CGS698B: Topics in Cognitive Neuroscience
Research Proposal: Quantitative and Neural underpinnings of Mental Effort

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Summary of the Proposal

Mental Effort is one of the most intuitive fixtures of human cognition. Different tasks that we come across in our lives require different levels of mental exertion. Despite the idea of mental effort being immediately available if we are introspecting, it is a tough task to disassociate it from its subjective nature and pin it down as an object of objective study. This proposal shall aim to put to test the various models describing the allocation process of Mental Effort in more naturalistic settings and aim to identify the neural substrates involved more precisely by extending the study to animal models.

Background

Mental Effort is defined to be the mediator between the characteristics of the target task and the subject's available information-processing capacity; it also governs the task performance or the fidelity of the information processing operations performed. It refers to the processes which determine what level of performance will be realised and the quality of that performance.[Shenhav et al., 2017]

Mental Effort be manifested in a variety of forms:

- Overriding of default actions or habits
- Maintaining attention from beginning to end of the task
- Task switching between different tasks having different kinds of demand
- Working Memory maintenance
- Performing mental feats like reasoning

Mental Effort is important in various life outcomes like academic performance, social competence and professional choices. Many computational models have aimed to understand cognitive effort as a cost-reward optimisation problem, because mental effort is always taken to be aversive (costly) and discounts the reward of the task. Higher rewards, in any case, do lead to better performance.

Costs of Control

The costs of cognitive control of mental effort are of two types, intrinsic costs and opportunity costs. Intrinsic costs reflect the limit on how much effort can be exerted at a given time and duration of control-demanding process poses an opportunity cost. [Shenhav et al., 2017] As shown on Figure 1. there are three penitential sources of intrinsic costs give by:

- Resource-based accounts (green) propose that control costs reflect the limitations of a central metabolic resource that depletes in proportion to amount and duration of exertion
- Control capacity–based accounts (blue) propose that control costs reflect the limitations posed by limited storage and maintenance capacity

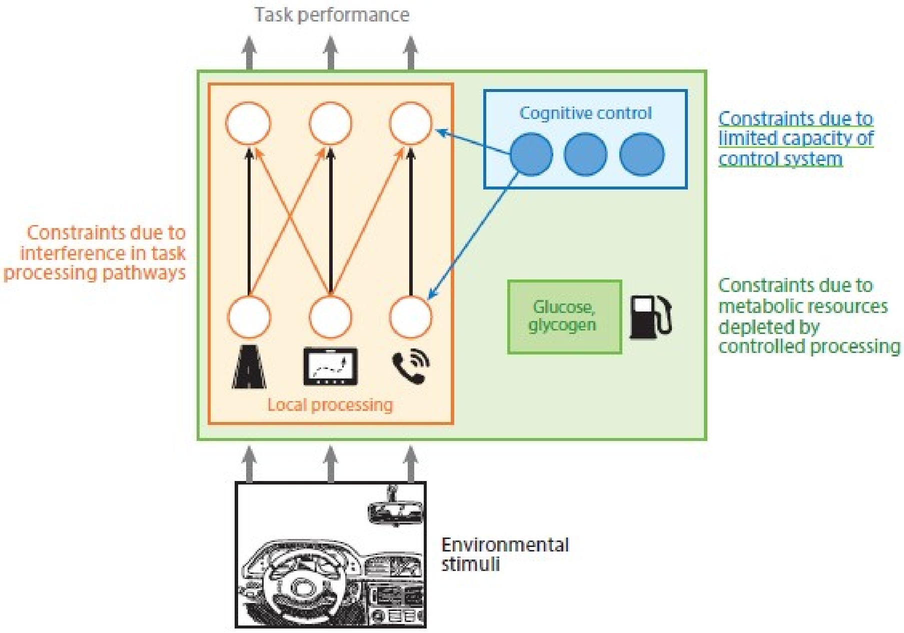

Figure 1: Constraints that make Mental Effort Costly [Shenhav et al., 2017]

- Interference-based accounts (orange) propose that control costs reflect the risks to performance associated with the over-allocation of control as well as deleterious effects of cross talk in the processing system.

Apart from numerous intrinsic costs, mental effort reflects the opportunity costs associated with allocating a valuable but limited resource—the capacity for control.

How is Cognitive Effort Allocated?

The VOC and EVC described below emphasise different kinds of control costs (those that scale with time alone and those that scale with level of control engagement).

The Value of Computation

Value of Computation is defined as the difference between expected utility gained by engaging those computations and the expected cost of the computational resources it will consume.This theory says that mental effort should be allocated to achieve the optimal trade-off between the expected utility of its outcome and the opportunity cost of the required time. [Shenhav et al., 2017] A lot of previous studies suggest that people invest mental effort rationally with respect to their mental model of the (time) costs and rewards for potential strategies. In other words, VOC selects between various possible operations based on expected reward as well as the costs associated with the time requirement for the said operation.

