Controlling the self: The role of the dorsal frontomedian cortex in intentional inhibition

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ABSTRACT

Intentional inhibition refers to the suppression of ongoing behavior on the basis of internally-generated decisions. This ability to cancel planned actions at the last moment is thought to be critical for self-control and has been related to activation in a circumscribed region of the dorsal frontomedian cortex (dFMC). Preliminary theories of intentional inhibition were based on studies that exclusively examined the cancellation of motor responses, and consequently concluded that this region serves the suppression of motor output. Yet recent evidence suggests that the dFMC is also involved in inhibitory control over more abstract internal states such as emotions or desires that have no immediate behavioral output. In this review, we therefore wish to put forth a new integrative perspective on the role of the dFMC in human self-control. We will argue that by virtue of its anatomical location and functional connections, this area may subserve the disengagement from current urges and impulses, thus facilitating successful exertions of self-control across a wide range of contexts by overcoming a self-focused perspective. We will discuss the fit of this view of the dFMC with the existing literature, identify critical experimental determinants for engaging the dFMC in intentional inhibition, and outline promising perspectives for future research.

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1. Introduction

The ability to withhold behavioral impulses in favor of higher-order goals is central to human self-regulatory behavior (Baumeister, Vohs, and Tice, 2007). To date, this ability has been investigated in two distinct research domains, namely cognitive and social psychology. In cognitive psychology, research on inhibitory control typically employs experimental paradigms that require participants to withhold simple key presses in response to pre-instructed stop or nogo signals (henceforth referred to as externally guided inhibition, Chikazoe, Konishi, Asari, Jimura, & Miyashita, 2007; Logan & Cowan, 1984; Verbruggen & Logan, 2008, 2009). While this research has the advantage of providing maximal experimental control, the transfer to inhibition and self-control in everyday life is limited. In particular, most situations that require self-control do not provide external signals that indicate whether or not to withhold a specific behavior. By contrast, social psychological research on self-control has investigated behavioral inhibition under more complex and ecologically valid circumstances (see Hagger et al., 2010 for a review). Because of the complex experimental settings that are used, however, it is often very difficult to determine the exact neurocognitive mechanisms that are involved in these forms of self-control. Recently, the theoretical concept of *intentional inhibition* has been introduced to combine elements of both research traditions (Brass & Haggard, 2007; Brass & Haggard, 2008; Filevich, Kühn, & Haggard, 2012). Intentional inhibition refers to the voluntary and internal decision to withhold from executing a prepotent action tendency. In this sense, the concept of intentional inhibition is much closer to social psychological conceptions of self-control.

In the current review, we will first give an overview of research in the domain of intentional inhibition. We will argue that the concept strongly relies on the assumption that intentional inhibition can be distinguished from externally guided inhibition on the basis of its functional neuroanatomy. In particular, intentional inhibition has been related to a specific part of the medial prefrontal cortex, namely the dorsal frontomedian cortex (dFMC), although the precise functional contribution of this region remains elusive. Therefore we will try to explore the role of the dFMC in the broader context of self-control. Thereafter we will argue, based on the location of this area at the intersection of brain areas involved in cognitive motor control and those involved in more complex self-reflective and social cognitive processes, that it contributes to self-control by facilitating disengagement from impulses and urges[1]. On the basis of this new

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[1] We use the term 'impulse' to denote particularly sudden or spontaneous response tendencies, whereas 'urge' refers to a subjective motivation that develops over time.

conception, we will outline crucial experimental determinants for investigating intentional inhibition and sketch future perspectives in this research domain.

2. Previous findings: what do we know about intentional inhibition?

The concept of intentional inhibition is relatively young and only dates back a few years. As outlined above, it evolved as an extension of classical inhibition research in cognitive psychology, which focused primarily on externally guided inhibition. Following the logic of intentional action research, in which intentional action is usually contrasted with stimulus-guided action (e.g., Passingham, Toni, & Rushworth, 2000; Toni, Rushworth, & Passingham, 2001), early paradigms tried to introduce a choice component preceding the inhibition process. From this perspective, intentional inhibition, like intentional action, is internally generated. Yet because intentional inhibition paradigms do not present a stop signal, it becomes difficult to derive chronometric measures such as stop signal reaction times (SSRTs). Thus, the only behavioral dependent measure that can be used is the proportion of inhibition trials (e.g. Brass & Haggard, 2007; Lynn, Van Dessel, & Brass, 2013; Rigoni, Kühn, Gaudino, Sartori, & Brass, 2012). Brain imaging techniques such as fMRI therefore provide valuable tools that permit the delineation of neural activity preceding intentional decisions to inhibit behavior.

