INVESTIGATION OF HOW TASK RELATED PROGRAMS AFFECT ACTIVATION OF FRONTOPARIETAL REGIONS

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Investigation of How Task Related Programs Affect Activation of Frontoparietal Regions
By İpek Çiftçi
January 2023

We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

INVESTIGATION OF HOW TASK RELATED PROGRAMS AFFECT ACTIVATION OF FRONTOPARIETAL REGIONS

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M.S. in Neuroscience
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We prepare breakfast, take a shower, do grocery shopping. While completing these daily goals we don't individually execute many components. For instance, while preparing instant coffee we sequentially execute subtask such as 'take the coffee, boil water, put coffee and water to a mug, take a spoon, mix it with spoon' under the goal of preparing the coffee but we don't individually execute them. We execute this whole temporally extended task as one entity which is called 'preparing instant coffee' in this example.

We execute a temporally extended, goal-directed behavior as one entity. The construction of this extended behavior in cognition is hierarchical since it consists of subtasks that complete the subgoals in different levels. For example, the step 'put coffee and water to a mug' completes the subgoal of putting necessary ingredients together. Mixing them completes the actual goal. In terms of goal completion, former one is in a lower level than latter one.

Execution of extended behavior that subsumes the entire task occurs via programs. Programs are related to the entire task. These programs are constructed in the beginning of episode. A program of a longer task requires larger programs than same but shorter task. Executing a longer task as one entity is more demanding than a shorter task. So, the program load of the longer task higher than the shorter one. it has been shown that the reaction time of the first item in a longer task is greater than the same but a shorter task [1]. A set of fronto-parietal regions (also known as Multiple Demands (MD) regions) activates in response to goal-directed tasks that require cognitive control and attention. Activation in MD regions higher for more demanding tasks. Demanding task here can be the tasks that have more working memory load or requires more cognitive control demands. In other words, a higher cognitive load is associated with higher activity in MD regions. Can it be a different cognitive load processing differently than the defined above? If the program loads differently than the typical cognitive load defined in the literature, the activity pattern in MD regions should be different than the typical effect of cognitive load in MD regions. In this study, we investigated this issue. In the experiment, participants executed 3-back task in 2 conditions. One condition had high working memory load (high cognitive control demands) and high program load. The other condition had low working memory load (low cognitive control demands) and low program load. Results showed that activity in low working memory load conditions in MD regions was higher than the activity in high working memory load condition. This indicates that the program load has different construction from working memory load because, it reflects different pattern of activity in MD regions.

Keywords: hierarchical control, task related programs, cognitive control, working memory, attention network, multiple demand regions, frontoparietal regions, cognitive load.

ÖZET

GÖREVLE İLGİLİ PROGRAMLARIN FRONTOPARIETAL BÖLGELERİN AKTİVASYONUNU NASIL ETKİLEDİĞİNİN İNCELENMESİ

İpek Çiftçi
Nerobilim, Yüksek Lisans
Tez Danışmanı: Ausaf Ahmed Farooqui
Ocak 2023

Günlük hayatımızda kahvaltı hazırlıyoruz, duş alıyoruz, market alışverişi yapıyoruz. Bu günlük hedefleri tamamlarken pek çok bileşeni tek tek uygulamıyoruz. Örneğin hazır kahve hazırlarken kahveyi hazırlama amacı altında, sıra ile 'kahveyi al, suyu kaynat, kahveyi ve suyu bir bardağa koy, bir kaşık al, kaşıkla karıştır' gibi alt görevleri yerine getiriyoruz ama bunları ayrı ayrı, tek başına görevler olarak yürütmüyoruz. Bu örnekte 'hazır kahve hazırlama' olarak adlandırılan zamansal bir sürece yayılmış ve bir çok alt görevden oluşan bu görevi tek bir görev olarak işliyoruz ve yürütüyoruz.

Zamansal sürece yayılmış ve içinde adım adım yapılması gereken görevler içeren hedefe yönelik bir davranışı tek bir görev olarak yürütürüz. Bilişteki bu, sürece yayılmış davranışın davranışın inşası, farklı seviyelerdeki alt hedefleri tamamlayan alt görevlerden oluştuğu için hiyerarşiktir. Örneğin, 'bir bardağa kahve ve su koyun' adımı, gerekli malzemeleri bir araya getirme alt hedefini tamamlar. Bu malzemeleri karıştırma adımı asıl hedefi tamamlar. Hedef tamamlama açısından, birincisi ikincisine göre daha düşük seviyededir.

Tüm görevi kapsayan zamana yayılmış davranışın yürütülmesi, programlar aracılığıyla gerçekleşir. Programlar tüm görevle ilgilidir. Bu programlar görevin başında oluşturulur. Daha uzun bir göreve sahip bir program, aynı ama daha kısa göreve göre daha büyük program yükü taşır. Daha uzun bir görevi tek bir davranış olarak yürütmek, daha kısa bir göreve göre daha zahmetlidir. Bu nedenle, daha uzun görevin program yükü daha kısa olandan daha yüksektir. Daha uzun bir görevde ilk öğeye verilen tepki süresinin aynı ancak daha kısa bir görevdendaha uzun olduğu gösterilmiştir [1].

Bilişsel kontrol ve dikkat gerektiren amaca yönelik görevlere, bir dizi fronto-parietal bölge (Çoklu Talep (MD) bölgeleri olarak da bilinir) yanıt verir. Daha zorlu görevler için MD bölgelerinde aktivasyon daha yüksektir. Burada bir görevi zihinsel olarak daha talepkar yapan unsurlar, görevi daha fazla çalışan bellek yükü olan veya daha fazla bilişsel kontrol gerektiren görevlere dönüştüren unsurlardır. Başka bir deyişle, daha yüksek bir bilişsel yük, MD bölgelerinde daha yüksek aktivite ile ilişkilidir. Yukarıda tanımlanandan farklı bir 'bilişsel yük işleme' olabilir mi? Program, literatürde tanımlanan tipik bilişsel yükten farklı bir yükse, MD bölgelerindeki aktivite paterni, MD bölgelerindeki bilişsel yükün tipik etkisinden farklı olmalıdır. Bu çalışmada bu konuyu inceledik. Deneyde, katılımcılar 3-geri görevini 2 koşulda yürüttüler. Bir koşul, yüksek işleyen bellek yüküne (yüksek bilişsel kontrol talepleri) ve yüksek program yüküne sahipti. Diğer koşul, düşük işleyen bellek yüküne (düşük bilişsel kontrol talepleri) ve düşük program yüküne sahipti. Sonuçlar, MD bölgelerinde düşük işleyen bellek yükü koşullarındaki aktivitenin, yüksek işleyen bellek yükü koşulundaki aktiviteden daha yüksek olduğunu gösterdi. Bu, program yükünün çalışan bellek yükünden farklı bir yapıya sahip olduğunu gösterir çünkü MD bölgelerindeki farklı aktivite modellerini yansıtır.

Anahtar sözcükler: hiyerarşik kontrol, görevle ilgili programlar, bilişsel kontrol, çalışma belleği, dikkat ağı, çoklu talep bölgeleri, frontoparyetal bölgeler, bilişsel yük.

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Chapter 1

Introduction

1.1 Cognitive Control in Working Memory Tasks and Multiple Demand Regions

Working memory refers to temporal memory storage that has a limited capacity. In our working memory, we carry through some cognitive processes such as calculating, learning, decision-making, comprehension and reasoning. [9, 10]. Executing a goal-directed behavior takes place in working memory. [11, 9, 12, 13]. Working memory is necessary for goal-directed task execution since it requires holding the necessary information in mind while doing mental manipulation to complete the task. For example, if the goal is calculating the total price of market shopping, one must keep adding prices of the products one by one. To reach the total amount, one must keep the cumulative price in mind, then add the price of a new product, update the cumulative total from the last summation and repeat the process until s/he reaches the final price amount (see figure 1.1). Furthermore, one must be able to focus on the correct stimuli to reach the goal during task execution. For example, if a person already counts a price of a product, S/he shouldn't count that product again in her calculation. Likewise, if she wants to calculate the price of only green groceries but not any meat she bought, she needs to focus on price of some specific items such as apples, cucumbers while intentionally excluding everything that is not in green groceries category from summation. This type of ability to execute a goal-directed behavior in the face of distractors is called cognitive control [13].

