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How Untidiness Moves the Motor System

Francesca Fiori[1,2], Andrea Ciricugno[3], Maria Luisa Rusconi[4], Ryan J. Slaby[1], and Zaira Cattaneo[3,4]

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Abstract

Humans tend to prefer order to disorder. Orderly environments may provide individuals with comfort due to predictability, allowing a more efficient interaction with objects. Accordingly, a disorderly environment may elicit a tendency to restore order. This order restoration tendency may be observed physiologically as modulation within corticospinal excitability; the latter has been previously associated with motor preparation. To test these hypothesized physiological indices of order restoration, we measured possible changes in corticospinal excitability, as reflected by the amplitude of motor-evoked potentials (MEPs) elicited by single-pulse transcranial magnetic stimulation (TMS) over the primary motor cortex while participants viewed ordered and disordered rooms. We found that images depicting disorderly environments suppressed excitability within the corticospinal tract, in line with prior findings that motor preparation is typically associated with decreased corticospinal excitability. Interestingly, this pattern was particularly evident in individuals that displayed subclinical levels of obsessive-compulsive traits. Thus, a disorderly environment may move the motor system to restore a disorderly environment into a more orderly and predictable environment, and preparation for "order" may be observed on a sensorimotor basis.

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Introduction

It is still not perfectly clear what exactly constitutes "disorder" and "order" (Keizer et al., 2008). Disorder is commonly defined as the lack of order, while an orderly environment may provide a schematic representation congruent with a spatial designation for the arrangement or disposition of the environment on hand (Torralba et al., 2006). Previous psychological and social science studies showed that disorder may have negative consequences on the self, such as **perceived** powerlessness (Geis & Ross, 1998; LaGrange et al., 1992), distress (Cutrona et al., 2000), depression, anxiety (Ross, 2000), **and** a sense of failure in self-regulation (Chae & Zhu, 2013). **While** some research has shown that viewing disorderly rooms leads to higher creative thinking and a higher preference for novelty (Vohs et al., 2013), perceiving order may provide comfort**,** due to its association with predictability (Harmon-Jones & Harmon-Jones, 2002**). Since a** more orderly environment corresponds with a simple**r** and **more** predictable environment, people **have been found to** prefer orderly and descriptively simple bundles of goods (Evers et al., 2014). Viewing orderly rooms predicted simple and conventional choices **and** normatively good behavior, such as **improved** diet and charitable donations (Vohs et al., 2013). **Most** research investigating order and disorder **has** focus**ed** on the consequences of exposure to a disorderly environment by solely considering **factors** linked to social disorder, **but** neglecting the **effects of neurological** processing visual disorder (Keizer et al., 2008; Kotabe, 2014; Kotabe et al., 2016).

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In this study, we were interested in the cognitive aspect of **perceiving** environmental disorder, as operationalized by Kotabe (2014**, p. 1)**: "Perceived disorder is an interpreted state of the world in which things are in non-patterned and non-coherent positions." To our best knowledge, only one study **has** investigated real-time neural signals **(i.e., event-related potentials or ERPs)** related to the perception of **images of order/disorder of the** physical environmental (Li et al., 2019). Li et al. (2019) observed significant differences in the response to disorder images versus order images at different time windows. Despite some inconsistency between responses recorded from posterior and frontal electrodes, the**se** authors suggested that the significant differences in negative ERP components found at both the frontal and posterior electrodes from roughly 250–350 ms most likely depended on the unpredictability or unexpected nature of the disorder stimuli.

Given both the comfort from order restoration and the association between order and predictability, we reasoned that a**n image of a** *disordered room* **would** elicit a tendency to restore order, which **would** allow individuals to confidently pursue goals and effectively interact with their environment (Harmon-Jones & Harmon-Jones, 2002). We hypothesized that the tendency to restore order **would** be translated neurophysiologically

by means of corticospinal excitability (CSE) modulation when participants **were** exposed to disorderly environments. Indeed, the corticospinal pathway is thought to play a key role in voluntary movement (Lemon, 2008), and it has been shown that both actual and imagined movement preparation is associated with transient changes in CSE (Lebon et al., 2019). Specifically, motor preparation is typically associated with a decrease in CSE (Bundt et al., 2019). This preparatory inhibition may assist action selection processes, by preventing the release of premature or incorrect responses (Duque et al., 2010; Quoilin et al., 2018), but it may also facilitate rapid motor initiation (Vassiliadis et al., 2020). Accordingly, if disordered environments call for action to restore order, we should observe a decrease in CSE during the viewing of disordered versus ordered environments.