In the first study to introduce the concept of intentional inhibition, Brass and Haggard (2007) employed a modified version of the method introduced by Libet, Gleason, Wright, and Pearl (1983), which required participants to perform self-paced button presses (i.e., action trials) and to monitor the moment in time when they felt the intention to execute the movement. In addition, participants were instructed to occasionally prepare such movements but cancel them at the very last moment prior to execution (i.e., inhibition trials). Contrasting brain activity on inhibition trials with action trials yielded increased activation in the dFMC, as well as in the left and right anterior insula, and the superior temporal sulcus. This neural signature was in striking contrast to findings resulting from externally guided response inhibition, which typically engages a neural network around the right inferior frontal gyrus, the pre-supplementary motor area (pre-SMA), and the basal ganglia (rIFG; see Aron, Robbins, & Poldrack, 2004; Aron, Robbins, & Poldrack, 2014 for reviews), implying that these two types of behavioral inhibition rely on largely different control mechanisms.

Importantly, a number of follow-up studies that employed quite disparate experimental procedures could replicate the involvement of the dFMC in intentional inhibition. For instance, Kühn, Haggard, and Brass (2009) introduced the so-called "ramp task" in which participants saw the image of a marble moving downwards on a ramp and breaking into pieces when it reached the end of the ramp. Participants could freely choose between preventing the marble from breaking via a button press, and inhibiting their urge to do so. Importantly, the shattering of the marble was associated with an aversive glass-breaking sound and a monetary loss in order to create an incentive of responses over response omissions, which ties intentional inhibition more closely to realistic scenarios of self-control in which highly prepotent behavior needs to be suppressed. As in the study by Brass and Haggard (2007), inhibition-related brain activity was found in the dFMC, leading to the idea that the dFMC constitutes a "veto area" that generates endogenous top-down signals in the service of the intentional cancellation of behavior. However, this interpretation of the dFMC as being involved in intentional inhibition rests on the assumption that activity in this brain area precedes the inhibition process. Given that the temporal resolution of fMRI is rather poor, this assumption requires independent proof. A recent EEG study addressed this question (Walsh, Kühn, Brass, Wenke, & Haggard, 2010) using a variant of the Libet task similar to Brass and Haggard (2007).

Frequency analyses of brain oscillations shortly after the experience of an intention to move revealed an increase in spectral power over frontal electrodes that was specific for trials in which the movement was then inhibited, highlighting that the neural signature of intentional inhibition has a plausible time course during motor preparation.

3. The role of the dFMC in intentional inhibition

Despite this converging evidence for the general importance of the dFMC in intentional inhibition, it is still largely unknown *how* this area exerts control over behavioral impulses. Recently, Filevich et al. (2012) embedded the concept of intentional inhibition in a more general model of motor control, based on internal feedback loops. This model includes an inner loop that continuously adjusts movement parameters based on a comparison between predicted and perceived sensory feedback, and an outer loop that monitors the long-term consequences of ongoing actions and compares them with general goals. Intentional inhibition is conceived as a braking mechanism that links both loops by canceling ongoing behavior when the anticipated outcome seems no longer desirable. In line with this idea, the dFMC has been shown to exhibit increased functional connectivity with the pre-SMA during intentional inhibition (Kühn et al., 2009; Kühn, Haggard, & Brass, 2013). This finding is of particular interest, given that the pre-SMA is involved in action planning (e.g., Cunnington, Windischberger, Deecke, & Moser, 2002; Cunnington, Windischberger, Deecke, & Moser, 2003) as well as in externally guided response inhibition (e.g., Simmonds et al., 2008). Accordingly, the pre-SMA may constitute a common pathway for the implementation of different types of motor decisions, with the dFMC directing the outcome of this decision.

