Department of Psychosomatic Medicine at the Albert-Ludwig University in Freiburg, and written informed consent was obtained.

Participants performed the Libet-type experiments for the movement condition, the so-called W-task (Libet et al., 1983). An analogue clock was presented on a computer screen (visual angle: 3 degrees in diameter) with a clock-hand rotating clockwise with a revolution period of 2,550 msec. Subjects gazed the center of the clock, with their right index finger placed on the left button of a computer mouse. The clock-hand appeared after a short period (1-2 sec) and started rotating from a random position. They were instructed to spontaneously press the button with their index finger at a moment of their own choice when they felt the urge to move after the clock-hand had finished the first revolution. After a random interval of 1 to 2 sec following the button press, the clock-hand stopped and disappeared. Subjects were then asked to indicate the clock-hand position at the moment when they felt the urge to move (w-time). They were encouraged to minimize eye movement and blinking during the clock-hand rotation. Presentation of the clock and collection of the response data were performed by the E-Prime 2.0 software (Psychology Software Tools, USA). The control condition, a no-movement condition (T-task), followed. It was identical to the W-task except that subjects were asked to report the onset time of the tone (t-time) that occurred at a random time from 2.5 to 7.5 sec after the beginning of each trial. After a random interval of 1 to 2 sec following the tone, the clock-hand stopped and disappeared, and then subjects were asked to indicate the onset time of the tone. In this T-task, subjects were not asked to press the button spontaneously. Each task contained 40 trials in separate blocks and each trial was initiated by the participant when he or she felt ready. Between these two tasks, two or three other Libet-type tasks were performed for other purposes. Two subjects missed the T-task for technical reasons. Therefore, a comparison between tasks was done with 11 subjects.

Brain activity was recorded from the scalp with a 64 channel DC-EEG recording amplifier using active electrodes (Brain Products, Germany) in an acoustically and electromagnetically attenuated chamber. Electrode impedance was kept under 5 K Ω . Four electrooculography (EOG) electrodes were placed to record both horizontal and vertical movements. To estimate the onset of finger movement, a single axis accelerometer (1.7g) was placed on the mouse button to measure the exact onset time of the button press. All electrophysiological data was recorded at a sampling rate of 1,000Hz.

Data analyses were performed with the help of EEGLAB (Delorme and Makeig, 2004) and ERPLAB (<http://erpinfo.org/erplab>). EEG data was re-referenced to linked mastoids before being bandpass filtered (high-pass 0.01Hz, low-pass 35Hz, 24 dB/octave). The data stream was then segmented into event-locked epochs ranging from 2.5 sec before the events (either the button press or the onset of the tone) to 1 sec afterwards. The first 200 msec of each epoch was used for baseline correction. Eye movement and muscle artifacts were reduced based on independent component analysis (ICA) and with EOG through visual inspection. In addition, on average, in 3.8% of the epochs the button press occurred during the first rotation, mostly by one subject, and these were excluded. The slope of each epoch was estimated by fitting a first order polynomial function to the averages of 9 electrodes around the vertex (FC1, FCz, FC2, C1, Cz, C2, CP1, CPz, and CP2) before the events. According to either negative or positive slope, each

epoch was classified as either negative or positive epoch, respectively. Subsequently, both negative and positive epochs were averaged separately across 13 subjects for the W-task and 11 subjects for the T-task.

For statistical analysis, the averaged negative and positive shifts were segmented into 25 non-overlapping 100 msec-bins. All statistical comparisons for matched pairs were performed with paired two-tailed t-tests; if unpaired, an unpaired two-tailed t-test was performed, unless otherwise stated.

Results

The SCP epochs preceding either the movement or the tone by 2,500 msec were classified as showing a negative or positive shift. In order to distinguish these shifts, a first order polynomial fit was applied to the average of 9 electrodes around the vertex. If the slope of the fitted function of a single-trial epoch was negative, it was classified as negative epoch; otherwise as positive epoch. The ratio between negative and positive epochs revealed that for the W-task, the proportion of positive epochs was smaller in comparison to the T-task (grand mean of percentage, W=32.84%, T=50.45%; n=11, p=.002). The pooled epochs across 11 subjects are shown in **Fig. 1b**. Next we assessed how the proportion of positive epochs correlated with overall amplitude of the RP in the W-task across 13 participants (**Fig. 1c**). This significant correlation of $r=-.77$ (Pearson correlation, p=.002) demonstrates that smaller proportions of positive epochs are related to larger negative RP amplitudes (Vaez Mousavi and Barry, 1993; additional supporting information in **Supplementary Material**).