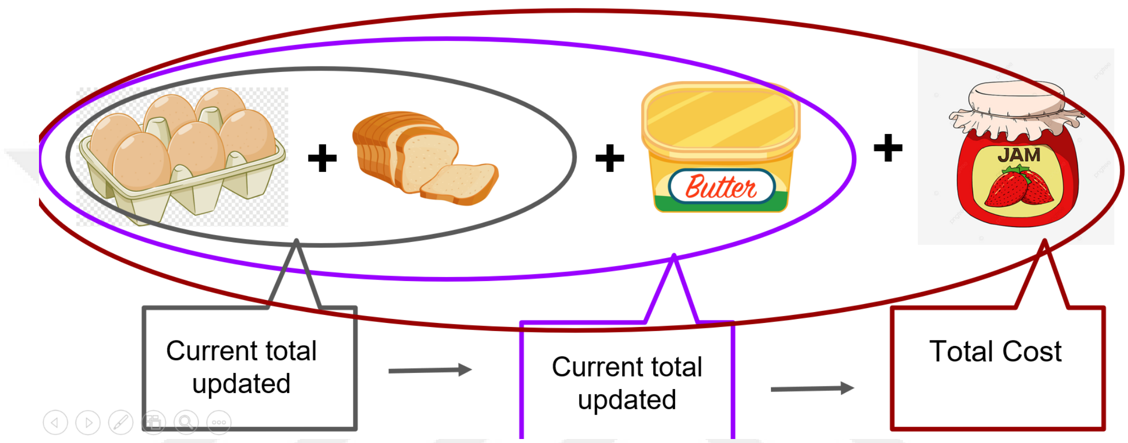

Figure 1.1: An example of cognitive control in a working memory task. This task requires updating information, focusing of relevant prices for summation during task execution to reach the task goal

One task execution can be more demanding than another in terms of cognitive control. One way to increase cognitive control demands is increasing the number of items in working memory (increasing working memory load) while executing the task. Since the goal of holding extra items in mind to use it later requires cognitive control, it would be more demanding to execute the task. For example, if a person wants to compare the total price of green groceries and meats, she needs to keep the total price of green groceries in mind while calculating the total price of meats. If she wants to calculate only the total price of meats, it would be easier than the previous example.

One suggestion is that prefrontal cortex is responsible for cognitive control. In an fMRI study, cognitive control demands were manipulated in a working memory task by increasing the number of items in working memory. N-back task was used in the experiment as the working memory task. In the n-back task, participants have seen some visual stimuli one by one and they were required to compare the current stimuli with the n-previous stimuli and decide whether they were the same or not. For example, if the task is 3-back, in each trial participants were required to remember 3 previous picture while encoding the current picture and also holding the 2 and 1 previous picture in the memory. So, the stimuli in working memory are needed to be updated in every 3 trials. 1-back task only requires remembering the previous one while encoding the current picture. So, executing 3-back task has higher cognitive control demands than executing 1-back task. In the experiment, 1,2 and 3 back tasks were used. They found that for high functioning younger adults left prefrontal cortex activity increased with increased cognitive load (1 back to 3 back) [14].

It has been proposed that not only prefrontal cortex shows activation in cognitive control demands but also a set of fronto-parietal regions (dorsolateral prefrontal cortex, anterior cingulate cortex, middle frontal gyrus, inferior frontal cortex) shows activation. These set of regions commonly are activated by working memory tasks, any task that requires cognitive control [11, 15, 2, 16, 17, 18, 19]. The fronto-parietal regions that show a common pattern of activity in response to many kinds of cognitively demanding task were called Multiple demand regions (also known as attention network, cognitive control network) These regions are inferior frontal sulcus (IFS), intraparietal sulcus(IPS), supplementary motor area (SMA), anterior insula, anterior cingluate cortex (ACC), rostrolateral prefrontal cortex (RPFC) [2] (see figure1.2).

A meta-analysis demonstrated that different types of executive functions/cognitive control such as inhibition, planning, decision making are associated with Multiple Demand Network activity [20]. It has been shown that manipulating cognitive control demands affect MD regions' activity. A pet study [21] showed that working memory load positively correlated with the activity in frontoparietal regions. In the experiment, stimuli matching task was used. The stimulus consisted of different shape patterns in different colors. There were three conditions in the experiment which are simple matching, alternate matching and control condition. In simple matching condition, participants were required to press a button if the stimulus on the screen has the same color or geometrical pattern as the target stimuli. The target stimulus was shown at the beginning of the task. Steps in this condition can be described as; holding two features of the target in working memory, and compare the features with the stimuli. In

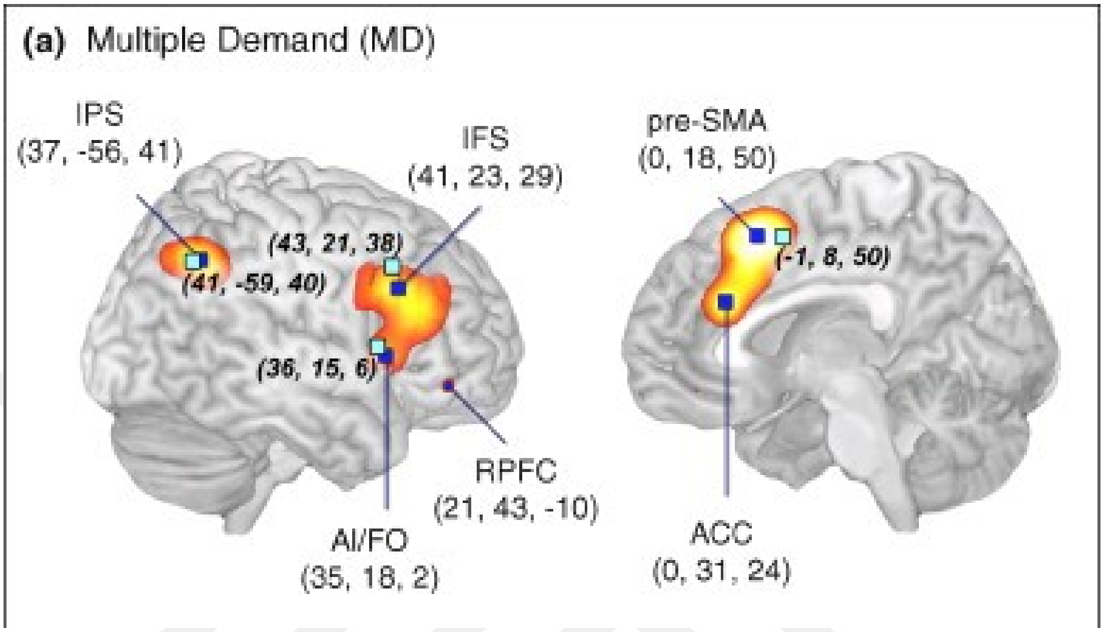

Figure 1.2: Multiple Demand Regions. inferior frontal sulcus (IFS), intraparietal sulcus(IPS), supplementary motor area (SMA), anterior insula (AI), anterior cingluate cortex (ACC), rostrolateral prefrontal cortex (RPFC) Reproduced from [2] with permission.

alternate matching condition, participants needed to compare only one feature but alternately. Steps in this condition are hold the two target features, alternate the rule according to the previous rule, apply the relevant rule. There was a third condition which is used as the control condition. In this condition the same type of stimuli was used and participants responded when the stimuli feature changed. Results showed that compared to the control condition, there were higher activation in left fronto-parietal regions such as IFS, some areas in aPFC, cingulate cortex, anterior insula, anterior inferior parietal cortex in simple and alternating matching condition. Both conditions have more task demand than the control condition. The higher task demand here, holding the features of the target that was shown at the beginning of the sequence through the sequence and deciding which rule to apply. When cognitive control demands in the working memory task increased, more activity in left MD regions were observed. Similarly, Dumontheil et. al. (2011) showed that when more rules were added to the task which makes the task more complex, baseline MD activity increased. Another fMRI study investigated the effect of attentional control on frontoparietal activity both during auditory and visual working memory tasks. It was proposed that MD regions are responsible for controlling attention during a working memory task. Both working memory tasks elicited MD region activity above baseline. Whole brain contrast of high attentional control minus low attentional control in auditory condition showed activation in left IPS, left dorsalateral PFC. In the experiments mentioned above, introducing new steps to task execution adds cognitive control demands to task execution. İncreased cognitive control demands, results in higher activity in MD regions.