Additional research has concurrently shown that the dFMC is not only involved in the inhibition of overt behavior, but also in the suppression of other psychological states such as emotions (Kühn, Gallinat, & Brass, 2011; Kühn et al., 2013), cigarette cravings (Brody et al., 2007; Hanlon et al., 2013; Hartwell et al., 2011), or gambling desires (Campbell-Meiklejohn, Woolrich, Passingham, & Rogers, 2008). While these findings strengthen the general notion that the dFMC is a brain region crucial for the successful exertion of self-control, they also indicate that the functional contribution of this region might be more general than previously assumed, and extend beyond the suppression of motor output.

In the following, we will put forth a broader perspective of the role of the dFMC in self-control, arguing that this area allows for disengagement from one's current impulses and urges. We will first review the social psychological literature in order to highlight that such disengagement strategies are an effective functional mechanism for exerting self-control. Thereafter we will outline that the dFMC is well situated to perform this self-regulatory function because of its anatomical location and functional connections. Finally, we will illustrate that this new conception of intentional inhibition is capable of explaining seemingly inconsistent findings in the literature, and helps to further bridge the gap between cognitive and social psychological conceptions of inhibition.

4. Disengagement as a functional mechanism for self-control

Evidence for the role of disengagement in self-control dates back to the famous delay-of-gratification experiments (e.g., Mischel, 1974) in which preschoolers were able to choose between a smaller but immediately available reward, and a larger reward with a temporal delay. Successful delay strategies on the part of the children included

self-distraction or redirection of attention (e.g., hiding their faces) and altering the way they mentally represented the desired object (i.e., reappraisal or reframing; see Mischel et al., 2011 for a recent review). Interestingly, such distancing strategies do not appear to be used exclusively by children, but persist into adulthood. For example, while engaged in a smoking cessation program, smokers tend to initially psychologically distance themselves from their archetype of the typical smoker, until such time as they have successfully broken their habit (Gibbons, Gerrard, Lando, & McGovern, 1991). Likewise, in the realm of emotion suppression, it is well known that people employ specific reappraisal strategies, most notably distancing, when attempting to decrease their emotional response to stimuli (e.g., Gross, 1998; 1999). Indeed, participants in several emotion suppression studies were specifically trained and instructed to maintain an objective viewpoint by detaching themselves from the emotional target stimulus during inhibition trials (Kühn et al., 2013; Lévesque et al., 2003; Ochsner et al., 2004).

Conversely, when the capacity for self-control is impaired, as in the case of ego depletion (Baumeister, Bratslavsky, Muraven, & Tice, 1998), people tend to adopt a self-focused, first-person perspective. In the case of Achtziger, Alós-Ferrer, and Wagner (2011), ego depleted participants engaged in an Ultimatum game employed maladaptive and self-centered strategies in which they not only proposed lower amounts for their partner, but rejected low offers themselves, accepting instead zero financial reward for both players, rather than attending to an absolute monetary calculation or value. Similarly, Macrae et al. (2014) found that self-regulatory failures were exacerbated both when adopting a first- versus third-person perspective, and when adopting a near versus far distal perspective (under both temporal and physical conditions).

Altogether, these findings indicate that disengagement from one's current urges and impulses is an effective means of boosting one's regulatory abilities. This idea is furthermore in line with recent theoretical work on self-control by Fujita (2011), who describes it as "the general process by which people advance abstract, distal over concrete, proximal motives in judgment, decisions, and behavior." Accordingly, to successfully self-regulate, one must achieve a measure of mental remove from their present circumstances.