To examine the differences in negative and positive potential shifts preceding the events in both conditions (movement onset and tone presentation, respectively), we took data solely from the C3 electrode over the contralateral central area of the right hand, where the RP is maximal. In order to compare the specific shape of either positive or negative epochs we inverted the positive epochs by multiplying a negative sign (**Fig. 2a, b**). As can be seen in the **Fig. 2a**, the significant difference between the average of negative epochs (tick trace) and of positive epochs (thin trace) in the W-tasks occurs around 500 msec before the button press, while the early part shows no difference. This boundary is consistent with the onset time of the late RP reported in the literature (Shibasaki and Hallett 2006). Since the RP amplitude is influenced by the proportion of positive epochs and the two polar shifts show the same slope until around 500 msec before the button press, the assumption that the early part of the RP appears to be an averaging artifact reflecting the ratio of negative and positive epochs rather than a sign for a decision or a preparation process to move can be made. In addition, in the T-task, in which no decision had to be made, the shape of negative and positive shifts shows no difference until the onset of the tone (**Fig. 2b**). Here, since negative (49.55%) and positive (50.45%) epochs are equally distributed, a lack of any averaged potential shift before the tone results (**Fig. 1a**).

To test the implication of our results, i.e. that the early RP may not be related to preparatory processes to move, we compared the two different polar shifts between movement (W-task) and no-movement (T-task) conditions. The difference between tasks in both negative and positive shifts was observed in the late part from around 500ms before the events, but not in the early part (**Fig. 1d**). We performed a two-factor repeated measure ANOVA for both positive and negative shifts, separately. The *task* (W and T) and *time* (23 100 msec-bins from -2.3 sec to the events) were used as factors and the amplitude as the dependent variable. Analyses revealed a significant main effect of *time* in both negative ($F_{1,42,14,22}=31.29$, $p<10^{-4}$) and

positive ($F_{1,58,15,79}=21.92, p<10^{-4}$) shifts. These results reflect the slow ongoing negative or positive shifts, respectively. In negative shifts, no significant effect was observed in the *task* \times *time* interaction ($F_{1,99,19,90}=1.39, p=.27$), while a significant effect of the *task* \times *time* interaction ($F_{3,21,32,07}=3.54, p=.023$) was found in positive shift trials. To determine the precise time at which potential shifts in the two tasks started to differ, we performed paired t-tests on the averaged epochs in 100 msec-bins. It can be seen that the positive shift in the W-task turns into the negative direction at around 500 msec before the button press (see the black trace in **Fig. 2d**). However, no difference was observed in negative shifts, though the W-task on average showed a slightly more negative amplitude as compared to the T-task in the late part (see the black trace in **Fig. 2c**). This stronger negative deviation during positive shifts was clearly observed when the ongoing shifts are detrended (see **Fig. 3a**). The slope from -600 ms to the button press was steeper for positive shifts as compared to negative shifts (-7.53uV/s and -1.74uV/s, respectively; $p=.001$; see **Fig. 3b**).

Discussion

One crucial experimental question posed by the Libet experiment is whether the onset of recorded RP is a valid indicator of the time when cerebral processes begin to produce an action (Libet, 1985). Recent reports studying Libet's experimental setup have revealed the occurrence of negative potential shifts in conditions other than movement preparation (Trevena & Miller, 2010; Miller et al., 2011). Following from this and other findings (for an overview see Guggisberg and Mottaz 2013), the RP may not represent an adequate marker for movement decisions but may be related to general processes of task expectation. Moreover, the shape of the RP was fitted to a stochastic accumulator model, suggesting that the RP is merely an average of spontaneous fluctuations in neural activity (Schurger et al., 2012). To address the question, we thus investigated the effects of spontaneous SCPs on the RP by sorting the ongoing potential shifts before the button press into negative and positive shifts, and compared these shifts between a self-initiated movement condition (W-task) and a no-movement condition (T-task).