We further predicted that this pattern in CSE modulation **would** be particularly evident **among** individuals showing subclinical obsessive-compulsive traits that are quite common in the general healthy population (e.g., Fineberg et al., 2013; Jelinek et al., 2021). Although compulsive ordering (and a drive for symmetry) is typical of individuals with obsessive-compulsive disorder (OCD, American Psychiatric Association, 2013; Leckman et al., 2010), it may also manifest in individuals with subclinical obsessive-compulsive traits who may experience discomfort when presented with disorder. Therefore, the decrease in CSE associated with motor preparation may be more evident **among** individuals displaying subclinical obsessive-compulsive traits when viewing disorderly environments versus orderly environments. **In** this regard, it is **notable** that OCD is usually associated with baseline motor cortex hyper-excitability, likely reflecting decreased intra-cortical inhibition (Greenberg et al., 2000; Khedr et al., 2016; Radhu et al., 2013) and possibly suggesting that dysregulated inhibitory processes could lead to deficits **in the** inhibition of irrelevant information and response control that are typical **persons with OCD** (see Chamberlain et al., 2005).

We tested these hypotheses by presenting healthy participants with photographed images of rooms depicting either disorder or order while measuring **participants'** changes in CSE**, as** assessed non-invasively by means of transcranial magnetic stimulation (TMS). TMS works by passing a large, brief current through a wire coil placed on the scalp; the transient current produces a large and changing magnetic field, which induces electric current in the underlying cortical surface (for a recent review, see Pitcher et al., 2021). When single-pulses of TMS are applied to the hand-area of the primary motor cortex (M1), TMS produces contraction in the contralateral hand muscles. This contraction can be recorded using surface electromyography (EMG) electrodes placed over the hand muscle of interest (typically, the first dorsal interosseus, FDI) as motor-evoked potentials (MEPs). Critically, TMS-induced MEPs have been used as a reliable outcome measure of CSE changes, with larger MEP amplitudes indicating higher CSE and smaller amplitudes indicating lower CSE (Bestmann & Krakauer, 2015; Hannah, 2020; Lefaucheur et al., 2014). As mentioned above, our hypothesis was that MEPs amplitude should be lower in response to the viewing of disordered versus ordered rooms, because the former call for the action to restore order (i.e., motor preparation typically associated to reduced CSE, cf. Bundt et al., 2019).

Moreover, we expected this pattern to be particularly evident in participants showing strong obsessive-compulsive traits as assessed by the Obsessive-Compulsive Inventory—Revised scale (OCI-R; Foa et al., 2002), a self-rating scale that is designed to assess the severity and type of symptoms of those potentially coping with OCD.

Method

Participants

Twenty-two Italian university students participated in this study (*M* age = 22.8, *SD* = 2.6 years; 2 males; 20 females). All **participants** were right-handed, based on the Edinburgh Handedness Inventory (Oldfield, 1971), had normal or corrected-to-normal vision, and were naïve as to the purpose of the experiment. Prior to the TMS experiment, all participants **completed** a questionnaire (translated from Rossi et al., 2011) to **identify any** contra-indication to TMS (Rossi et al., 2009; Rossini et al., 2015). W**e obtained w**ritten informed consent from all participants **and conducted the experiment** in accordance with the 1964 Declaration of Helsinki **with approval from our** local **research** ethi**c**s committee.

Stimuli

Visual stimuli consisted of 32 pairs of colored photographed images of various rooms selected from a larger database as the result of a preliminary validation study (see Supplementary Materials). Each pair consisted of ordered/tidy and disordered/untidy version**s** of the same room (e.g., bedrooms, kitchens, studios). Each **image in the** pair w**as** shot with the same camera angle and illumination**, and** the exact same objects were included in each pair **so that** the only diffe**rence in the photographs** was the arrangement of the objects in the room.