5. The dFMC is well situated to support disengagement from urges

Having illustrated that distancing is an adaptive self-regulatory strategy, this section will describe why the dFMC is a brain region particularly well situated to perform this function. The past two decades of brain imaging research have yielded a general consensus that endogenous control processes rely most critically upon the integrity of the medial frontal cortex (MFC; see Amodio & Frith, 2006; Passingham, Bengtsson, & Lau, 2010; Rushworth, Walton, Kennerley, & Bannerman, 2004 for reviews). At the same time, the MFC does not constitute a functional unit, but rather consists of distinct sub-regions that serve dissociable functions (see Fig. 1). As such, the posterior parts of the MFC are clearly implicated in cognitive motor control (Krieghoff, Waszak, Prinz, & Brass, 2011; Nachev, Kennard, & Husain, 2008). Two regions have been of particular interest in this respect: the rostral cingulate zone (RCZ), a region extending dorsally and caudally from the anterior cingulate cortex (ACC), and the supplementary and pre-supplementary motor areas (SMA/pre-SMA). The RCZ has been identified in disparate lines of research and linked with both resolving conflicts between incompatible response tendencies (Botvinick, Cohen, & Carter, 2004; Lau, Rogers, Haggard, & Passingham, 2004; Lau, Rogers, & Passingham, 2006; Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004), and with the intentional selection of movements (Krieghoff,
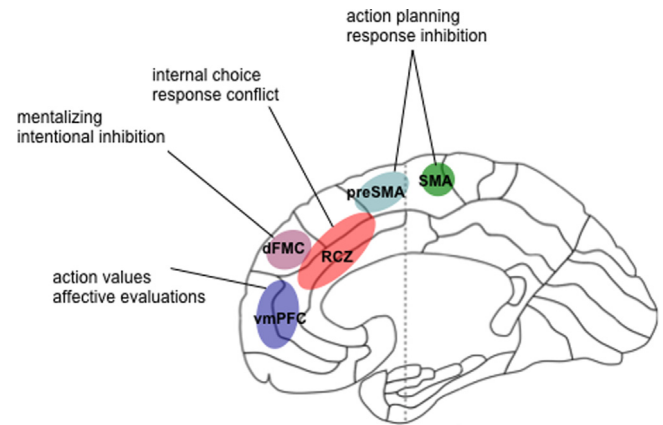

Fig. 1. Schematic overview of brain regions in the medial frontal wall, along with their assumed functions.

Brass, Prinz, & Waszak, 2009; Mueller, Brass, Waszak & Prinz, 2007; Walton, Devlin, & Rushworth, 2004) and tasks (Demanet, De Baene, Arrington, & Brass, 2013; Forstmann, Brass, Koch, & von Cramon, 2006). Brass and Haggard (2008) argued that the RCZ's sensitivity to both conflict and volition might reflect a common process of choosing between different response alternatives. This integrative perspective has recently been formalized in a computational model (Holroyd & Yeung, 2012). The SMA/pre-SMA is also critical for the planning and control of movements, yet its contribution seems to be more closely related to the implementation of motor decisions. On the one hand, this area has been linked to the planning and generation of self-initiated movements (Cunnington et al., 2002, 2003; Debaere, Wenderoth, Sunaert, Van Hecke, & Swinnen, 2003; Deiber, Honda, Ibañez, Sadato, & Hallett, 1999). In line with this, electrical stimulation of the pre-SMA can induce the sensation of an "urge to move" (Fried et al., 1991). At the same time, the SMA/pre-SMA is also critical for re-programming and inhibiting movements (Nachev et al., 2008; Neubert, Mars, Buch, Olivier, and Rushworth, 2010; Sumner et al., 2007). This is also illustrated by the so-called "anarchic hand syndrome" that can result from unilateral lesions to the pre-SMA. Patients with anarchic hand syndrome exhibit an inability to inhibit stimulus-induced action tendencies with the hand contralateral to the lesion, despite the phenomenological experience of having an intention to do so (Della Sala, Marchetti, & Spinnler, 1991; Kritikos, Breen, & Mattingley, 2005; Pacherie, 2007). Accordingly, the SMA/pre-SMA may be critical for adjusting the degree of action readiness (Cunnington, Windischberger, & Moser, 2005; Forstmann et al., 2008) that can yield facilitation or suppression of motor output, presumably via projections to the basal ganglia and the primary motor cortex (Picard & Strick, 2001). It is currently unclear to what extent the SMA/pre-SMA itself is the generator of top-down motor control, and to what extent it relies on input from other areas, such as the dFMC or the rIFG.