The present study demonstrated how an apparently negative RP emerges through an unequal ratio of negative and positive potential shifts preceding self-initiated movement. We investigated ongoing potential shifts prior to the events of movement onset and the tone presentation in both W-task and T-task, respectively. The ongoing potential shifts were compared within task and between tasks. In the W-task, we observed no difference of shape between the ongoing negative and positive potential shifts until around -500 ms before the button press. In addition, these two potential shifts showed the same pattern as in the T-task, in which participants were asked to refrain from a movement (see **Fig. 1d**). However, we observed difference ratios of negative and positive shifts between the W-task and T-task, which results in different shapes of event-related potentials (ERP; see **Fig. 1a**). Given these results, it is clear that the unequal ratio of ongoing potential shifts of SCPs has a significant effect on the RP amplitude. Moreover, it is in agreement with recent reports that spontaneous SCP fluctuations appear to have an essential impact on promoting a decision on self-initiated movements, with negative shifts making them more likely (Schurger et al., 2012).

The difference of positive and negative slopes in the ongoing potential shifts as seen in the late RP in the W-task may suggest different underlying neuronal processes (see **Fig. 3**). One interpretation is that

ongoing negative shifts are related to less effort in starting a movement as compared to positive shifts. According to the theory behind SCP shifts, a negative electrical potential shift on the scalp is associated with an increase of negative charges in the apical dendrites of the cortical pyramidal neurons, which leads to a lowering of the excitatory threshold and, thereby, an increased probability of movement execution (Mitzdorf, 1985; Birbaumer et al., 1990; McCallum and Curry, 1993). If such a lowering of the threshold is experienced as an urge to move in the Libet task, a self-initiated decision can be interpreted as an agreement with an inner activity, which is reflected in the negative SCP shift. That is, the negative deflections of SCPs facilitate a movement in the near future, but they are not a neural sign of decision processes to move.

Our findings challenge the common interpretations of Libet's experiment. Do participants actually perform a volitional movement during the task? Participants may be waiting for a feeling of the intention to act and then perform a movement according to this feeling rather than carry out a "voluntary" movement. In other words, an individual who has focused attention on internal events (Keller and Heckhausen, 1990) or has more awareness of his or her inner activity might press the button more often during negative deflections of SCPs, resulting overall in a large RP amplitude as the correlation in **Fig. 1c** shows. In this view, attention to intention of movement may lead a participant to sense the negative deflections of SCPs that might be influenced by the experimental paradigm (Birbaumer et al., 1990).

Taken together, the results of our study using the Libet task suggest that the RP does not indicate a 'will' that independently initiates an action or a 'will' that causes the RP to rise. In contrast, negative deflections of SCPs are linked to a higher probability of button press occurrences, since they might more readily lead to an impulse to act than positive deflections. In this view, we further suggest that the RP in principal cannot be used to solve the question of free will because it only reflects general preparation processes as it is correlated with an increase in the likelihood of an action.

Conclusion

In this study, our results propose that individual negative and positive shifts of SCPs have different effects on self-initiated movement, suggesting that negative shifts make a movement more likely. This indicates that at least the early part of the RP, which is often interpreted as the time when neural processes prepare for an action, is not a neural correlate of preconscious motor preparation but may reflect spontaneous neural activity during the task.

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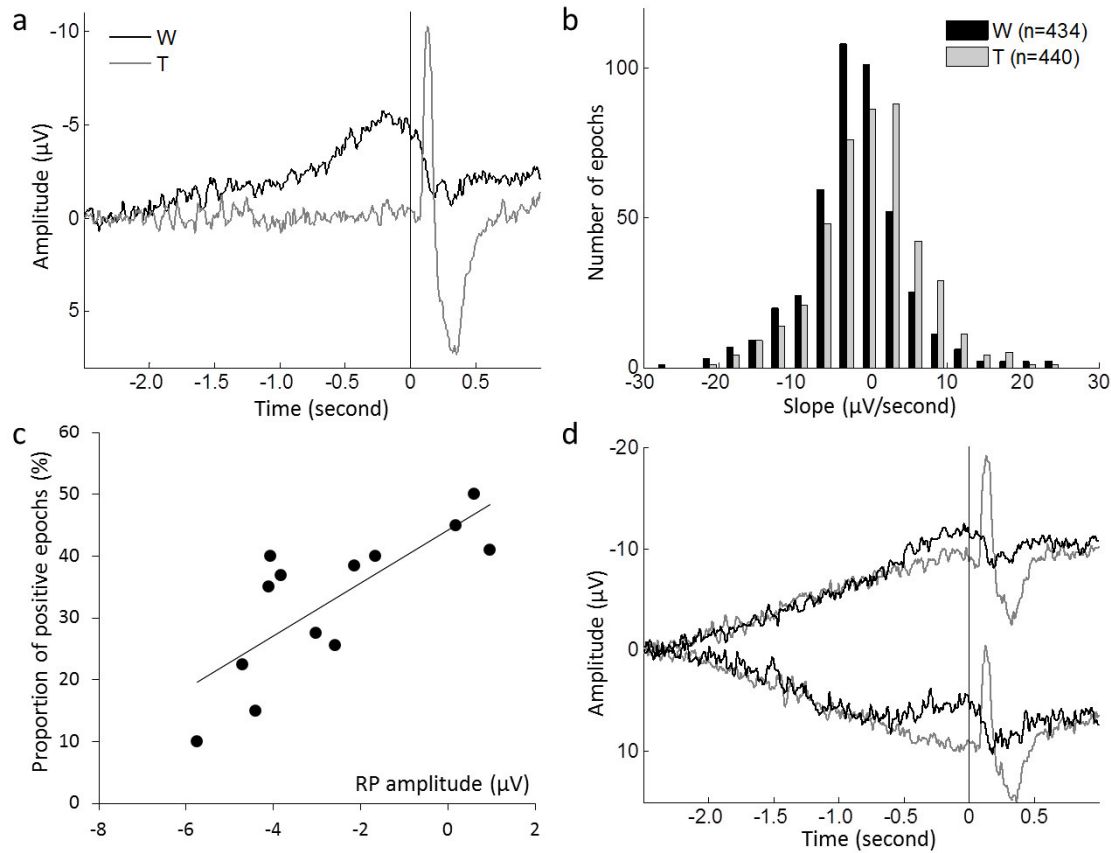