An fMRI study showed that MD activity is sensitive to task difficulty. In the experiment, participants needed to select the shortest line among others on the screen. The conditions were varied in their difficulty. For example, in an easy condition, the shortest line was clearly shorter than others. However, in the difficult condition, the length of the lines was similar. Whole brain contrast of high-level difficulty minus low-level difficulty showed MD regions activity [22]. Let's consider the result of this study with the above studies that was mentioned. It can be suggested that there was a distinctive MD activity not only when cognitive control demands increased by introducing new rules to determine a target but also increasing cognitive control demands by making the target less salient among distractors.

The experimental findings that were mentioned in this section indicate that MD regions respond to changing cognitive control demands. The task demands can be increased by adding an additional rule or step to reach a goal [21, 23], making the distractors similar to target [22], or adding items to working memory [14]. Based on these results, choosing the MD regions as regions of interest would be meaningful if a study involves manipulation of cognitive control demands in the experiment.

1.2 Hierarchical Cognitive Control

A goal-directed behavior consists of subgoals and substeps to complete the goal. This branching of the behavior makes the task execution hierarchical. Hierarchical control is something we apply to our goal-directed everyday tasks. For example, the goal of taking a shower is cleaning. It has some sequential subtasks to complete the subordinate goal such as shampooing the hair, cleaning the face and so on. These sequences are executed under temporal abstract which is sustaining the aim of the action over time and it unites the sequence of episodes according to the final goal. Each subgoal should be monitored relative to its place in the sequence so that it gives information about what to do next or which tasks were completed. So, there should be an episodic control for each subtask to continue the sequential goal-directed action (see figure 1.3) [3].

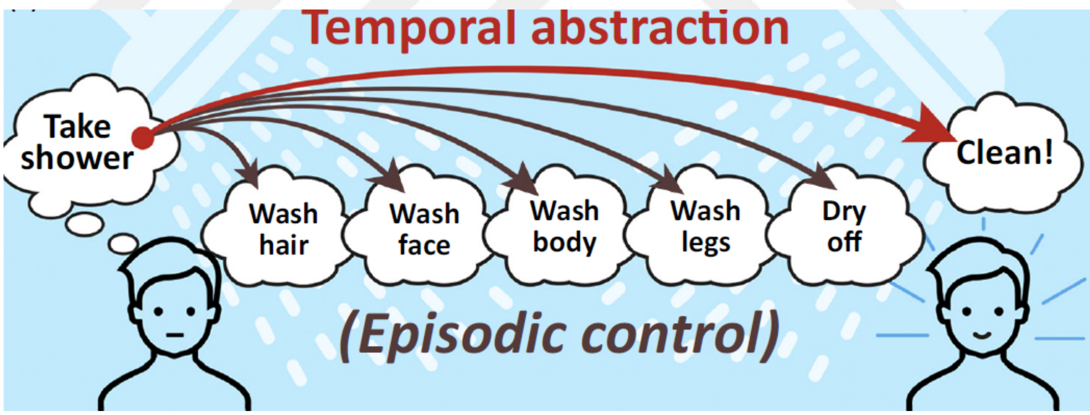

Figure 1.3: A representation of sequential goal-directed behavior. It consists of subgoals such as clean hair, clean face, etc. Temporal abstraction refers to maintaining the final goal in cognition throughout the behavioral execution. Episodic control is monitoring the subgoal relative to its temporal position of goal completion. Reproduced from [3] with permission.

The terms temporal abstraction and episodic control can be defined as functions of working memory. Since an extended working memory task requires keeping the goal for a period of time, it involves temporal abstraction. Considering what is done and what to do in the next step, requires episodic control. In other words, before completing the final goal, one must execute the necessary action for each subgoal while maintaining the final goal in working memory to monitor what is left to do for task completion [24].

In conclusion, to be able to investigate hierarchical cognition, using a sequential working memory task would be meaningful. In a sequential task, updating or selecting task items from working memory can be a core mechanism of hierarchical control [3]. Because, the roles of working memory in hierarchical control firstly, maintaining high-level representation of the task over the course of execution of the task. Secondly, the representation of the subtask should be updated in working memory. Lastly, the selection of action should be updated within a subtask (see [25] in review [24]). In other words, the highest to lowest level goal completion takes place in working memory. Furthermore, a sequential task can be considered hierarchical since the steps of the task complete subgoals and the last step completes the final goal. Let's consider the example of calculating the total price of market shopping again. We have 4 items in our shopping cart. During task execution, we keep adding the price of a new item and updating the current total. So, each update of summed price completes subgoals such as completing the calculation of 2 item, then 3 item, then lastly 4 item. Adding the price of last item on summation completes the final goal. So, the last summation is hierarchically the highest one in terms of goal completion. Consequently, sequential tasks are hierarchical in their nature.

1.2.1 How Hierarchy in Cognition is Represented in Brain Regions

It is thought that if the organization of behavior is hierarchical in cognition, its traits can be observed in brain activity. Based on this assumption, some findings were discussed in this section.

The studies on patients with prefrontal damage demonstrate that even though patients are capable to perform simple cognitive control tasks, they had deficits to perform hierarchical cognitive control tasks. It has been proposed that DLPFC maintains goal information through nested hierarchical steps based on neurophysiological findings [26] (see in review [24]). RLPFC considered to be responsible for hierarchical cognition. Because the region showed activity while participants were holding a goal in mind and at the same time, performing a subtask. Additionally, RLPFC was active when participants need to use temporal context to understand the stimulus context [3, 27]. Likewise, in a sequential working memory task, updating the hierarchically higher-order rules activated the rostral prefrontal cortex and updating lower-order rules activated the caudal prefrontal cortex [28].

Prefrontal cortex is not the only region that is thought to be responsive to hierarchical control. It has been shown that almost all multiple demand regions activate in response to hierarchically organized task episodes. Farooqui et. al. (2012) showed that the amount of task related activity in MD regions is correlational with the hierarchical organization of the trials in a task episode. The experiment consisted of two subtasks. In the first subtask, participants were asked to covertly find the three-letter word that is shown at the beginning of the episode. 40 letters appeared on the screen one at a time. They were required to find the words in order. For example, if the word is 'DOG', The first target(T1) is 'D', the second target(T2) 'O' and the third target that completes the first subtask was 'G' (T3). The second subtask was finding the letter 'X' after completing the word task. Each letter should have been searched after the previous target was detected. At the end of the episode, 'X?' appeared on the screen. This last screen asked whether they see 'X' after they see all letters of the word task. Participants responded via button box as yes and no. When we think about the whole episode as one task; actually, episodes consist of searching 4 letters in order. Participants were primed to think that the episodes consist of two subtasks by introducing the episode tasks as searching 3 letters of a world and searching the letter 'X'. In this way, finding T4 (finding 'X') is highest in the hierarchical organization of task completion. Because, it completes the task episode. Likewise, T3 (last target of the word task) completes the first subtask. T3 is hierarchically lower than T4 and higher than T1 and T2 (see figure 1.4).

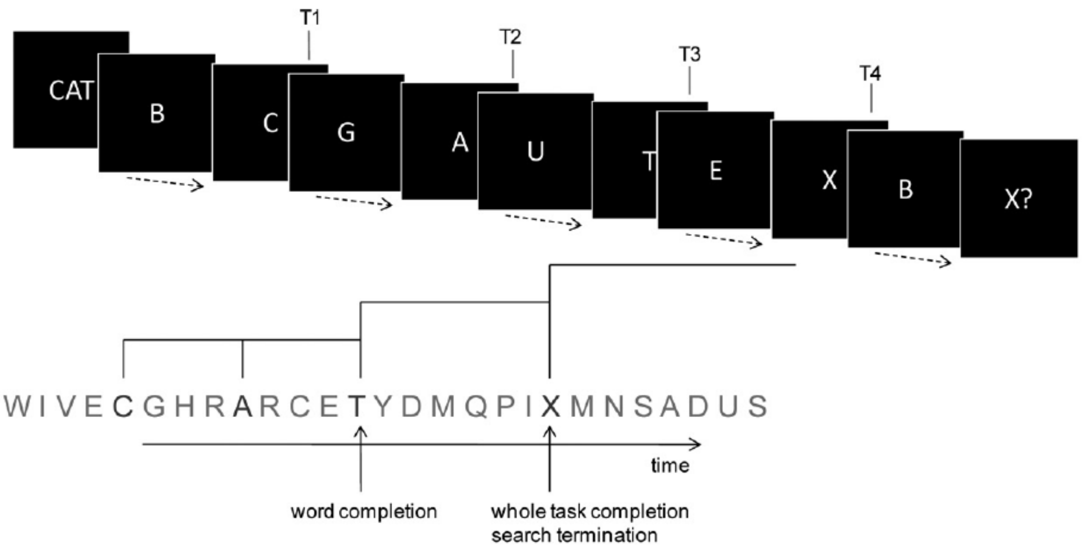

Figure 1.4: First page shows 3 letter words for letter searching. T1 is the first letter, T2 is the second letter, T3 is the third letter target. T3 completes the word letter searching task. T4 completes the whole task. Reproduced from [4] with permission.