The Expected Value of Control

The EVC is defined as the difference between the expected gains (reward rate) and the expected control cost associated with a given configuration of control signals. [Shenhav et al., 2017] The EVC theory proposes that control signals are specified along two dimensions: an identity (what to attend) and an intensity (how strongly to attend, relative to a default or automatic level). Adjusting the intensity of effort, the likelihood of reward can be increased, as well as efficiency of doing a task can be modulated.

Another salient feature of Cognitive Effort is that information processing lies along a continuum of automaticity [Shiffrin and Schneider, 1977], on one end of the spectrum are processes (typically heavily practised ones) able to be deployed more reflexively and with less threat of interference from other ongoing thoughts; on the other end are processes that require increasing commitments of cognitive control to reconfigure information processing away from default (more automatic) settings.

Neural Mechanisms

The dorsal anterior cingulate cortex (dACC) is one of the key areas involved in cognitive control or mental effort allocation. dACC has been found to track how aversive control demands are to an individual, [Shenhav et al., 2017]their experienced frustration, their preference against performing particular tasks, and how subjects devalued the rewards associated with an effortful task. It is predicted to oversee effort-sensitive cost-benefit analysis, in other words it does the cost-reward optimization. There have been observed changes in dACC activity which predict subsequent adjustments in exerted control (response slowing, attentional shifts); and causal manipulations of dACC have been shown to influence these adjustments. [Heilbronner and Hayden, 2016]

Like dACC, inferior pre-frontal cortex (iPFC) has also been found to be associated with preferences to avoid cognitive effort and with signatures of cognitive fatigue.[Heilbronner and Hayden, 2016] This may suggest a role in signalling control costs, perhaps at a more abstract or heuristic level but could also suggest that iPFC provides a more sensitive readout of the level of cognitive effort being exerted at a given time. The current models for mental effort derive their skeleton from workings of an operating system of a computer. For example, VOC is the measure of computational and time complexity for instance of a task, while EVC is like allocation of memory and CPU time distribution for different tasks as decided by the Operating system.

Unanswered Questions

Although a lot of research is taking place in the theory and mechanisms behind mental effort, very little progress is made in the following: [Shenhav et al., 2017]

- It is evident that mental effort is aversive and is supported by the psychological theory of humans being 'cognitive misers', how is this associated cost quantified by the brain circuitry is more or less obscure.
- None of the signatures of mental effort or control including RT response, pupil diameter, avoidant preferences, activity in dACC are selective to control costs (show similar signatures of sympathetic arousal)
- The current theoretical models do not incorporate concepts highly specific to humans like boredom, frustration, distractions, breaking the inertia in starting (difficulty associated with starting a particular task), problems of procrastination,stress etc.
- The various models in the field which are related but need to be merged to give a complete picture, and models need to be validated by identifying precise neural mechanisms of mental effort allocation.
- We know that dACC plays a crucial role in the cognitive control process, but whether the role reflects the costs, the demands, output of allocated control etc. is not precisely known.
- Exact relationship between the mechanisms and phenomenology of mental vs. physical effort needs more detailed probing, comparative analysis of the degree to which different species discount rewards for a similar amounts of cognitive vs physical effort needs to be done after quantifying the 'similar' for each species
- Improving the understanding on the question 'what makes it hard to think and what can we do about it' to help people improve their responses where they fail to exercise optimal mental effort (exploring why this breakdown occurs) and minimising the resultant health, safety, relationships, educational attainment, and financial loses of cognitive or physical effort.

Hypothesis

The mental effort and physical effort share common underpinnings of cost analysis and optimisation of effort vs reward. Across people, there will be some interactions between mental and physical effort costs. We aim to understand what is the critical reward for which people (if they do) switch between exerting mental vs physical labour. Since this shall be the first of its kind analysis we shall go in with an approach to acquire and analyse all the data we can acquire about this trade off and then draw possible correlations. However, we describe some outcomes we might expect in the section below.

Method and Outcomes Expected

The sample population would consist of healthy students from a higher education institute/ university, from the age group of 18-30 years. To get a homogeneous sample, the selection shall be completely randomised from people who volunteer for the experiment. The target no. of participants shall be around 400-500, and the gender ratio shall be maintained at about 0.5 approximately to have analysis across gender too.

We give the participant a choice between two tasks requiring t_m time of mental work, t_p time of physical work and tell them that they will be rewarded r_m and r_p in the respective cases. t_m is a representative of the complexity of the mental task while t_p is a representative of how vigorous the physical task is. They are given time t_d to make the decision. We keep t_m, t_p, r_p fixed and vary r_m from 0 to some upper bound $r_{\max} > r_p$, and see when the participant switched from mental work to physical work or vice-versa. We call that the cost of mental effort, denoted by $c_{t_d}(t_m, t_p, r_p, \text{participant})$ (here the variable participant signifies that this function will change according to the participant who does the experiment.). This function will be the main output of this experiment. A baseline choice of each participant is recorded for $r_m = 0$, $r_p = 0$ and $t_m \approx t_p$, for the predisposition of mental effort vs physical effort. Then the rewards are made non-zero for further trials. The aim is to understand how the brain performs the cost analysis. The above method for calculating c is explicitly given by