Fig. 1. Grand average of 9 electrodes around the vertex and its single epochs. **(a)** Grand averages of the W-task (black trace, $n=13$) and the T-task (gray trace, $n=11$) are shown. The vertical thin line indicates the event times, either the button press or the tone. The subjective reports of mean w-time and t-time were -239 msec and -67 msec, respectively (two-tailed unpaired t-test, $p=.036$). **(b)** The slopes of each single epochs pooled together from 11 subjects show normal distribution in both tasks (mean slope; W-task=-2.1, T-task=0.1; two-tailed unpaired t-test, $p<10^{-5}$). The slope was measured by a first order polynomial fit before the events. **(c)** According to the slope, each epoch was distinguished either as negative or positive epoch. The overall RP amplitude showed a linear relationship with the proportion of positive epochs across 13 subjects ($r=.77$, $p=.002$). The mean RP amplitude was measured from -1.0 to -0.5 sec before the button press. **(d)** Grand average of negative and positive epochs at the C3 electrode across 11 subjects. No difference was found in subjective reports between negative and positive epochs (w-time, $p=.533$; t-time, $p=.458$).

Fig. 2.

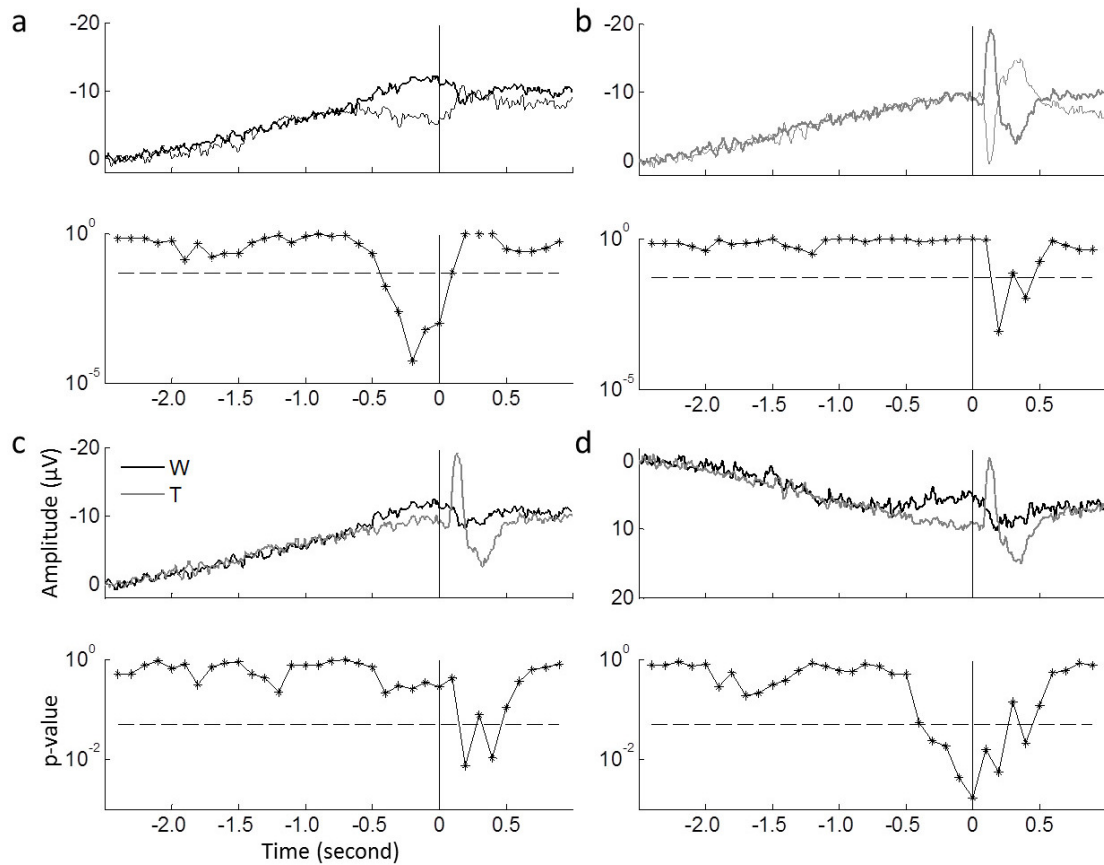


Fig. 2. (a, b) Comparisons between ongoing negative and positive (inverted) shifts. The grand averages of potential shifts at the C3 electrode within 11 subjects are time-locked to the button press (W-task; black traces in **a**) or to the onset of the tone (T-task; gray traces in **b**). The polarity of ongoing