They did fir analysis for IFS-L, IFS-R, IPS-L, IPS-R, APFC-L, APFC-R, pre-SMA, AI, ACC. The fir analysis showed that the trial (T4) that completes the whole task episode demonstrated the highest activation in MD regions. Furthermore, T1 and T2 which are the lowest levels in the hierarchy showed the least activation. The ANOVA for each region confirmed that target type has a significant main effect. Additionally, the activity difference related to target type was greater in the right ROIs. Pairwise comparison showed that activity for T3 was greater than the average activity of T1 and T2 in APFC, ACC, and right IPS. T4 ('X') activity was greater than T1 and T2 in all ROIs except left IFS. Also, T4 activity was greater than T3 activity in all ROIs. Consistent with the ROI results, whole brain contrast showed that T3 activity was greater than average of T1 and T2 in ACC, APFC, a region in pre-SMA, precuneus and right lateral parietal cortex. The contrast of the final target and the average of T1 and T2 was also consistent with the ROI results (see figure 1.5).

To make sure that the results from experiment 1 did not stem from the position of the target but the hierarchy of target completion, experiment 2 was conducted. As in experiment one, experiment 2 was finding the 4 letter target in an episode.

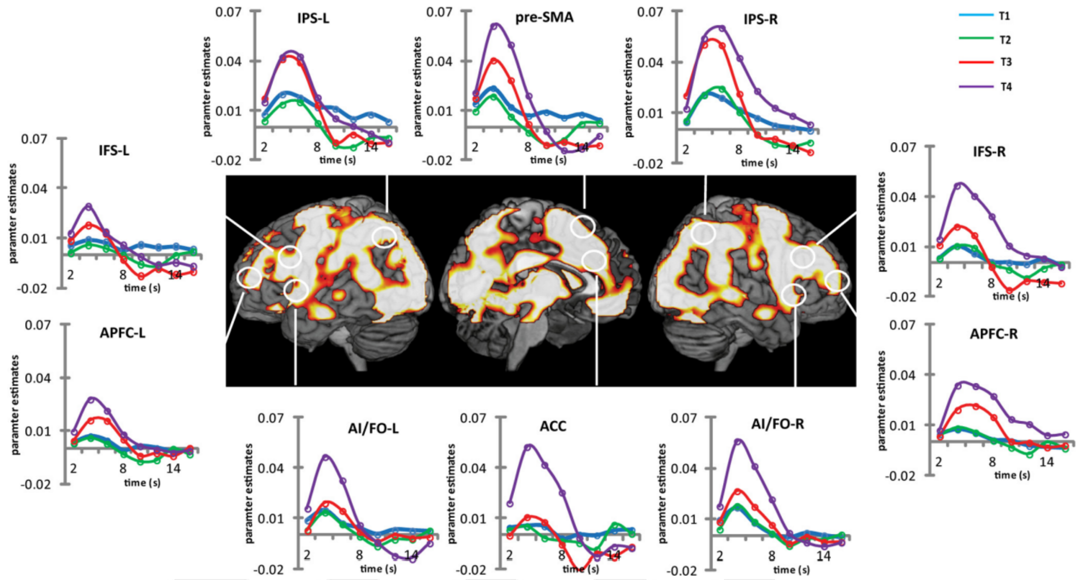

Figure 1.5: FIR results of MD regions in response to each target. The trial(T4) that completes the whole task episode demonstrated the highest activation in MD regions Reproduced from [4] with permission.

However, this time, subtasks were divided into the first 2 letters and always the same last two letters 'MY'. So that, T2 here completes the first subtask instead of T3. Results showed that T3 activity was not greater than T2. In fact, T2 activity was greater than T3 activity in several regions. It is evident that the activity increase in T3 in experiment 1 was not because of the target position, it was because of the hierarchical organization of the target in the task episode. The results of the experiment showed that MD activity corresponds with the idea that organization of behavior is hierarchical.

In the experiment mentioned above, the subgoals in the task were the same. Each subtask was detecting the target letter. In the experiment of Sigala et. al. (2018) [5], there were task steps that has different goals and they required different executive processes. Authors revealed that different task phases (subgoals/subtasks) of a task episode are coded in different patterns by lateral prefrontal cortex neurons in macaque monkeys. Furthermore, correlated coding was seen within a task phase. Cell activities were measured by single cell recording. They used cue-target task in the experiment. Two monkeys learned 3 cue-target associations before the experiment. The task consisted of a cue picture, delay period, and target. Monkeys were required to keep fixation until the target picture appeared in a task episode. The delay period after the cue presentation consisted of other pictures which can be a target picture of another cue or completely new pictures. After the target picture vanished, the monkey was required to indicate that it was the target by making a saccade towards the side where target appeared (see figure 1.6).

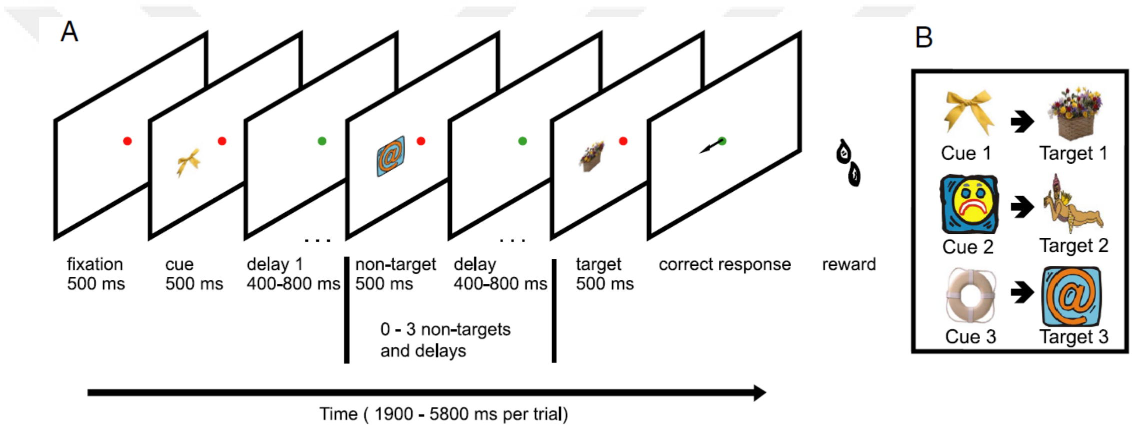

Figure 1.6: cue-target task. After the appearance of the cue, monkeys were required to keep fixation until the target picture appeared in a task episode Reproduced from [5] with permission.

Cluster analysis showed that there is a strong positive correlation between the same task phase (different cue pictures) in the same hemifield, a weak positive correlation between the same task events in different hemifields. The correlation between different event types (cue, delay, target) was approximately zero. In other words, the data showed orthogonal or independent lateral prefrontal cortex representation for different task events (cue, delay and target). Orthogonal coding yielded discriminative representation of different event types in PFC (see figure 1.7). In this experiment, separate subtasks which require different cognitive operations are represented orthogonally in PFC. Orthogonal coding between task phases suggests that a task episode as one entity segregated into subtasks. Correlational coding within a task phase suggests that within a subtask, the same cognitive operations are applied to different stimuli types.

Both experimental results mentioned above show, it is possible to find traces

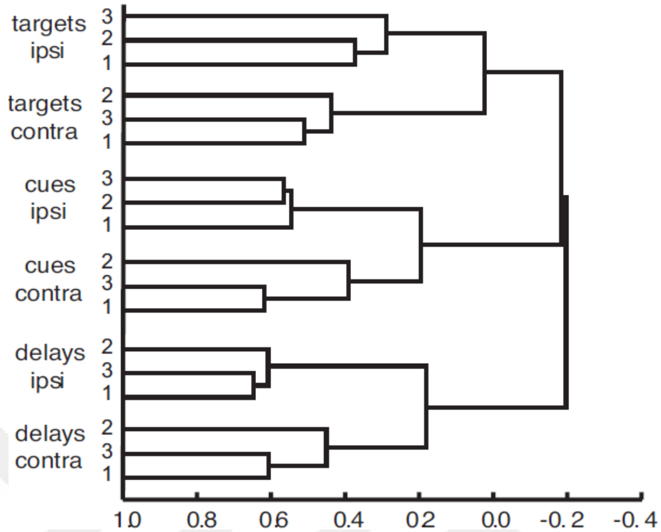

Figure 1.7: Results of cluster analysis. Orthogonal coding between different task phases. Correlational coding within a task phase. Reproduced from [5] with permission.

of hierarchical organization of behavior from brain activity. How is this hierarchy coded in the brain? To divide a task into its subtask, the whole episode to assign some trials/parts as a part of subgoal/subtask must be known. So, is there an overarching program that organizes task execution hierarchically? If there is a program, what kind of results indicate such cognitive operation? I would like to focus on this idea in the next section.