Transcranial Magnetic Stimulation and **E**lectromyographic **R**ecording

Throughout the experiment, participants were comfortably seated within a quiet dimly lit room and in a chair with armrests that was approximately 60 cm in front of a 15.5 (1280 × 800 pixels) **personal** computer monitor. Surface disposable electrodes were arranged in a belly-tendon montage over the participant's right hand, with the ground electrode placed on the wrist. TMS pulses were delivered over the left ~~primary motor cortex (~~M1~~)~~ to induce ~~motor-evoked potentials (~~MEPs~~)~~ from the participant's right first dorsal interosseus (FDI). ~~Electromyography (~~EMG~~)~~ signals were acquired by means of a CED Power 1401 electromyograph controlled with the software Signal 3.13 (Cambridge Electronic Devices, Cambridge, UK). **The** EMG signal was amplified with a Digitimer D360 amplifier (Digitimer Ltd, Welwyn Garden City, Hertfordshire, UK) by means of filters set at 20 Hz and 2 kH. Traces were digitized with a sampling rate of

5 kHz and stored for offline analysis. TMS was delivered by means of a 70-mm figure-of-eight coil connected to a Magstim Rapid[2] stimulator (Magstim Co, Ltd, Whitland, Dyfed, UK). The resting motor threshold (rMT), defined as the minimal intensity of the stimulator output able to evoke 5 out of 10 consecutive MEPs of at least 50 μV of amplitude from the right FDI resulted in **a** mean **amplitude of 56.5% (**SD = 6.9%) of the maximum stimulator output (MOS). The optimal scalp position for inducing MEPs was found by moving the coil in steps of ∼1 cm over the left M1 until the largest MEPs were found. The position was then marked with a pen on a tight-fitting swim-cap worn by participants. The coil was held tangentially to the scalp with the handle pointing backward and laterally at ∼45° angle away from the midline (Kammer et al., 2001; Rossi et al., 2009). During the experiment, the intensity of magnetic pulses was set at 120% of rMT. TMS pulses were delivered with an inter-pulse time interval of ∼8–10 s (see the Procedure section, below). This procedure allowed us to **be certain** that TMS effects were **not** due **having induced** any plasticity **from** repeated stimulation (Chen et al., 1998).

Procedure

Before starting the experiment, participants underwent a baseline session in which 15 MEPs were collected. During this session, TMS pulses were delivered at a random inter-trial ranging from 8–10 s for a total of ∼2.5 min, and participants were kindly instructed to keep their eyes open and to passively look in front of them. Following the baseline pre-session, participants were presented with the room images on the computer monitor. The experiment consisted of 96 trials: 32 in which an ordered room was depicted, 32 **in which a** disordered version of the same room **was depicted,** and 32 consisting of a scrambled version of the ordered room. The scrambled images served as a baseline **control** within the experimental session and allowed us to monitor any possible changes in CSE over the experimental session.

