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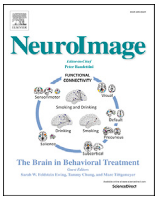

Response of the multiple-demand network during simple stimulus discriminations

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ABSTRACT

The multiple-demand (MD) network is sensitive to many aspects of task difficulty, including such factors as rule complexity, memory load, attentional switching and inhibition. Many accounts link MD activity to top-down task control, raising the question of response when performance is limited by the quality of sensory input, and indeed, some prior results suggest little effect of sensory manipulations. Here we examined judgments of motion direction, manipulating difficulty by either motion coherence or salience of irrelevant dots. We manipulated each difficulty type across six levels, from very easy to very hard, and additionally manipulated whether difficulty level was blocked, and thus known in advance, or randomized. Despite the very large manipulations employed, difficulty had little effect on MD activity, especially for the coherence manipulation. Contrasting with these small or absent effects, we observed the usual increase of MD activity with increased rule complexity. We suggest that, for simple sensory discriminations, it may be impossible to compensate for reduced stimulus information by increased top-down control.

Introduction

Diverse studies examining a range of cognitive demands have found of a set of frontal-parietal regions that are consistently involved in a variety of tasks, ranging from response inhibition to working memory to decision making (e.g., Duncan and Owen, 2000; Fedorenko et al., 2013; Niendam et al., 2012; Stiers et al., 2010). Included in this pattern are regions of the dorsolateral prefrontal cortex, extending along the inferior/middle frontal gyrus (IFG/MFG), and including a posterior-dorsal region close to the frontal eye field (pdLFC), parts of the anterior insular cortex (AI), pre-supplementary motor area and adjacent anterior cingulate cortex (pre-SMA/ACC), and intraparietal sulcus (IPS). Together they have been termed the multiple demand (MD) network (Duncan, 2010), cognitive control network (Niendam et al., 2012), or task positive network (Fox et al., 2005).

Activity in the MD network increases with increases in many kinds of task difficulty or demand, such as with additional subgoals (e.g., Farooqui et al., 2012), greater working memory demand (Manoachet al., 1997), resisting strong competitors (e.g., Baldauf and Desimone, 2014), task switching (e.g., Wager et al., 2004), or a wide range of other task demands (e.g., Crittenden and Duncan, 2014; Jovicich et al., 2001; Marois et al., 2004; Woolgar et al., 2015a). Increased activity in more difficult conditions can also be accompanied by stronger information coding, shown by multivoxel pattern analysis (e.g., Woolgar et al., 2015a; Woolgar et al., 2011; Woolgar et al., 2015b). Reflecting these widespread effects of demand, the MD network has been suggested to implement top-down attentional control, optimally focusing processing for the requirements of a current task (Miller and Cohen, 2001; Duncan, 2010; see also Norman and Shallice, 1980).

One simple way to manipulate task difficulty is through the quality of stimulus information. Some experiments have shown clear MD responses as stimulus discriminability decreases (e.g., Crittenden and Duncan 2014; Deary et al., 2004; Holcomb et al., 1998; Jiang and Kanwisher, 2003; Sunaert et al., 2000; Woolgar et al., 2011), but this has not always been the case (Cusack et al., 2010; Dubis et al., 2016; Han and Marois, 2013; Muller-Gass and Schroger, 2007). For example, Cusack et al. (2010) contrasted hard and easy trials of a task in which participants had to detect a barely perceptible ripple in an oscillating dot field and found no neural activation differences between the two sensory difficulty levels, despite substantial differences in behavioral performance, and robust BOLD contrast to a different task manipulation (attention switching).

In an important study, Han and Marois (2013) investigated activity in parts of the MD system during a task in which three letter targets were to

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be identified in a rapid stream of digit nontargets. In the baseline condition, the three letters occurred in immediate succession; to increase demand, they either inserted a nontarget into the series of three targets, or reduced exposure duration. While activity in frontal-parietal areas increased with the addition of a distractor, exposure duration had little effect. To interpret their findings, Han and Marois (2013) appealed to the distinction made by Norman and Bobrow (1975), between data-limited and resource-limited behavior. Norman and Bobrow (1975) proposed that, for any task, some function (the performance-resource function or PRF) relates performance to investment of attentional resources. When this function is increasing, behavior is said to be resource-limited, and additional investment is repaid by improved performance. When the function asymptotes, further investment has no positive effect, and performance is said to be data-limited. In line with a link of MD activity to attentional investment, Han and Marois (2013) used these ideas of data- and resource-limitation to explain their findings. They proposed that, in their task, brief exposure duration created data limits, which could not be offset by increased fronto-parietal recruitment, while adding a distractor introduced resource limits by calling for increased attentional focus.