1.3 Task Related Programs

Let's consider the shopping cart example again. This time, you have 4 items in your shopping cart and your friend has 7 items in her shopping cart. Both of you want to calculate the total amount in your own shopping cart. Let's consider that both of you commonly have 4 items and you sum them up in the same order (see figure 1.8). So, the working memory load until the end of the first 4 items should be the same. The only difference is that your friend continues adding up 3 more items. Even though both of you doing the same task, your friend's task is longer. It is important to emphasize that during task execution working memory/cognitive control are the same. The only difference is the length of the tasks. Is this difference result in a different kind of cognitive load?

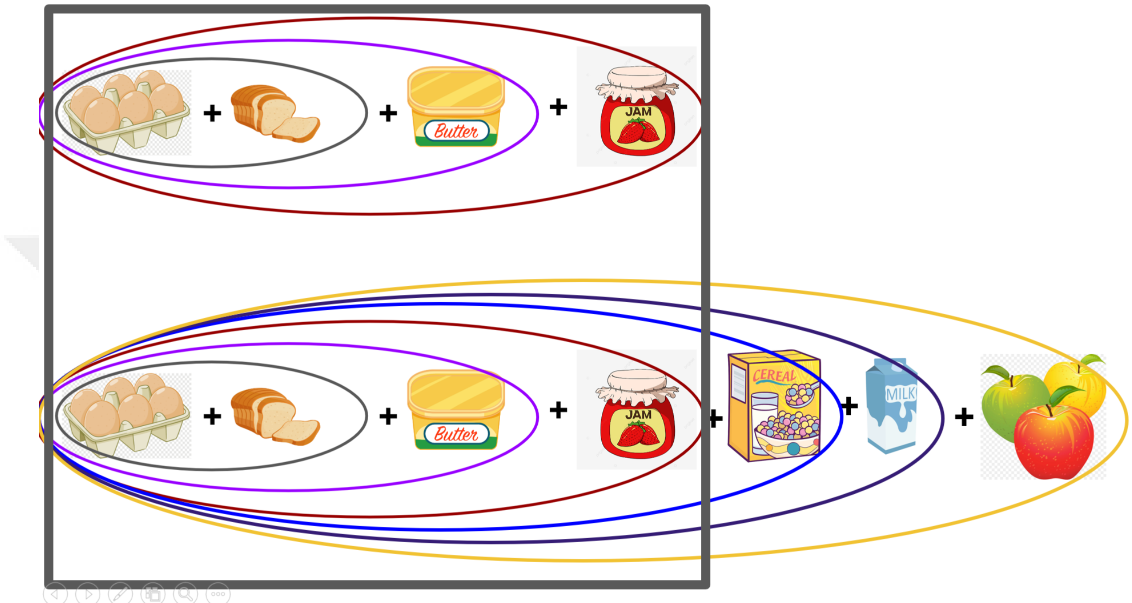

Figure 1.8: We execute a temporally extended, goal-directed behavior as one entity. The construction of this extended behavior in cognition is hierarchical since it consists of subtasks.

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We execute a temporally extended, goal-directed behavior as one entity. The construction of this extended behavior in cognition is hierarchical since it consists of subtasks. Execution of extended behavior that subsumes the entire task occurs via programs. Programs are related to the entire task. Are programs the same at the beginning of short and long tasks? These programs are constructed at the beginning of the episode. A program of a longer task requires larger programs than same but shorter task. Executing a longer task as one entity is more demanding than a shorter task. So, the program load of the longer task is higher than the shorter one.

How do we know that programs are constructed at the beginning of the episode? A response difference between the first item and rest of the items in the task episode can be an indicator. Schneider and Logan (2006) found that the reaction time of first item of a task episode is always the highest [6]. In the experiment, episodes consisted of 4 trials. Participants were required to apply rule A or B to the trials (for example rule A: decide the shape of the stimuli and rule B: decide the color of the stimuli). They found that the reaction time of the first trial was always the highest even though there was no rule switch on the episode boundaries. In their experiment, same episode sequence was executed repeatedly. For example, if the sequential rule of an episode is ABBA, the following task episodes had the same sequence (see figure 1.9).

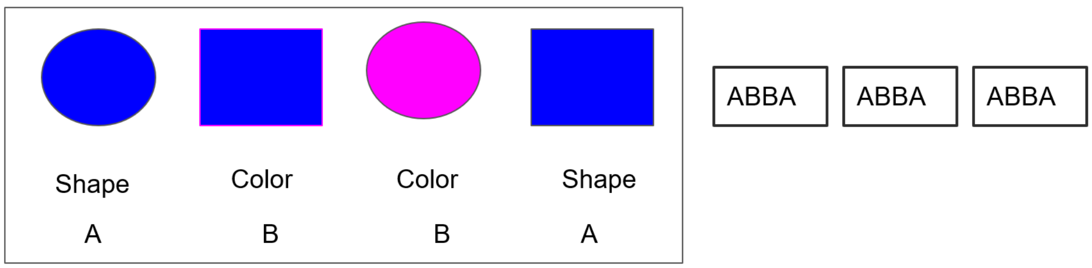

Figure 1.9: A visual representation of experiment [6] and [7] episodes consisted of 4 trials. Same episode sequence was executed repeatedly. For example, rule A: decide the shape of the stimuli and rule B: decide the color of the stimuli.

Since the last trial of an episode and the first trial of the following episode have same rule (the previous one ends with A, and the current one starts with A), there was no rule switch cost on task boundaries that might cause higher RT. Rule switch cost is defined as an increase in reaction time when the rule of a trial is different than the previous one. Since the task rule was same on task boundaries, we can't mention rule switch cost. In fact, it was expected to observe task repetition benefit. The benefit of repetition is responding quicker to the trial if the rule of trials is repetitive. Although there were rule switches at the beginning of trial 2 and 4, the reaction time of the first trial was the highest. This indicates that task execution sensitive to episode boundaries. These results point out the hierarchical organization of the task episodes. Because if episode boundaries weren't taken into account, reaction time (RT) of trials 2 and 4 were expected to be highest due to rule switch cost. The results also indicate that an episode that consists of 4 trials executed as one entity even though trials weren't dependent on one another. An fMRI experiment that has a very similar design to the experiment above found consistent results. The fMRI study used a rule switch task to investigate the pattern of activity in response to a task episode. In each trial, they either picked the shape of the stimuli or the color of the stimuli out of two options. In each trial, both shape and color options were presented on the screen. Each episode was divided into 4 trials. At the beginning of the fMRI run, a screen showed to indicate the order of the rules for each trial. (eg. color color shape shape) Participants were required to apply same rule for following repetitive trials. So, participants should count the trials inside to apply the necessary rule for the current trial. In other words, episodic control was necessary throughout the episode. A ramped activity of RLPFC were observed through first to last trials and the activity peaked at the last trial of the episode [7] The result points out that representation of episode boundaries as a brain activity indicates the hierarchical organization of cognition. Because it indicates that a whole episode processed as one entity since activity throughout episodes repeats itself and always peaked on the last trial.

In the following experiment of Schneider and Logan (2006), task complexity increased the reaction time of the first trial at the beginning of the episode. In their second experiment, they compared the reaction time of episode sequences 'AAABBB' and 'AABABB'. The first one has one rule switch in the episode and the second one has 3 rule switches in the episode. The second one has more task demands than the first one since participants needed to alternate the rule 3 times in one condition, it requires more cognitive control. Results showed that reaction time at the beginning of the episode was less in low task demand conditions (see figure 1.10).