Each trial began with a gray screen for 1250 ms followed by a fixation cross that lasted 500 ms, then a room's image (or a scrambled image, in the 32 baseline trials) was presented for 350 ms at the center of the screen (see Figure 1). The trial ended with an inter-trial gray screen that lasted for a random time ranging from 5–6 s. Participants were instructed to look at and to pay attention to the images without providing any response; because, later in the session, they would be asked some questions about them. TMS pulses were delivered at 320 ms after image onset, which is consistent with the previously stated evidence that identified an event-related difference between the disorder and order conditions in the N2 component peaking within the 240–350-ms interval (Li et al., 2019). Ordered, disordered, and scrambled versions of the images were presented in random order. After every 32 trials, **participants received** a short break of 2–3 min. The experimental block lasted 20–25 min, including breaks**, after which** participants underwent a second baseline post-session, in which **we collected** 15 MEPs as in the baseline pre-session.
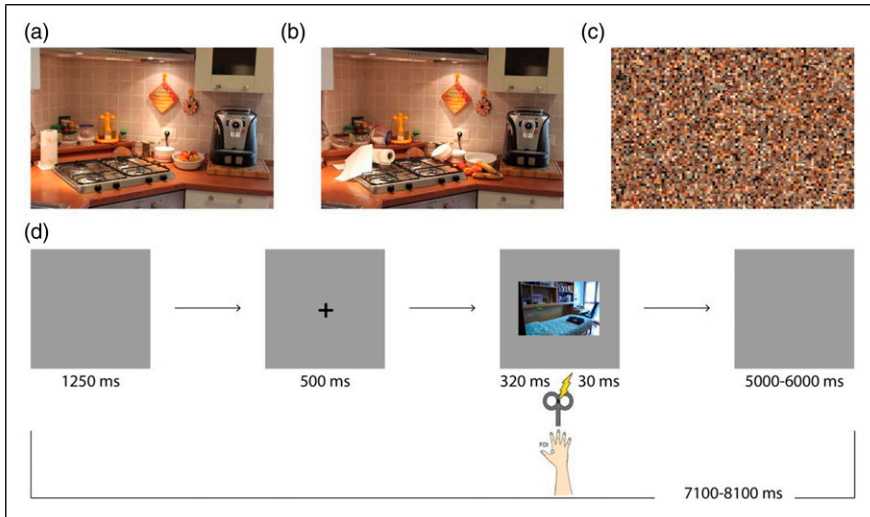
Figure 1. Visual Stimuli and Trial Timeline. A, B, C Example Room. (A) Ordered, (B) Disordered, (C) Scrambled Version, and (D) Exact Timeline of a Single Trial.

After TMS, all participants **completed** the Italian version of the ~~Obsessive Compulsive Inventory~~—Revised (OCI-R; Foa et al., 2002; see Table 1; for the validated Italian version see Marchetti et al., 2010). The OCI-R is a self-rating scale, that is designed to assess the severity and type of symptoms **that might be experienced by persons** with OCD. It contains 18 items (each scored on a 5-point scale from 0 to 4) **within six** subscales (checking, washing, ordering, hoarding, obsessing, and neutralizing). The possible range of scores is from 0–72, and the recommended cut-off score **for likely OCD** is **at or above** 21 (Foa et al., 2002). **T**he OCI-R is primarily used as a screening tool, and **a follow-up** clinical evaluation is necessary to ascertain **a diagnosis of** OCD. The experiment was programmed using the software E-prime 2.0 (Psychology Software Tools, Pittsburgh, PA).

Statistical Analyses

Neurophysiological data were processed offline and MEP amplitudes were measured from peak to peak (mV). Before proceeding with the statistical analyses, we discarded all trials with EMG background activity > 2 SD from the mean rectified signal across the 100 ms prior to TMS pulses. Moreover, in each condition, MEPs with amplitudes deviating from the mean by more than 2.5 SD were removed, resulting into the removal of 6% of the overall collected MEPs. To check if any changes in CSE occurred as a consequence of the prolonged stimulation over time, **we conducted** a preliminary pairwise t-test to compare the MEP amplitudes collected across the two baseline blocks (pre- and post-session). Th**is** comparison showed no differences $t(21) = .383$, $p = .706$

Table 1. Exemplary Items for Each Subscale of the Obsessive-Compulsive Inventory—Revised.

	Obsessive-compulsive inventory—Revised
Subscale	Exemplary item
Hoarding	I have saved up so many things that they get in the way
Checking	I check things more often than necessary
Ordering	I get upset if objects are not arranged properly
Mental Neutralizing	I feel that there are good and bad numbers
Washing	I sometimes have to wash or clean myself simply because I feel contaminated
Obsessing	I find it difficult to control my own thoughts

(mean MEP amplitude in the baseline-pre = .893 mV, SD = ± 0.33 mV; mean MEP amplitude in the baseline-post: .933 mV, SD = ± 0.46 mV), suggesting that TMS *per se* did not change CSE over time. After this preliminary analysis and for each participant, **we normalized the recorded** MEP amplitudes during room presentation **by dividing them** by the baseline MEP amplitude recorded during the presentation of scrambled versions of the images. We then performed a paired *t*-test on **the** normalized MEP amplitudes to compare changes in CSE associated with the view of ordered versus disordered rooms. Further**, we ran** one sample *t*-tests to explore the modulation that occurred in normalized MEP amplitudes collected during the exposure to ordered o disordered rooms as compared to the baseline. Finally, we performed a correlation analysis between MEPs modulation during the experiment and scores obtained in the OCI-R**; this permitted us** to examine **any** possible relationship between modulation of MEP amplitudes in response to ordered/disordered images and individual obsessive-compulsive traits.