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Algorithm 1 Calculating cost of mental effort

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procedure C(t_d, t_m, t_p, r_p,person)
  $r_m \leftarrow 0$
  Give person choice to do physical task of time t_p with reward r_p or mental task of time t_m with reward r_m. *Time given to take decision*$=t_d$
  if person chooses mental task OR $r_m = r_{\max}$ **then return** r_m
  else Increment r_m

To analyse this data, we will first choose a reference $t_d^*, t_m^*, t_p^*, r_p^*$ and define

$$C_{\tau_d}(\tau_m, \tau_p, \rho_p, \text{participant}) = \frac{c_{t_d}(t_m, t_p, r_p, \text{participant})}{c^*(\text{participant})}$$

where

$$c^*(\text{participant}) = c_{t_d^*}\left(t_m^*, t_p^*, r_p^*, \text{participant}\right)$$
$$\tau_d = \frac{t_d}{t_d^*}, \quad \tau_m = \frac{t_m}{t_m^*}, \quad \tau_p = \frac{t_p}{t_p^*}, \quad \rho_p = \frac{r_p}{r_p^*}$$

We non-dimensionalise our function in this way so that any universal trends may become visible.

Then we divide our data into homogeneous populations $\mathcal{P}_1, \ldots, \mathcal{P}_n$ (depending on survery reviews taken after the experiment) and define

$$\bar{C}_{\tau_d}(\tau_m, \tau_p, \rho_p, \mathcal{P}_i) = \text{average of } C_{\tau_d}(\tau_m, \tau_p, \rho_p, \text{participant}) \text{ over all participant} \in \mathcal{P}_i$$

Some expected outcomes are

- We expect to see some universal behaviour in *each population*
- $\bar{C}$ will increase with τ_m (Cost increases with complexity)

- $\bar{C}$ will decrease with τ_p at large values of τ_p
- At large values of τ_p and ρ_p, then $\bar{C} \sim \rho_p$

This shall be an fMRI/neuroimaging study [Shiffrin and Schneider, 1977] [Khachouf et al., 2017] and we shall be looking mainly for characteristic activity while making the decision, i.e. where the cost analysis would take place after being exposed to the choice between the mental as well as physical effort challenge. We shall also record the brain activity if and when the participants choose to take up the cognitive task, this shall help us understand at what specific centres in the brain does cognitive effort reside.

The mental tasks shall be borrowed from preexisting standards which take an average person from the population some time t_m to do, these can either be dense literature readings or standardised mathematical problems. Or the mental task could be multiplication of numbers of varying sizes with number of digits proportional to the time assigned to the task.The physical activity can be chosen to be running on a treadmill for a time t_p. The rewards r_m, r_p will be monetarily scaled.

In the paper [Schmidt et al., 2012], they make participants perform mental task (numerical Stroop task) versus physical task (squeezing a hand grip) for a particular reward each, one after another and results suggest that the expectation of a reward is encoded in the ventral striatum, which can then drive either the motor or cognitive part of the dorsal striatum, depending on the task, in order to boost behavioural performance. We shall look for similar signature although our key decision making idea is how individuals discount reward for mental vs physical effort,

We shall also include a background questionnaire documenting participants disposal to physical activities in day-to-day lives versus what sort of mental challenges they encounter as well details like age and gender. Review questions about boredom and frustration shall be included and backtracking from that we can hope to derive to some correlations.

Future Directions

Quite a few technical details are yet to be pinned down in the formulation of this experimental design, the trial structure proposed is just an algorithmic proposal and the nuances, exact time costs etc. need to be decided after deeper literature surveys and analysis. Tp make this experiment viable across species, mental effort tasks like solving of elementary puzzles, using newer tools etc. vs brute force can be studied in macaques to further probe into neural recording data after we have the behavioural and approximate brain area information from this experiment. Once we have figured out the regions which play salient roles in the cost benefit analysis process, we can further use TMS to manipulate the processes in the areas that come out to be significant in the imaging analysis. This study can help in establishing standards for mental vs physical trade-off in healthy individuals and can help clinical diagnosis of people incapable of exerting mental effort required of them.

Although, much research is done on group dynamics in collaborative environments, research in which group instead of individual mental effort is the focus of attention has not yet received much attention. Maybe turning the current proposed study to a group task can also bring about new insights to the field.

In [Coecke et al., 2016], Bob Coecke, Tobias Fritz and Robert W. Spekkens have developed a mathematical theory of resources. That is, they have developed a formalism into which any resource theory should fit in terms of 'symmetric monoidal categories enriched in posets' which are well-defined and formalised mathematical entities. We should be able to put any theory of mental effort as such a theory with resources given by time, memory, attention span etc. This will allow a rigorous mathematical understanding of the theory, and also possibly allow derivation of testable consequences of the theory.

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