Since the reaction time at the beginning of the episode is always the highest, there might be a cognitive preparation at the beginning of a task episode before executing the task as one entity. Additionally, higher first trial RT of high demanding episode indicates that this cognitive preparation takes more time for more demanding task. This cognitive preparation that subsumes the task execution as one unit by assembling its sequential task steps were called task related programs in the paper of Farooqui and Manly (2019) [1]. They suggest that these programs were instantiated at the beginning of the task and maintains until the goal completed. Consistent with the result of Schneider and Logan [6], Farooqui and Manly (2019) [1] demonstrated that the reaction time of the first trials of

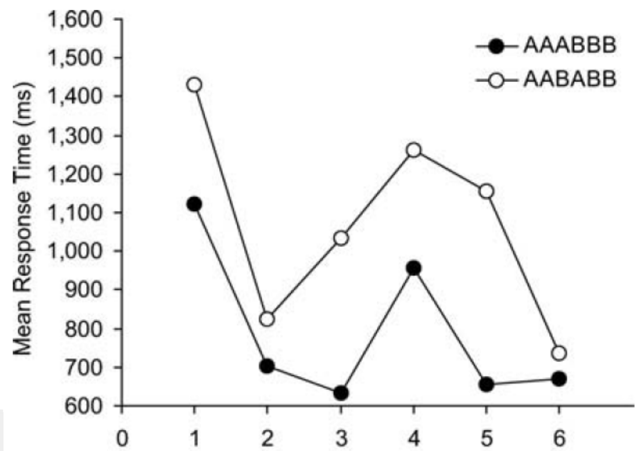

Figure 1.10: Reaction time at the beginning of the episode was less in low task demand condition. Reproduced from [6] with permission.

each episode was longer than the rest of the following trials within the episode. Secondly, they showed that the reaction time of the first trials of long episodes was greater than the short episodes. Trials in task episodes in the experiment were identical in terms of their working memory and attention load. So they concluded that the difference cannot be explained by the differences in attention requirements. Authors indicate that, because task related programs assemble at the beginning of episodes, reaction time of first trials was greater than the rest. Furthermore, since the programs of longer task requires more time to assemble, its first trial reaction time was longer than the shorter episode. The experimental task was a rule switch task. The experimental design was slightly different than the experiment of Schneider and Logan. In the experiment of Schneider and Logan, participants knew the order of the 4-item sequence. Even though the experiment of Farooqui and Manly [1] consisted of episodes with 4 items, participants had not known the rule sequence of episodes. The rule of trial is indicated within that trial. Each stimulus consisted of 2 different numbers on the screen. One of the number's font was quite bigger than the other. If the square frame around the numbers were blue, the smaller number should have been chosen. If the frame was green, smaller font should have been chosen. In the first experiment, participants were instructed to count the trials as 1-2-3 or 1-2-3-4-5. So that, they construct the 3 or 5 trials as an episode. It has been found that the rule switch cost or repetition benefit was not observed in the episode boundaries but they were observed within an episode. Not able to observe this phenomenon in the episode boundaries indicates that at the beginning of each episode, task-related program renews itself. In the second experiment, a variation of the experiment 1 task was used in two conditions. In one condition, participants were primed to see 3 or 5 trials as one episode. There was no episode priming in the second condition (see figure 1.11). It was hypothesized that if each episode was individually executed rather than part of an episode, task-related programs should be executed individually for each trial. Consistent with this hypothesis, results showed that the RT times of trials that did not belong to an episode were greater than the episode condition even though the 1st trial RT of 3 and 5 episodes were included in the calculation.

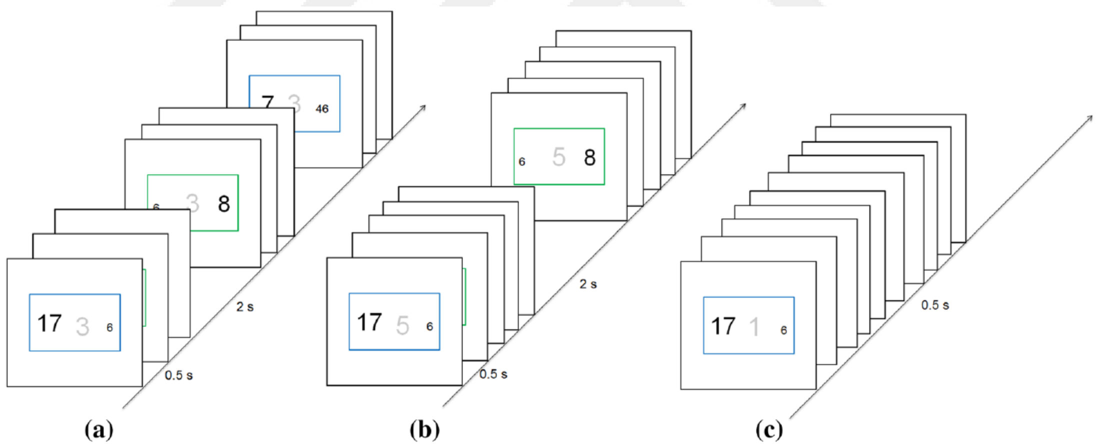

Figure 1.11: a)episodes with 3 trials b)episodes with 5 trials c) individual trials Reproduced from [1] with permission.

In the following experiment, they tested whether the reaction time of 1st trial was a result of the difference in temporal length of episodes or the difference in trial numbers. There were 3 conditions. In the 3 trials short and 5 trials short conditions, there were no inter trial interval between trials in an episode. In the long 3 trials condition, each trial interleaved in 2 seconds (see figure 1.12. Results showed that not only the first trial but also the 2nd and 3rd trial's reaction time of 5 trials short condition significantly higher than the 3 trials short condition. Authors concluded that "maintaining larger program did decrease the amount of cognitive reserves available for trial execution." [1] Furthermore, when the 3 short and 3 long trials episode compare, trial 1 RT slower in long 3 trial episode. It suggests that, episode related program also affected from the temporal aspects of the episode.

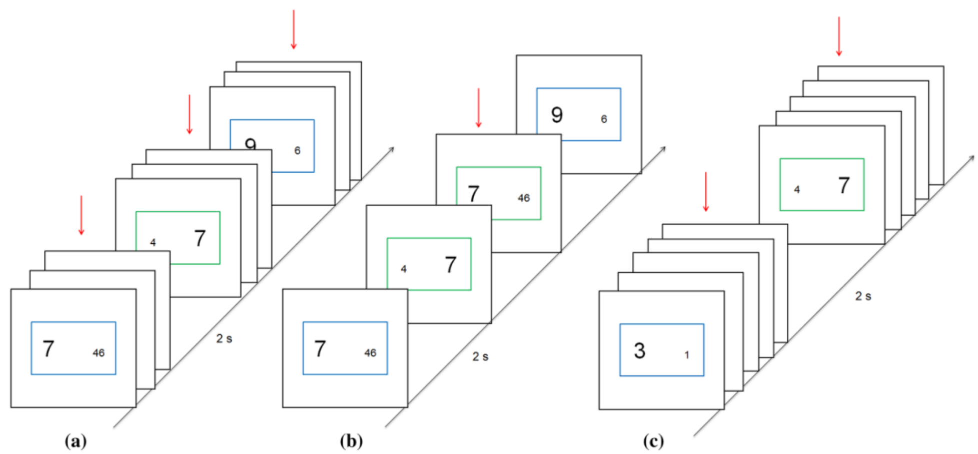

Figure 1.12: a)short 3 trials episode b)long 3 trials episode c) short 5 trials episode Reproduced from [1] with permission.

In an fMRI experiment, the construction of individual 4 trials as an episode showed deactivation at the beginning of episode that decreased gradually throughout the episode in many brain regions such as Default Mode regions (it is known for their deactivation in response to any goal directed task) as well as some MD regions show [8]. A rule switch task was used. In the experiment, participants didn't know the order of the rules in an episode. They see which rule to apply within the trial. The rule of the presented trial indicated by the color of rectangle frame around stimuli. Stimulus consists of a number and a letter. If the frame was blue participants decided whether the letter was vowel or consonant. If the frame was green participant decided whether the number even or odd. There were also a pale number in the background that indicates the position of the trials in an episode (a countdown 4 to 1). The countdown on the background was used to prime participant to perceive 4 trials as an episode. Other than the countdown cue, trials were independent from each other and the rule of the trial were random (see figure 1.13).

Consistent with the results of Schneider and Logan (2006) [6], Farooqui and Manly [8], first trial RT of the episode significantly higher than the other trials.