Results

The mean or normalized MEP amplitude**s** wa**s** 1.08 (SD = 0.29) for the ordered condition and 0.91 (SD = 0.21) for the disordered condition. The paired *t*-test between normalized MEP amplitudes (MEPs order/MEPs scrambled vs. MEPs disorder/MEPs scrambled) showed a significant difference, $t(21)$ = 2.768, p = .012, Cohen's d = .59 (see Figure 2). One sample t-tests (scrambled images **as baseline**) showed that presentation of disordered room significantly reduced MEP amplitudes, $t(21)$ = −2.104, p = .048, Cohen's d = .45, while exposure to ordered rooms did not significantly modulate MEP amplitudes, $t(21)$ = 1.271, p = .218, compared to baseline.

Mean OCI-R scores were 18.23 (SD = 9.9), with **six** participants presenting scores higher **than** the 21 cut-off **for likely OCD** (but not **a diagnosis of OCD that would have required** clinical evaluation **to confirm**). Individual differences in the total OCI-R score were negatively associated with individual rMT (r = −.442, p = .04) (see
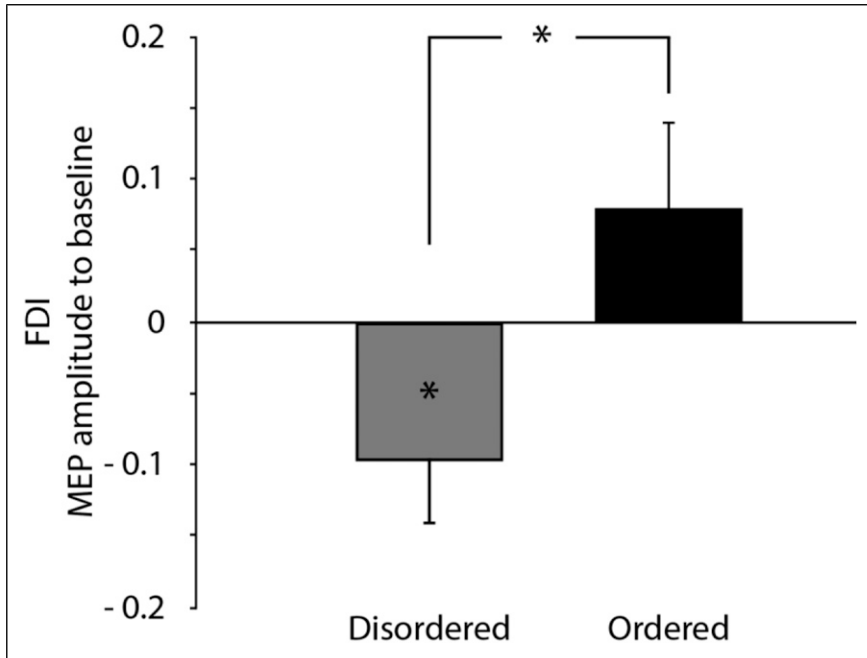
Figure 2. MEP **A**mplitude **M**odulation as a **F**unction of **D**isordered versus **O**rdered **R**ooms'. *Note*: MEP amplitudes are represented with respect to their baseline value of excitability (normalized MEP-1) recorded during the observation of the scrambled images of the rooms. Viewing images of disordered rooms significantly reduced MEP amplitudes, as compared to viewing **images** of ordered rooms and as compared to the baseline. Vertical bars represent standard error of the means. Asterisks indicate significant differences between conditions.

