The point of no return in vetoing self-initiated movements

SUPPLEMENTARY INFORMATION

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Supplemental Figure S1

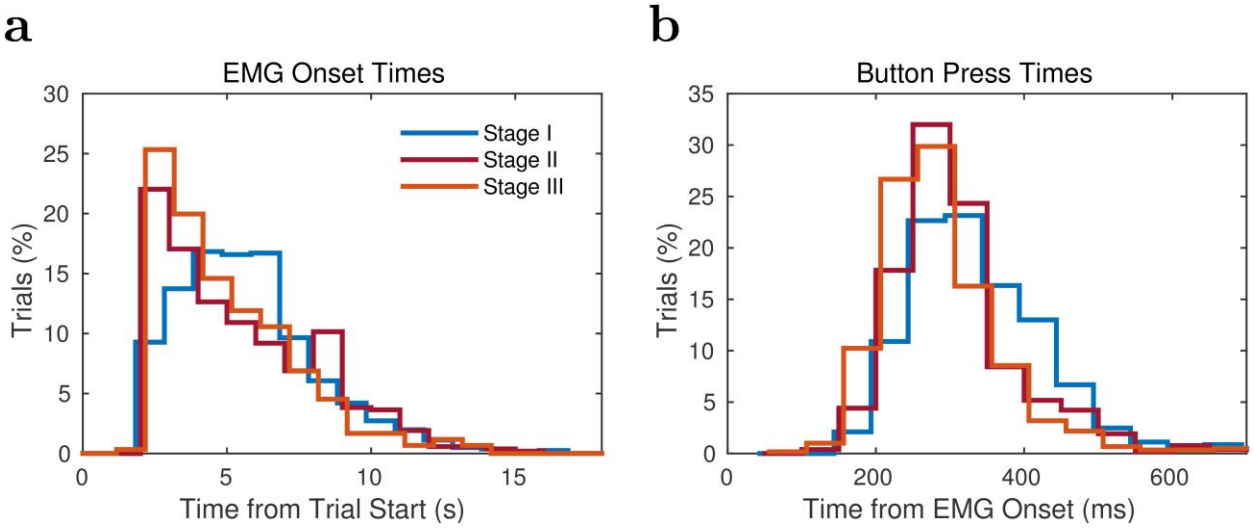

Figure S1: (a) Distribution of waiting times (time from trial start to EMG onset) for the three stages, pooled across all subjects. Waiting times shorter than 2 seconds were discarded from all analyses. The mean waiting time across subjects was 5995 ms, 5462 ms and 4907 ms in successive stages I, II and III, respectively. (b) Distribution of button press times relative to the time of EMG onset for all three stages (as in a). The mean duration of movements from EMG onset to button press was 345 ms, 305 ms and 303 ms in stages I, II and III, respectively.

Supplemental Figure S2

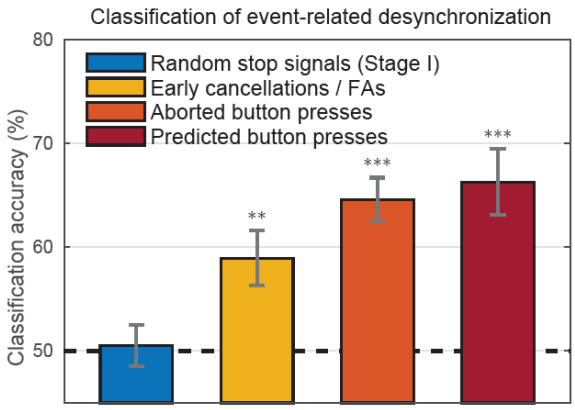

Figure S2: Classification accuracies of a classifier trained to detect an impending movement based on the event-related desynchronization (ERD) (26). The bars show the mean accuracies over subjects (error bars=SEM). The classifier was trained on EEG spectral features from four frequency bands: low alpha (8 – 10 Hz), high alpha (11 – 14 Hz), low beta (15 – 19 Hz) and high beta (20 – 27 Hz). Therefore, for each band individually, CSP filters were defined that maximize the power contrast between “movement” and “no movement” windows (49). Those were 500 ms long EEG segments, the former immediately preceding EMG onset, the latter from -1500 to -1000 ms relative to EMG onset. The classifier was trained using the log variance features from all CSP filtered signals and eventually applied to equivalent “movement” and “no movement” windows (relative to the time of stop signal) of trials with stop signals and the classification accuracy calculated for each trial type individually. As expected, classification performance was at chance level for the random predictions in stage I (mean 50.5% ±2.0% SEM, t_9=0.26, p=0.79). BCI predictions in ambiguous trials of stages II and III, however, could be classified with accuracies that were significantly above chance level (mean 58.9% ±2.6% SEM, t_9=3.38, p=0.008). For the same two reasons given in the RP-based analysis, classification accuracies of predictions in trials which involved actual movements were better (mean 64.6% ±2.0% SEM, t_9=6.99, p=0.0001 and mean 66.3% ±3.2% SEM, t_9=5.08, p=0.0007).