In general it is not known when performance will be resource- or data-limited, but within this general framework, many patterns of results are possible. Fig. 1A illustrates a case in which, as difficulty level varies, there is no reason to expect increased attentional allocation. In this case, PRFs asymptote at different performance levels for the different levels of task difficulty, but across difficulty levels, the asymptote occurs at the same level of allocated resource. Fig. 1B illustrates an opposite case, with increased task difficulty potentially offset by increased resource allocation. This uncertainty over the role of attentional investment in different cases of perceptual discrimination could help to explain disparate results in the literature, with some cases (e.g. Han and Marois, 2013, manipulation of exposure duration) more resembling Fig. 1A, and others (e.g. Han and Marois, 2013, distractor manipulation) more resembling Fig. 1B.

In our first experiment, we sought to strengthen the evidence that, for simple sensory discriminations, MD activity can be rather independent of task difficulty, providing an exception to the “multiple demand” pattern. For this purpose we used a motion discrimination task with two kinds of difficulty manipulation – motion coherence and salience of task-irrelevant dots. For the strongest possible effect, we manipulated both variables over a wide range, moving performance from close to ceiling to close to chance. In the task demand literature, several studies have shown that, as opposed to a monotonic increase of MD activity with task difficulty, there was an inverted U-shape response (Callicott et al., 1999; Linden et al., 2003), or a plateau after a certain difficulty level (Marois and Ivanoff, 2005; Todd and Marois, 2004; Mitchell and Cusack, 2008). A possible interpretation is that MD activity initially increases with task demands, but plateaus or even declines once the task becomes impossible even with maximal attention. In our study we examined MD activity over the full range of possible task difficulties.

In addition to manipulating both aspects of difficulty over a wide range, between participants we varied whether difficulty levels were mixed or blocked. In the mixed design, levels of difficulty were presented in random order, without advance cueing of the level to be experienced on a given trial. In contrast, difficulty level was known in advance in the blocked design. With this manipulation, we asked whether MD activity is driven more proactively, by expectancy of forthcoming demand, or more reactively, when high demand is experienced on a current trial.

Finally, in modeling our fMRI data, we attempted to remove effects of decision time, expected to increase with either sensory or selection difficulty. In two prior studies of motion coherence, trials were modelled simply as events, without regard for their duration (Kayser et al., 2010a, 2010b). In this case, greater brain activity associated with decreasing motion coherence may simply have reflected longer processing times. To diminish such effects, our fMRI model explicitly included decision time for each trial.

Though PRF shapes are generally unknown, our use of two different demand manipulations afforded the possibility of different outcomes. In particular, we expected that top-down control could be especially important in the irrelevant-dots condition, leading to larger effects of demand on MD activity. Though Experiment 1 showed results in line with this expectation, they occurred against a background of generally weak effects, and no significant difference between the two manipulations. In Experiment 2 we reexamined coherence and irrelevant-dots conditions in a new group of participants, and compared these sensory demands with a manipulation of rule complexity.

Methods

Experiment 1

Participants

Participants were randomly assigned to either the blocked or mixed group, with this variable manipulated between participants to minimize carryover effects. A total of 40 participants took part in the experiment. Twenty-one participants (9 male, 12 female, ages 19–31, mean = 25.7) took part in the blocked group, and nineteen participants (11 male, 9 female, ages 19–36, mean = 23.9) took part in the mixed group. Participants were recruited from the volunteer panel of the MRC Cognition and Brain Sciences Unit and paid to take part. An additional 16 participants were excluded (10 participants had excessive motion > 5 mm, and another 6 had poor performance with accuracies more than three median absolute deviations below the median in at least one condition). All participants were neurologically healthy, right-handed, with normal hearing and normal or corrected-to-normal vision. Procedures were

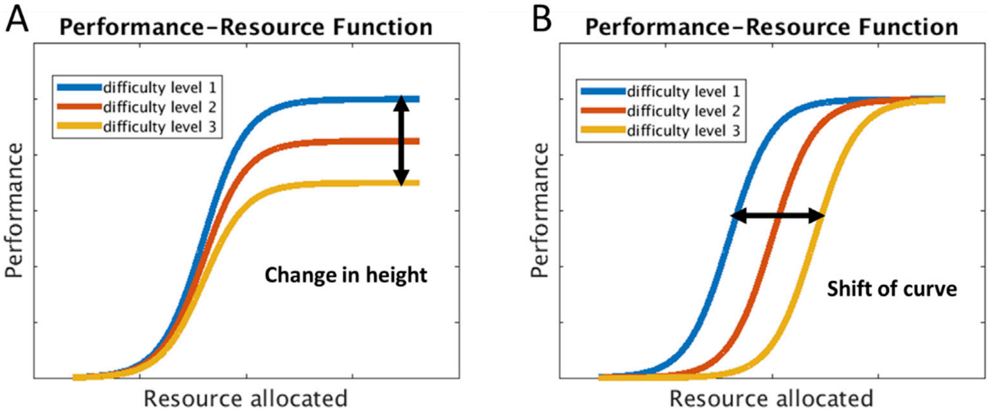

Fig. 1. Theoretical performance-resource function (PRF) plots. (A). Difficulty might change the asymptote of the PRF. Increased difficulty cannot be offset by increased resource allocation. (B). Difficulty might shift the PRF. Increased difficulty can be offset by increased resource allocation.