positive shifts (thin line) was switched for the comparison with negative shifts (tick line). **(c, d)** Comparisons between movement (W) and no-movement (T) tasks. Ongoing potential shifts were compared between the W- and the T-task for both negative (**c**) and positive shifts (**d**). The grand averages of potential shifts at the C3 electrode were time-locked to the button press for the W-task (black trace) and to the onset of the tone for the T-task (gray trace). Lower panels below the ERPs show the p-value in 100 msec-bins. The dashed horizontal line indicates $p=0.05$ (two-tailed paired t-test). Note that the p-value is in logarithmic scale.

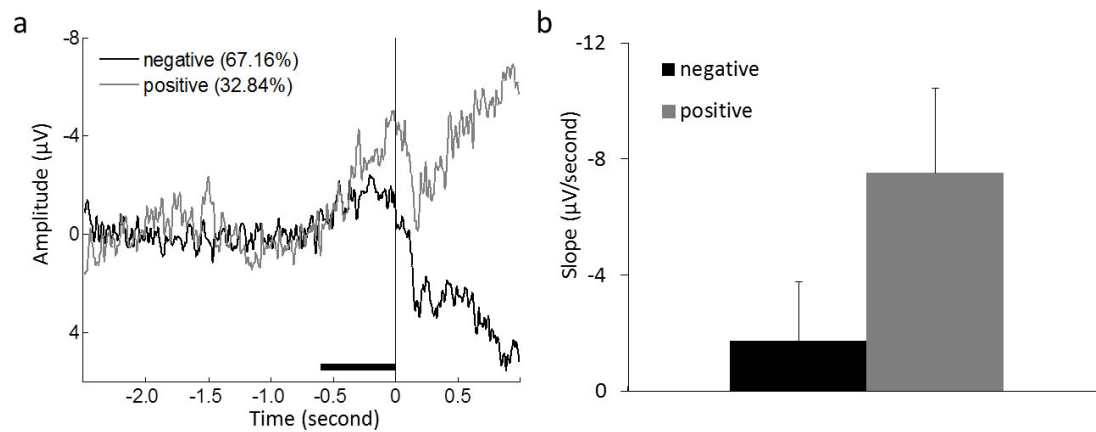


Fig. 3. Detrended negative and positive shifts of the W-task. **(a)** Grand average of detrended negative and positive shifts at the C3 electrode are shown. A first order polynomial fit was applied from -2.5 to -0.5s before the button press to estimate the trends of negative and positive shifts across 13 participants. These trends were subtracted from each other over the range of the whole epoch. The percentages in parenthesis indicate the proportion of the grand mean. **(b)** A steeper slope was observed in positive shifts as compared to negative shifts during the interval indicated by the horizontal black bar in **a**, from -600ms to the button press (grand mean of the slope; negative shifts = $-1.74\mu\text{V/s}$, positive shifts = $-7.53\mu\text{V/s}$; $n=13$, two-tailed paired t-test, $p=.001$). The error bars represent the standard error of the mean.