Supplemental Methods and Results

Questionnaire: During stage I 4/10 participants reported trying to “wait as long as possible” before an interruption, which they described as a “risky” strategy (Supplemental Tables S1 and S2). Another 4/10 reported waiting until they “felt an interruption would come”. Furthermore, 4/10 participants said that they modified their strategy dynamically and “pressed earlier [on trials] after interruptions”. After stage II all of the participants reported that they made changes to *how* or *when* they chose to move. Notably, 4/10 participants reported acting more “unpredictably” or more “spontaneously” than during calibration and 1/10 participants reported ignoring the “urge” to move in favor of a deliberate strategy. After stage III 5/10 participants reported acting unpredictably or not thinking about their actions. 9/10 participants reported that they felt predicted while the remaining participant reported that s/he could not rule out the possibility. 7/10 participants reported that something related to foot movements caused the interruptions. Among these 2 participants reported that “everything” caused interruptions, 2/10 specifically mentioned “thinking about pressing”, 2/10 mentioned the change from being relaxed to preparing to move, and 1/10 mentioned movement onset. The remaining 3/10 participants reported feeling predicted but did not identify a specific event as being tied to predictions.

Supplemental Discussion

False alarm rate of BCI: When choosing the BCI predictor's threshold for the detection of a readiness potential, there is a trade-off between sensitivity and specificity. A low threshold increases the probability of early predictions but comes at the expense of a higher rate of false alarms, while a high threshold minimizes the false alarm rate. The specific choice thus depends on the purpose of the study. One such purpose is the development of asynchronous BCIs, which allow individuals to control a device at their own pace (29-30). For such systems a very low false positive rate is essential, while the temporal resolution of detections is negligible. In contrast, in our study a detailed investigation of the timing of potential cancellations of movements required that we predict and interrupt subjects as early as possible. Consequently, our choice of the threshold resulted in a false alarm rate that was appropriate for our goals but higher than in other BCI studies (36). Thus, a certain level of missed button presses is expected because the BCI predictor was adjusted conservatively to avoid false positives in the long waiting period before a movement is finally elicited. The missed button presses do not necessarily reflect an ability of subjects to deliberately change or suppress their readiness potential when they move.

Supplemental Table S1

"Did you use a particular strategy during the last round?"		
Stage I	Stage II	Stage III
Pressed earlier on trials following after interruptions. (n=4)	Got 'hit' more often, so pressed earlier overall. (4)	Tried to be unpredictable [or] didn't think about movements. (5)
Tried to wait as long as possible [or] played "riskier". (4)	"Tried to be more spontaneous [or] didn't think [or] tried to be unpredictable." (4)	"I pressed faster." (3)
Waited until "I felt an interruption would come" and then pressed. (4)	"I didn't wait for the interruptions, I played safer." (3)	"I was more relaxed [or] meditative." (2)
Pressed randomly (avoided rhythms, heart rate, breathing) (2)	"I tried to be less tense just before movements." (2)	Ignored the "feeling" or "urge" to move. (2)
Pressed faster or "I tried to play it safe." (2)	"I had more of a strategy, it was less of an 'urge'." (1)	"I tried to ignore when I was interrupted." (1)
Thought about other things, pressed when the 'urge' came. (1)		"I tried harder." (1)
"I don't know." (1)		

Table S1. Summary of Responses to Question 1. Each participant was questioned at the end of every ten minute block (two per stage) during the experiment. Participants were not prompted but openly volunteered different strategies that they felt they had followed intentionally or unintentionally. Because many responses overlapped this table includes quotes and paraphrased quotes without quotations grouped together with other similar answer types. Each group includes the number of participants, in parentheses, who volunteered the quoted information. Because participants could mention multiple strategies, the total for each stage can add up to more than 10.

Supplemental Table S2

"Did you feel there was a connection between your actions and the appearance of an interruption?"		
Stage I	Stage II	Stage III
"There was no consistent connection." (n=6)	Moving the foot caused interruptions. (4)	"There was no consistent connection." (3)
"I saw a pattern in the timing" of interruptions. (4)	"Thinking about pressing [or] the 'feeling/urge' to press" caused interruptions. (3)	"The switch from being 'relaxed' to 'going to push'" caused interruptions. (2)
"If I wait too long then an interruption comes." (3)	"There was no consistent connection." (2)	"Everything" related to foot movement caused interruptions. (2)
	"The moment of choice." (1)	"Thinking about pressing [or] the 'feeling/urge' to press" (2)
		"Heart rate" (1)
		Moving the foot caused interruptions (1)
		"I have no idea." (1)

Table S2. Summary of Responses to Question 2. Each participant was questioned at the end of every ten minute block (two per stage) during the experiment. Participants were not prompted but openly volunteered possible connections that they felt they experienced between their actions and the appearance of interruptions. Because many responses overlapped this table includes quotes and paraphrased quotes without quotations grouped together with other similar answer types. Each group includes the number of participants, in parentheses, who volunteered the quoted information. Because participants could mention multiple connections, the total for each stage does not need to add up to 10.