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Encoding, preparation and implementation of novel complex verbal instructions

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ABSTRACT

Verbal instructions allow humans to acquire and implement complex novel rules in few seconds. A major question that remains elusive is how the brain represents this information prior to successful task execution. In this experiment, we studied the brain regions involved in representing categorical stimulus information during the encoding of novel instructions, their preparation and also their implementation, as well as the relation of the fidelity of these representations to observable behavior. To do so, we devised a novel instructions paradigm to delimitate these three stages. Using univariate and multivariate analyses of functional magnetic resonance data, our study revealed that the semantic content (faces or letters) of complex novel instructions can be decoded several seconds before the onset of a target, as soon as instructions are encoded. Crucially, the quality of the information represented in domain-general and category-selective regions correlated with subsequent behavioral performance. This suggests that the rapid transformation of novel instructions into coherent behavior is supported by control mechanisms that use available, relevant information about the current rule prior to its execution. In addition, our results highlight the relation between these control processes and others such as prospective memory and maintenance of future intentions.

Introduction

The ability to implement verbal instructions allows humans to translate novel complex rules into behavior in mere seconds. How does the brain deal with new information in such a fast and efficient way? According to theoretical models, the path from instructions to overt behavior can be decomposed in different stages of processing (Bunge, 2004; Sakai, 2008). Initially, the content of the instructions has to be *encoded* in the system, employing representations of semantic rules that link specific stimulus features to concrete behaviors (Crone et al., 2006; Sakai, 2008). Once the target context (stimuli) appears, instructions are *implemented* by performing the appropriate actions according to the instructed rules. But before that, *preparation* entails a task set configuration (Meiran, 1996; Rubinstein et al., 2001). This stage of processing, understood as the adjustment to relevant task rules in anticipation of target stimuli (Rogers and Monsell, 1995) is a key component of complex task execution (Brass and von Cramon, 2002), and it is thought to be a cognitive state separable from related ones, such as the mere maintenance of task demands (Cohen-Kdoshay and Meiran, 2009; Liefooghe et al., 2013, 2012; Muhle-Karbe et al., 2014). Crucially, the adequate configuration of cognitive resources achieved during the preparatory period enhances behavioral performance (Sakai, 2008).

Neuroimaging data suggest that task preparation relies on a frontoparietal network, which has been related to complex cognitive control operations (Duncan, 2010). More specifically, when switching between tasks the Inferior Frontal Junction (IFJ) updates the rule representation, whereas stimulus-response associations engage the intraparietal sulcus (IPS; Brass and von Cramon, 2004, 2002). De Baene and Brass (2014) proposed that the pre-supplementary motor area (pre-SMA) suppresses actions from previous tasks and enhances the appropriate response for the new stimulation. Previous studies also point to a dynamic interplay between the lateral prefrontal cortex (LPFC) and brain regions linked to category-specific processing (Sakai and Passingham, 2006, 2003). For instance, when participants prepare to perform semantic operations, task cues engage areas involved in effortful semantic processing, such as the left inferior frontal gyrus, prior to the target onset (e.g. González-García et al., 2016). Some other studies have also reported category-specific connectivity patterns in absence of changes in activity (Sakai, 2008). Although preparation

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seems to play even a more important role when we have to implement novel instructions (Norman and Shallice, 1986), the neural architecture supporting this ability remains unclear.

Novelty brings larger requirements of control processes given the lack of pre-existing task-rule representations (Cole et al., 2013). However, in most studies of task preparation and switching, participants alternate between a small number of highly practiced tasks, and thus task sets are formed in advance and later retrieved from memory (Cole et al., 2013). Preparatory processes, however, seem to fulfill somewhat different demands with new tasks. When we face a novel situation, retrieval of previous full task sets does not suffice. Rather, new ones have to be generated from scratch: representations (e.g. of visual cues) have to be created for each new trial, including sensory, semantic and goal-related ones. Recent research has coined the term of Rapid Instructed Task Learning (RITL) to refer to the "ability to rapidly restructure one's behavior into novel configurations from instructions" (Cole et al., 2013). To differentiate this type of learning from others, such as trial-and-error learning, most of the RITL research focuses on the first time a given task set is presented. This strategy uses several new instructions together with practiced ones, which allows the comparison between the retrieval of previously practiced sets and the actual formation of novel ones. Some studies (Cole et al., 2010; Ruge and Wolfensteller, 2010) have assessed the *implementation* of novel instructions, suggesting a novelty-related gradient within the LPFC in which there is an anterior-to-posterior shift of activation as task sets transition from novel to practiced. Regarding *preparation* for novel tasks, the frontoparietal network also seems to be involved. For instance, Hartstra et al. (2011) highlighted the involvement of IFJ and IPS during the presentation of single words that encoded instructions. They also revealed the involvement of the dorsal pre-motor and M1 areas, a result that they interpreted as a correlate of motor imagery and the creation of memory codes for the instructions. Using also isolated words, a later study extended these results, revealing that the inferior frontal sulcus underpins the representation of task sets by creating a link between the stimulus and the motor response (Hartstra et al., 2012). Despite this suggestive evidence, these studies did not explore how the semantic content of the instructions was represented during their encoding and preparation. This is a crucial aspect, since relevant information is needed to create an accurate task configuration prior to task execution, as shown in task-switching. However, it is still unknown how and where this relevant information is represented during preparatory stages to support the translation of novel verbal representations into implemented rules.