In contrast to these motor control functions of the posterior MFC, the anterior MFC is involved in higher-order self-referential, social-cognitive, and emotional processes. The anterior MFC is typically divided into a ventral part and a dorsal part (Amodio & Frith, 2006; Forbes & Grafman, 2010; Lieberman, 2007; Mitchell, Macrae, and Banaji, 2006; Van Overwalle, 2009). The ventral part has been associated with automatic affective evaluations and the computation of reward values in decision making (Bechara, Damasio, Damasio, & Lee, 1999; Bechara, 2005; Kolling, Behrens, Mars, & Rushworth, 2012; Mauss, Bunge, & Gross, 2007; Reuter et al., 2005; Van den Bos, McClure, Harris, Fiske, & Cohen, 2007). The dorsal part, on the other hand, has been linked with both mentalizing about other people's internal states (Frith & Frith, 2003; Gallagher & Frith, 2003; Gilbert et al., 2006; Zaki, Weber,
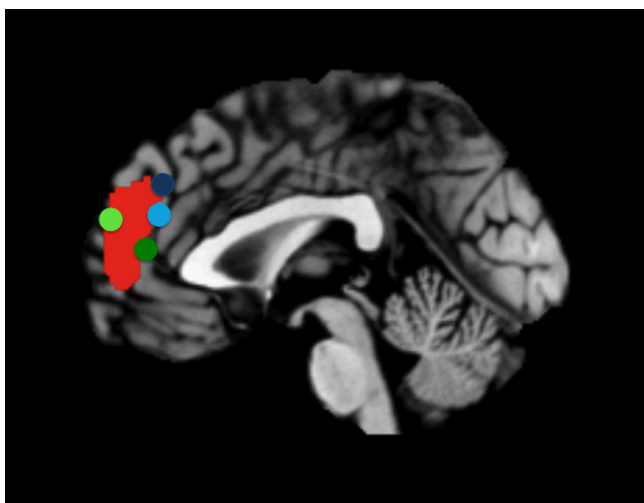
Bolger, & Ochsner, 2009) and active self-referential thought processes (Andrews-Hanna, Reidler, Sepulcre, Poulin, & Buckner, 2010; Whitfield-Gabrieli et al., 2011). This raises the question of how the very abstract role of the dFMC in social cognition can be reconciled with its role in intentional inhibition (see Fig. 2 for an illustration of the overlap). Although it is possible that different functions co-exist within the dFMC, we believe that intentional inhibition and mental state attribution share a common functional mechanism; both require disengagement from a strong self-perspective. In mental state attribution, overcoming the self-perspective is needed to attribute mental states to others that are inconsistent with one's own perspective. In intentional inhibition and self-control, overcoming the self-perspective is necessary for successfully disengaging from a strong impulse or urge to act.

Within the what-when-whether (WWW) model of intentional action (Brass & Haggard, 2008; Brass, Lynn, Demanet, & Rigoni, 2013), the dFMC would serve a regulatory function between areas that are involved in intentional choice (RCZ) and areas involved in the implementation of such choices (pre-SMA). The dFMC would enable the overcoming of a strong impulse or urge by down-regulating brain areas that are involved in the formation and implementation of such impulses, leading to a disengagement from the self-perspective. This is consistent with the functional connectivity data of the dFMC and pre-SMA outlined above. Furthermore, from this perspective, the frequent co-activation of the dFMC with the anterior insula in intentional inhibition (e.g., Brass & Haggard, 2007; Campbell-Meiklejohn et al., 2008; Lynn, Demanet, Krebs, Van Dessel, & Brass, 2014) might be re-evaluated. Thus far, the involvement of the insula has primarily been linked to a "feeling of let down" that may result from negative evaluations of not carrying out a response after preparing it (see Brass & Haggard, 2007). However, the prominent role of this region in awareness (see Craig, 2009 for a review) could also imply that the role of the insula in intentional inhibition is self-reflective in nature.

6. Critical determinants for engaging the dFMC

We will next revisit the existing literature on intentional inhibition and evaluate to what extent the disengagement account

is capable of explaining the data. Intentional inhibition has been applied to various contexts and experimental procedures, resulting in a heterogeneous pattern of findings with some studies replicating the involvement of the dFMC and others not. Based on the idea that this region supports the process of disengagement, we will first propose crucial determinants that experimental paradigms might need to satisfy in order to tap into this self-regulatory function. To elicit intentional disengagement it seems critical that the experimental setting meets three principle demands: First, participants must be operating under the circumstances of *choice*, and have to make an explicit decision to stop the behavior[2] Second, there must be enough *time* in which to form and implement this decision. Otherwise participants might decide to act or inhibit in advance of the trial (pre-decision) or, conversely, generally omit responding first and thereafter decide (post-decision). Finally, the decision to inhibit must be imposed in the context of a strong *urge or impulse* to act. Choice, temporal considerations, and urges may also interact; for example, the strength of a behavioral urge can modulate the impact of an internal choice, as in the case of holding one's breath. The body will permit oxygen starvation only up to a point, after which the urge to inhale will overcome all other response options. Similarly, choice can be implicitly biased via reward incentives. Below we will revisit existing literature on intentional inhibition and examine to what extent these paradigms have met the hypothesized determinants.