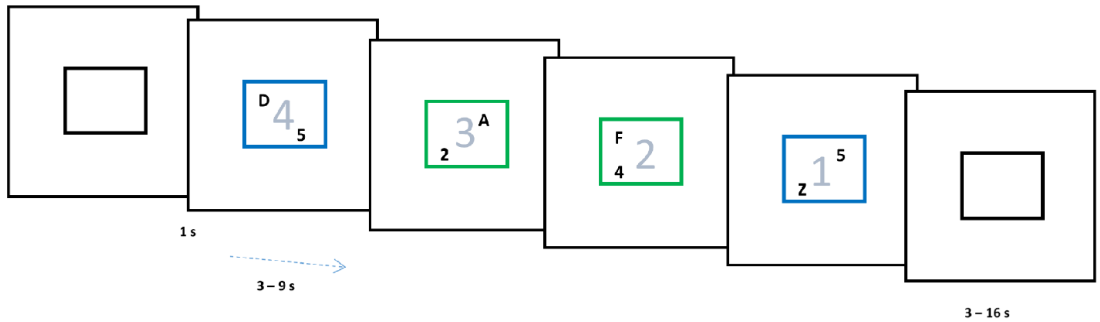

Figure 1.13: Rule switch task. blue frame: letter task (vowel/consonant). green frame: number task (even/odd). Pale numbers in the background indicates trial position Reproduced from [8] with permission.

FIR analysis on MD regions for each trials in the episode showed an initial deactivation for the first trial and gradual increase through last trials in the ACC, left-APFC, bilateral insula, right IFS. On the contrary, the activation across trials in left IFS, bilateral IFS and pre-SMA positive and non-differential across trials (see figure 1.14).

Authors argued that the pattern of activation first to last trials can be attributed to task related programs. Because the trials were same in their working memory, attentional cognitive control demands. Additionally, trials were independent from each other. If the task related programs weren't exist, the pattern of activity would be same across trials. The initial deactivation that gradually decrease might be task related program. Considering with the longest RT at the beginning, gradual decrease in deactivation might be the indicator of program preparation related to the episode.

In the following experiment in the same paper, they investigated does the deactivation in the beginning stem from control demands and deactivation decreases because attention of participants decrease throughout the experiment. If this was the case, deactivation in the beginning of 18 seconds task episode should be the same amount of deactivation at the beginning of 40 seconds episode. Additionally, if decreased deactivation is attributed to decreased attention and if the attention decreases through continuous task execution; at the 18th second, the trajectory

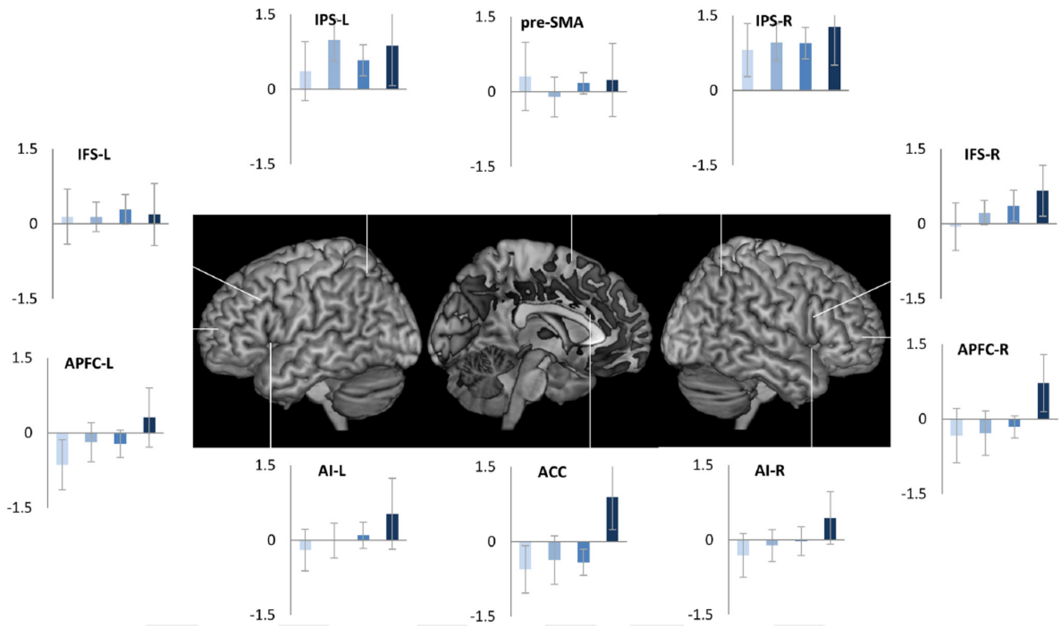

Figure 1.14: initial deactivation for the first trial and significant increase on the last trials in the ACC, left-APFC, bilateral insula, right IFS. Reproduced from [8] with permission.

of activation should be similar in both experimental tasks. However, if the decrease of deactivation linked to "task related program", decreased deactivation pattern would be different in short and long episode. In other words, deactivation decreases according to remaining subtask episodes. Again, they looked at the activity pattern in MD regions. Results showed that the deactivation beginning of the episode was smaller in the short episode than the long episode in bilateral IPS, bilateral IFS, SMA, anterior insula (see figure 1.15). The pattern wasn't observed in ACC and aPFC but left-aPPFC showed the trend. In both experimental conditions, the deactivation went back to baseline at the end of the episode. In other words, even though the participants did the same task, in short episode, deactivation returned to baseline after 18seconds, long episode returned to baseline after 40 seconds. Authors argued that two reasons why short and long episode activation are different and how different. Firstly, since the load of the short episode less than the long episode, The initial deactivation for the short episode would be less. Secondly, because the decrease of deactivation is parallel with the completed task, the deactivation returns to the baseline quicker in the short episode.

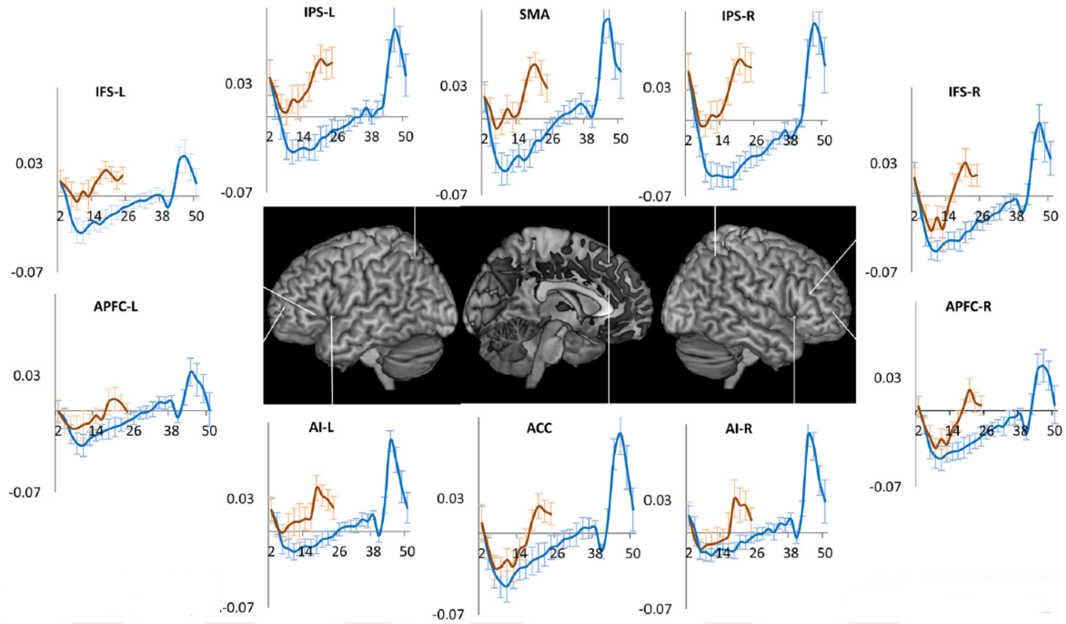

Figure 1.15: Red plots: FIR results of 18s long episodes. Blue plots: fir results of 40 seconds long episodes. the deactivation beginning of the episode was smaller in the short episode than the long episode in bilateral IPS, bilateral IFS, SMA, anterior insula. Reproduced from [8] with permission.

Considering the findings above, it can be stated that task related programs have a cognitive load. Since the programs subsume the temporally extended task, a longer task requires larger programs. So, same but a longer task has higher program load.