Figure 3A). The total OCI-R score was negatively correlated with the modulation of CSE during the **participant's** exposure to images of disordered rooms ($r = -.517$, $p = .014$) (see Figure 3B). In contrast, the correlation between the total OCI-R **score** and the modulation of CSE while viewing ordered rooms was not significant ($r = 342$, $p = .119$).

Discussion

In the current study, **to explore motor excitability during the perception of disordered and ordered environments, we presented photographs of orderly and disorderly rooms, by stimulating the left M1 with** single-pulse TMS. Given a **natural tendency for** individuals to **seek to** automatically restore order (Harmon-Jones & Harmon-Jones, 2002), **prior reports of** frontal and posterior differences in negative ERP components during the viewing of disorderly environments (Li et al., 2019), and **prior reports of** the suppression of CSE within action preparation (Bundt et al., 2019), we expected to observe a reduction of CSE in individuals viewing images of disordered
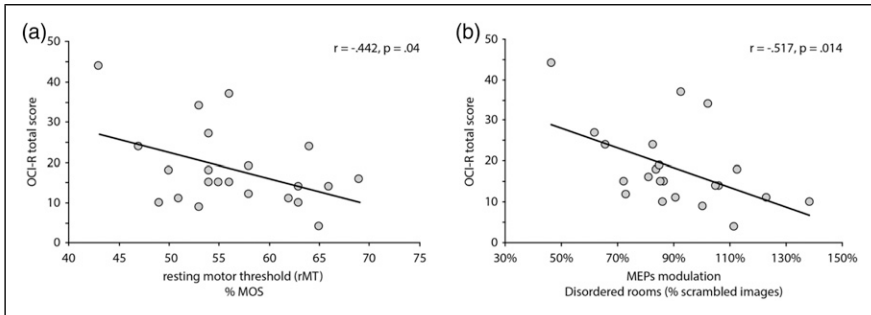
Figure 3. Scatterplots Showing the Relationships Between the Individual's Total **OCI-R** score and **(A)** Inter-Individual Differences in Resting Motor Excitability and **(B)** Inter-Individual Differences in Mean MEP Amplitudes Modulation During Exposure to Disordered Room Images. *Note:* In both Panels 3(A) and 3(B), the *y*-axis displays the individual's total **OCI-R** score; in Panel 3(A) the *x*-axis reports **resting motor threshold (rMT; %MOS), while in Panel B, the x axis reports** individual MEPs modulation (% of scrambled images, i.e., MEPs disordered room images/MEPs scrambled images).

rooms. **Our data support this hypothesis.** When compared to baseline, we found **suppressed excitability within the corticospinal tract (indicated by a reduced MEP amplitude) when participants viewed images of** disorderly environments; no changes emerged when **participants viewed** orderly **environments**. Thus, CSE **reduction** may reflect top-down effects on motor preparation within the M1 (Bestmann & Duque, 2016; Bundt et al., 2019) when deciding on a sufficient action to restore a disorderly environment to order. Moreover, **consistent with our expectation of** an association between an individual's CSE while viewing a disordered room and **her/his** OCD traits as assessed by the OCI questionnaire (Foa et al., 2002)**, we found** the modulation in CSE excitability, as measured by MEP amplitude from peak to peak, **while** viewing disorderly rooms compared to baseline negatively correlate**d** with the OCI-R total score**. A** higher OCD tendency was associated with a lower mean MEP amplitude in response to disordered rooms. Moreover, we also showed a negative relation between the OCI-R total score and the rMT, indicating that **higher tendencies toward ~~controlling~~ OCD** traits **related to** lower rMT.