6.1. Paradigms that identified dFMC activity with intentional inhibition

So far, three studies that were explicitly designed to investigate intentional inhibition have revealed inhibition-related activity in the dFMC. As described above, the study by Brass and Haggard (2007) employed a variant of the Libet task, a paradigm that clearly provides both a free choice between acting and not acting, and sufficient time to make this decision. Importantly, participants were asked to monitor the moment in time when they felt the intention to press the button. This likely increased the self-reflective engagement in the task and discouraged participants from pre-deciding to act or inhibit in advance of the trial. The only caveat of this paradigm resides in the fact that the choice between acting and not acting is relatively arbitrary, since there is no genuine incentive for either option. Nevertheless, dFMC activity was found when contrasting omissions versus action trials, located in the medial frontal gyrus dorsal to the anterior cingulate.

The second intentional inhibition paradigm, the ramp-task, subsequently introduced by Kühn et al. (2009), sought to overcome the problem of arbitrary response options and created a prepotency of acting over inhibiting. This was achieved by linking actions to instrumental outcomes (i.e., the avoidance of the aversive marble breaking sound, and a trial-based monetary reward). In this sense, the ramp task was a clear step towards situating intentional inhibition in more realistic settings by inducing a strong impulse to act. Moreover, this paradigm provided a free choice between acting and inhibiting. Consistent with the aforementioned determinants, dFMC activity was found for intentional inhibition, located slightly more ventrally than in the study by Brass and Haggard (2007). However, this paradigm has a number of limitations compared to the Libet task; the timing of the decision to act or inhibit is linked to the external event of the marble beginning to move, and participants were not required

Fig. 2. Overlap of brain activation related to mentalizing and intentional inhibition. The red cluster represents the results of an activation-likelihood estimation meta-analysis of 38 theory of mind studies (including 47 peaks) taken from Amodio & Frith, 2006 and Gilbert et al., 2006. Peaks from four intentional inhibition studies are represented as dots. Dark blue=Brass & Haggard 2007; light blue=Kühn et al., 2009; light green=Kühn et al., 2013; dark green=Lynn et al., 2014. The former two studies were motoric in nature, while the latter two involved emotions and urges, respectively.

[2] Note that intentional inhibition requires choice, but in fact, the choice component is typically averaged out when contrasting intentional inhibition with intentional action. In this sense, choice is a pre-condition for intentional inhibition, but not a part of intentional inhibition itself, whereas disengagement is the process by which intentional inhibition is implemented.

to monitor their internal states (e.g., their intention/urge to press the button), thus making pre-decisions on the participants' part more likely. Finally, the paradigm introduced substantial time pressure on the decision to inhibit or to act. These aspects may explain why the original findings resulting from this task have proven somewhat difficult to replicate absent reward. Schel et al. (2014) compared the ramp task to a stop-signal task, and found dFMC activation in the former task not for intentional inhibition versus stimulus-driven action, as in the previous study, but in a parametric analysis of the number of preceding go trials. Here, stronger dFMC activity (at a location similar to that of Kühn et al., 2009), a higher proportion of inhibition trials, and slower RTs were observed for choice trials when there were fewer preceding go trials. One interpretation (supported by the reaction times in particular) could be that responding becomes more automated following long sequences of instructed trials, and the more demanding decisions arise when alternating rapidly between instructed and free-choice scenarios, or when trying to keep one's decisions random in an extended choice scenario.

Another context to which intentional inhibition has been applied is emotion regulation (Kühn et al., 2013). Highly arousing images with negative valence were presented for a duration of two seconds before a cue appeared that either instructed participants to inhibit their emotional response to these images by means of distancing (exogenous inhibit), to allow their feelings to unfold (exogenous feel), or to choose between one of the two options (endogenous inhibit, endogenous feel). Thus, in contrast with previous emotion regulation literature, this study provided a condition that allowed participants to engage in emotion regulation on the basis of free choice. Moreover, participants were asked to rate the intensity of the emotions that they felt on each trial, making pre-decision strategies rather unlikely. Accordingly, the dFMC activation, observed for endogenous, but not exogenous, emotion inhibition is consistent with our proposal. Here, the focus of activation was located more rostrally than in previous studies, clearly beyond the cingulate gyrus.