Studies assessing the representation of specific information during stages of processing suggest that multivariate rather than univariate analysis of functional magnetic resonance images (fMRI) is more suitable for this matter. For instance, using single words as instructions, Cole et al. (2011) showed that a classifier could generalize to novel tasks when trained on practiced tasks with DLPFC fMRI patterns. Likewise, a classification algorithm was able to decode task sets within this region while the instructions were on the screen. However, there is an implicit difficulty to decode relevant preparatory information in classic RITL paradigms. Since participants have to encode a new instruction on every trial, it is hard to disentangle the activity specific to preparatory processes from encoding of the new verbal content of the instructions (Brass and von Cramon, 2002; Rogers and Monsell, 1995).

We designed a paradigm to isolate preparation from instruction encoding and later implementation. For this, we pseudorandomly manipulated the duration of the interval between novel instructions and novel target grids, and had participants prepare the novel instructions in only half of the trials. Similar strategies have been used to isolate the preparation component associated to novel instructions (Demanet et al., 2016). In addition, we employed complex verbal instructions rather than drawings or isolated words as used in previous studies (Cohen-Kdoshay and Meiran, 2009; Liefooghe et al., 2013, 2012). Although instruction implementation can be achieved via non-linguistic channels, verbal information is the most powerful means to convey novel instructions (Cole et al., 2013). Previous strategies, such as presenting novel symbols or images linked to specific responses, promote concrete stimulus-response pairings and visual imagery, which reduce the scope of the observations. Also, the instructions employed in the current study contained abstract rules, which entail less concrete commands than specific instructions (e.g. "If you see two squares, press A") and a larger number of potential perception-action scenarios (e.g. "If you see two vowels, press A"). Our verbal instructions posed yet another form of complexity as they allowed the combination of multiple rules (e.g. "If you see two contiguous green vowels of the same size, press A"), which is not easily achievable through non-linguistic instructions or single words.

In addition, our experiment employed a task designed to alleviate frequent confounds of task novelty and difficulty. As mentioned before, previous studies employ instructions practiced in advance as a contrast to novel ones (Cole et al., 2016, 2011; Stocco et al., 2012). However, this translates into practiced tasks that are easier to implement, since the mere presentation of the instruction elicits the adequate response, retrieved from memory, which leads to faster responses and higher accuracy scores. In our study, in contrast, every trial started with a *novel* complex verbal instruction. A subsequent cue indicated whether a novel or a practiced target grid would appear and prompted participants either to prepare to implement the previous instruction or to retrieve a response from memory upon later target presentation (see Section Design and procedure). This manipulation balanced demands across tasks and equated performance indexes across novel and practiced sets. Also, a secondary benefit was the increase in the number of novel instructions, which increased the power of the design to differentiate the encoding of instructions referring to different stimulus categories.

In sum, the main aim in our study was to advance our knowledge about how the brain uses new complex information to perform novel tasks. To do so, we used complex, fully grammatical verbal instructions referring to either faces or letters to assess which areas contained category-specific information during the encoding, preparation and implementation of novel rules. We predicted that partially differentiated patterns of regions would be involved in encoding vs. preparing for a new instruction, and that these would include areas related to cognitive control. Similarly, we expected that the semantic content of instructions would be decodable since their encoding, but that more regions would get involved when participant had to explicitly prepare, reflecting a finer tuning to relevant task information. In addition, we hypothesized that the degree of decodability of activity patterns of different categories would have a relation with observable performance, which would stress the relevance of these representations for actual behavior.

Materials and methods

Participants

Twenty-two students from the University of Granada (7 males; mean age: 23; range: 19–31) took part in the experiment and received 20€ in exchange. To encourage high performance during the task, participants were informed that the five of them with the highest scores (in terms of accuracy and reaction times) would receive 5 additional €. All participants reported normal or corrected-to-normal vision and no history of neurological disorders, and signed a consent form approved by the local Ethics Committee.

Apparatus and stimuli

We created an initial pool of 210 different verbal instructions that referred to either face or letter-related features of grids of stimuli. Face