As our findings are in line with prior evidence showing inhibition of CSE during the period preceding a movement, **there is support in these data for** an inhibitory effect of motor preparation commonly deemed *preparatory suppression* (Duque & Ivry, 2009; Duque et al., 2017; Greenhouse et al., 2015; Klein et al., 2016; Vassiliadis et al., 2020). This **CSE** inhibition during action preparation precedes the gradual increase in the MEP amplitudes recorded from the agonist muscle (e.g., 100 ms; Chen et al., 1998; Leocani et al., 2000). In particular, Duque & Ivry (2009) showed that TMS delivered 400 ms after the presentation of an informative cue evoked a suppression of CSE. This inhibition was generalized **to** both hand muscles, because, at this early decisional processing stage, either the left or right hand may be selected for the forthcoming

response. Duque & Ivry (2009) suggested that the inhibition might be functional to impulse control, which prevents premature and inappropriate movement activity during motor preparation. On the other hand, facilitation occurring immediately before the action onset at the selected hand is thought to reflect the excitation of the corresponding motor representation in the M1 through a joint modulation of facilitatory and inhibitory influences (Reynolds & Ashby, 1999). **The** exact level at which CSE suppression occurs is still unknown, and MEPs can disclose physiological processes that occur outside the M1, serving as a read-out of upstream processes not necessarily related to movement production (Bestmann & Krakauer, 2015). Some hypothesize that CSE suppression may reflect the recruitment of direct or indirect cortico-cortical **pathways** (Arai et al., 2012; Davare et al., 2009; Fiori et al., 2016, 2017; Koch et al., 2009), cortico-subcortical **pathways** (Gerloff et al., 1998; Neubert et al., 2010), or cortico-spinal **pathways** (Dum & Strick, 1991; Tokuno & Nambu, 2000). Thus, **while** it is likely that the CSE suppression we recorded is the result of an "impulse control" process synchronizing all components of the corticospinal tract, we cannot exclude the possibility that CSE suppression might be due to an increase in the intra-cortical inhibitory activity within the M1 (Kujirai et al., 1993).

Considering our OCI-R findings, we reasoned that the tendency to reinstate an orderly environment might be **part of a general** tendency to **purposefully seek** order. Thus, individuals with higher obsessive-compulsive traits and, consequently, a stronger **than normal** drive to restore order may demonstrate a stronger preparatory suppression in response to a disorderly environment. Accordingly, the negative correlation **we** found between CSE modulation **when viewing** the disorder**ed room** and the **participants'** OCI-R total score**s supports the idea that** higher obsessive-compulsive traits are associated with greater CSE suppress**ion** due to the inhibitory effect of motor preparation (Duque et al., 2017; Duque & Ivry, 2009; Greenhouse et al., 2015; Klein et al., 2016). This finding is **consistent** with previous studies showing **relationships between clinically diagnosed** OCD **and both** deficits in inhibitory control or impaired planning capacity (Dayan et al., 2014; van den Heuvel et al., 2005) and an enhanced reaction to external stimuli (Dayan et al., 2014; Hajcak & Simons, 2002). Moreover, the negative relations between the OCI-R total score and CSE**,** as assessed **by** the resting motor threshold, is consistent with past research showing a reduced resting (and active) motor threshold **in persons with** OCD versus **persons without OCD** (Greenberg et al., 2000; Khedr et al., 2016; Radhu et al., 2013).

Limitations and Directions for Further Research

Although our results support prior **investigations** exploring preparatory suppression, a direct comparison **of this study** to **past** studies **of** action preparation is difficult **because our predominantly female** participants viewed images passive**ly in a** relaxing setting without **motor output** instruc**tions. This restricted sample means that** further investigation**s of** sex differences (see Cattaneo et al., 2006; **and** other individual differences, such as age) **will** be **needed. Also of note,** although **most participants in our**

sample showed subclinical levels of OCD; approximately 27% of our sample scored above the **OCI-R scale** cut-off point (Foa et al., 2002). **O**ur results **should** be replicated within a clinical population **of participants diagnosed** with OCD.

Conclusion

Here we provide the first evidence that a disorderly environment moves the motor system**, seemingly** to restore a more predictable environment, grounding the abstract notion of "order" in the sensorimotor system (Costa et al., 2013). **In this article, we discuss relevant theory and past research to support this interpretation of our data; and, in our method and results, we detail a reliance on MEPs recordings and the assessment of OCD personality traits in the context of viewing ordered and disordered rooms to reveal our participants' natural associations (exacerbated by OCD traits) between a human preference for order/predictability and sensorimotor processing.**

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Supplemental Material

Supplemental material for this article is available online.

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