6.2. Studies that identified dFMC activity with externally guided inhibition

Interestingly, there are also a few studies that have found dFMC activation for externally guided inhibition. We presume that this is due to the fact that, although participants were cued to inhibit, the urge to act in these paradigms was so strong that even in the presence of a stop signal they had to explicitly decide to inhibit. The first study tried to introduce a more ecologically valid experimental setting by examining the suppression of an extremely strong behavioral urge, namely the avoidance of pain (Lynn et al., 2014). Here, participants received thermal pain stimulation to alternating inner wrists and could terminate the stimulation via button presses with the opposing hand. The benefit of this study was that the urge to inhibit built organically over time, and was present in each trial. In addition, participants were given sufficient time to make a decision on choice trials, with an equivalent proportion of choice and directed trials, discouraging them from pre-deciding. Accordingly, this paradigm could be expected to elicit a strong urge to act and to trigger disengagement in order to successfully inhibit the urge. Indeed, dFMC activation was observed when participants inhibited their pain avoidance response (peaking more ventrally in the amPFC but extending dorsally into the dFMC). However, in this study, equivalent dFMC activity was observed for both intentional and externally guided inhibition. This may reflect that the suppression of very strong urges relies on intentional disengagement regardless of how the decision to inhibit is initially determined.

This interpretation is bolstered by similar findings in the realm of addiction research, particularly regarding the suppression of cigarette cravings (Brody et al., 2007, Hanlon et al., 2013, Hartwell et al., 2011). In these studies, participants were instructed to apply different strategies when faced with craving-inducing stimuli, namely either to resist the craving via self-distraction or other strategies, or to permit the craving sensation to unfold. Although the response was entirely determined by the instruction, reliable activity was found in large clusters along the dFMC and the anterior cingulate when contrasting resist with permit conditions. Accordingly, when faced with extremely strong behavioral urges (particularly those involving self-preservation or physical needs), the difference between intentional and externally guided inhibition seems to be diminished because the demand to override prepotent response tendencies requires strong activation of the goal to inhibit. Instruction alone is insufficient to achieve that end, so internal resources must be recruited in order to comply with the experimental constraints.

6.3. Studies that did not identify dFMC activity with intentional inhibition

Finally, we would like to also mention two studies that did not identify inhibition-related dFMC activity, despite superficially appearing to involve similar demands. The first study was designed to mimic a stop signal paradigm but with a choice cue that left it open to participants whether to inhibit the response or not (Kühn & Brass, 2009). In 75% of trials, participants were instructed to press one of four keys in response to a stimulus in order to induce a very strong response tendency. When the color of the stimulus changed they either had to withhold the key press or to decide to press or inhibit depending on the color. When comparing trials where participants decided to inhibit (decide nogo) with trials where a stimulus indicated not to act (instructed nogo), massive activation in the RCZ was found, but no activation in dFMC. When comparing the decide nogo with the instructed nogo, no activation was found at all. SSRTs for instructed nogo and decide nogo were very similar, indicating that in a situation where the time pressure to decide between inhibiting and acting is very high, participants first inhibit the response and then decide whether or not to reinitiate the response. This later decision, however, does not require any disengagement from a strong impulse because the action had been inhibited beforehand. Therefore, no activation of the dFMC could in fact be expected.

Another study that tried to investigate intentional inhibition in a more ecologically-valid context examined the inhibition of taboo word utterances (Severens, Kühn, Hartsuiker, & Brass, 2012). Participants completed a word reading task with stimulus pairs that frequently elicit spoonerisms. For half of the word pairs, spoonerisms resulted in the utterance of socially inappropriate taboo words, and for the other half in neutral expressions. The authors contrasted taboo with neutral trials, under the assumption that taboo word pairs would elicit additional inhibition processes in order to avoid the utterance of socially inappropriate expressions. This contrast yielded activity in the right IFG, but not in the dFMC. Thus, although this paradigm did not entail any explicit external stop signals, the observed brain activity was very similar to studies investigating externally guided inhibition. This could be related to the fact that there was no real choice for participants in this study (both the explicit instruction to read word pairs and the implicit instruction to inhibit spoonerisms were constant across all trials). In addition, the speeded nature of the task did not leave any time for decision-making. Finally, it needs to be considered that in this case a social norm (not to utter socially undesirable expressions) might be internalized and act as a stop signal.

To summarize, it appears rather difficult to define a priori properties of tasks that can be used to predict dFMC activation in intentional inhibition, yet the criteria based on the disengagement account appear

to provide a stable means of navigating existing data. Paradigms that have been successful in revealing dFMC activation balance different characteristics. First, as outlined above, inhibition must be based on a decision to disengage from a strong impulse or urge. However, such a decision does not necessarily have to be an explicit requirement of the experimental paradigm but can also be induced by a very strong impulse to act. In situations where the urge to act is extremely strong, participants might be involved in a decision process even when they are explicitly told to inhibit and therefore formally do not have to decide. On the other hand, in situations where no explicit instruction to inhibit is given, inhibition might be nevertheless automatically induced by contextual information affording inhibition of the action (e.g. the inhibition of taboo words). Second, the timing of the inhibition process is crucial, with too much time pressure leading to 'offline' decisions to inhibit. However, if participants are not engaged in a specific behavior at the moment they decide to inhibit, no disengagement is required.

Given the above critical determinants of disengagement, and taking into account the varied paradigms employed thus far to investigate intentional inhibition, one may directly assess the intersection of self-control strategies and intentional inhibition by optimizing experimental designs to more closely test the disengagement hypothesis. It would also be useful to manipulate the disengagement strategy itself, by inducing a first- or third-person perspective prior to an intentional inhibition task that conforms to the above constraints. In this case, one might find that, in comparison to a first-person perspective, an objective stance promotes both behaviorally measured self-control, and dFMC activation.

7. Distinguishing intentional inhibition from proactive inhibition

Finally, we would like to distinguish the concept of intentional inhibition from the related concept of proactive inhibition. Recently, proactive inhibition has been introduced in an attempt to relate stop-signal response inhibition more closely to impulse control in realistic scenarios (see Aron, 2011 for a review). To this end, studies have examined how participants adjust their motor preparation when advance information is given about either the likelihood of a stop signal (e.g., by comparing blocks with and without stop signals) or its specificity (e.g., by comparing stop signals that apply to all vs. only certain possible responses). Accordingly, this setup allows for the investigation of how one "proactively" adjusts their response preparation for the possibility of a stop signal, rather than only focusing on the "reactive" implementation of inhibition in response to it. Preliminary evidence resulting from this procedure indicates that participants are able to use the advance information provided by the cues (i.e., their SSRTs on nogo trials is reduced and their RTs on go-trials is increased when they know a stop may occur), and these adjustments seem to rely on similar brain areas as the reactive implementation of inhibition (Chikazoe et al., 2009; Jahfari, Stinear, Claffey, Verbruggen, & Aron, 2010; Zandbelt, Bloemendaal, Neggers, Kahn, & Vink, 2013). This underscores the notion that the external inhibition network (i.e., the rIFG, the pre-SMA, and the basal ganglia) is not only activated bottom-up by the appearance of a stop signal, but also top-down on the basis of strategic adjustments.

However, although proactive inhibition can be considered as resulting from endogenous preparation processes, it still differs from the scope of intentional inhibition as outlined in this review. Most importantly, proactive inhibition is still concerned with stimulus-guided behavior in which the outcome (action or omission thereof) will be determined by external events, whereas intentional inhibition refers to the cancellation of behavior on the basis of free choice and internal states. In addition, proactive

inhibition influences primarily the readiness to perform or inhibit an action, whereas intentional inhibition operates on ongoing behavior. Nevertheless, it could be an interesting perspective for future research to examine how the brain networks involved in proactive and intentional inhibition may interact, especially under motivationally salient circumstances.

8. Conclusion

In this review, we have summarized previous literature on intentional inhibition, highlighting that this capacity has frequently been linked with the dFMC, though the precise role of this region has been elusive. We propose a disengagement hypothesis, whereby the dFMC contributes to self-control by separating a person from their immediate urges. This assumption is consistent with the location of the dFMC at the interface of motor control and social cognition. Furthermore, this hypothesis provides the means for an integrative account of intentional inhibition, moving beyond motor control and encompassing social psychological conceptions of self-regulation. Attending to the critical determinants of intentional inhibition would permit direct testing of this hypothesis, and likely inform future research on the core mechanisms underlying endogenous control of prepotent impulses.

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