1.4 Present Study

In this study, we wanted to investigate how fronto-parietal activity change if we manipulate program construction before task execution. We choose experimental task as 3-back task. Because it is well known that goal directed extended task execution activates multiple demand regions [2, 8]. Specifically, it is known that cognitive control in working memory task activates MD regions [7, 5].

1.4.1 Episode related program load manipulation

Episode related program construction was manipulated by giving/not giving precise information about episodic control. In addition, episode length was always longer in the condition in which participants didn't know about the episode length.

Experimental task was 3-back task in two conditions. In fixed length condition, participants had known how many pictures they would see on the upcoming episode. This information is related to episodic control of the episode, since it gives opportunity to construct what kind of cognitive control strategies they would use at the beginning of the episode. For example, if the participant know that upcoming episode has 9 trials, they can reason that they don't need to encode trial 7, 8, 9 and don't need to maintain that in their working memory. Cognitive control of fixed length condition requires encoding first 3 trials, then from 4 to 6 trials they need to recognize whether the current trial same with the 3 previous one while encoding the current trial and hold it in the working memory to use for decision making in 3 next trial. For the last 3 trials they only need to compare them with the 3 previous trial without holding the current trial in the working memory.

In the variable length condition, they hadn't known in which item episode would be finished. So, the participant cannot build a concrete episode control strategies that precisely subsume the end of the episode. Cognitive control strategies for variable length would be encoding the first three trial, and then from 4th trial encoding the current trial for future use while making a decision about whether the current trial same with the three previous one until the last trial.

The information of number of trials in fixed length condition makes this condition as low load episode related program condition compare to variable length. Episode related programs subsume the entire task execution. Information related to episode length in the beginning make construction of overarching episode related program easier. This is one reason why program load of fixed length condition lower than variable length condition. The second reason that cause of program load differences is the episode length. Variable length condition consisted of episode with 9 or more trials. Since programs are related to whole task, longer task requires larger programs. In other words, executing shorter task as one entity less demanding than longer but same task.

1.4.2 Manipulation of Cognitive Control Demands

The two experimental conditions were not only varied in their program loads but also varied in their cognitive control demands. Fixed length condition has lower cognitive control demands compare to variable length condition. Because in fixed length there are number cues under each picture that indicates episode order. The numbers always goes as 1, 2, 3. This sequence goes repeatedly. For example, 1 was written under the 1st, 4th and 7th picture. 2 was written under the 2nd, 5th and 8th picture, 3 was written under the 3rd, 6th and 9th picture. These cues lessen the cognitive load since it provides information about which picture was the relevant picture for comparison. For example, if 2 was written under the presented picture, participants compare the previous 2nd picture with the present one. On the other hand, in variable length condition, there were no such cue. So, considering the previous example, participants need to count themselves to determine which picture was the previous 2nd picture. Keep tracking the picture orders adds additional cognitive control demands.

1.4.3 Hypothesis

It is known that higher cognitive control demands correlated with higher multiple demand network activity [2, 29]. However, task with same cognitive control demands but different program loads show different pattern of activity in MD regions. Longer episode which has larger program loads shows greater deactivation in some DMN and MD regions compare to shorter episode (which has smaller program load but same amount of cognitive control demands)[8]. Then initial deactivation gradually returns to baseline. Since the cognitive control demand were same throughout the episodes, a gradual increase in activity through the episode cannot be related to cognitive control demands [4]. Instead, it can be the reflection of gradual decrease in episode program load towards the episode ending. Furthermore, deactivation of shorter episode returns the baseline before the longer episode. So, DMN and MD activity shows consistency with the amount of program load [8].

The results show that program load is affected by the temporal aspect of the task. We would like to investigate the validity of this inference by using a different kind of task paradigm. In the experiment [8] which compares brain activity in short and long episode, (the experiment mentioned above, also see figure 1.4) the target was already determined at the beginning of task episode. Since we are using 3-back task. Target changes in every 3 pictures. Additionally, in that experiment [8], the response was given only at the end of the trial. In our experiment, we have opportunity observe response related activity for individual trials in a task episode. Furthermore, in comparison to the previous studies, in this study cognitive control demands of working memory task were manipulated as well. Both of the condition was 3-back since we wanted to compare the response of each trial according to their positions. One condition has low cognitive control demands and low program load demands. The other condition has high cognitive control demands and high program load. In this way, if we don't find the well-known positive correlation between cognitive control demands and MD region activity, we can indicate that there must be another factor affecting MD regions activity.

We model episode trials as stimulus to response time. Results showed that high program load group shows lower MD activity then the low program load group even though high program load condition has higher cognitive control. The results indicates that program loads affect MD regions different than the cognitive control demands.

Moreover, FIR results showed different activity pattern at the end of the episode between variable length and fixed length condition. This result indicated that information related to episode length affect activity in some frontoparietal regions. Additionally, fixed length short and long episodes were compared. Even though, the pattern of activity was similar along the episode, peak activity at the end of the episode were higher for long episode. This can be an indicator that task related programs sensitive to episode length and episode boundaries.

Chapter 2

Methods

2.1 Participants

There were 29 participants (18 female, mean age: 21.14, SD:2.6). All of the participants were right-handed and they had normal or corrected vision. The experiment was announced via Bilkent University mail service. Participants got a monetary reward or course credit for their participation. Before the experiment, informed consent was signed by participants. The compatibility of participants with the MR machine for their safety was ensured before the experiment. The study had the approval of Bilkent Ethics Committee. The study was funded by Tubitak. Tubitak project number is 120k924.

2.2 Experimental Design

The experimental task was a variation of n-back task [30]. Participants saw indoor or outdoor scenes in the middle of the screen. They saw one picture at a time. The pictures were randomly selected among 89 pictures for each experimental run. It was a 3-back task. The task required comparing whether the current

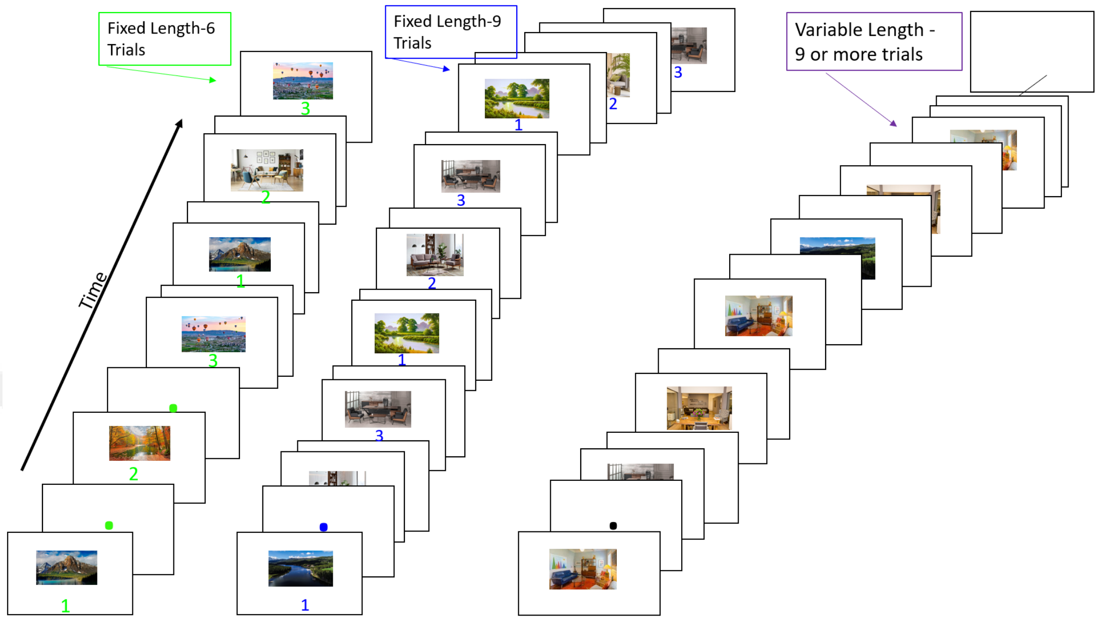

Figure 2.1: Episode types in the experiment. Left to right: short episode fixed-length, long episode fixed-length, variable-length. The page between trials represents inter trial intervals. in fixed length episodes there were cue numbers under each trials as 1,2 or 3. There were no such cues in the variable length condition

picture on the screen same as the 3 previous picture or not.

There were 2 types of 3-back fMRI sessions (see figure 2.1). In the fixed-length sessions, participants had known how many pictures they would see in the upcoming episode. It was indicated at the beginning of each episode. Green number 6 or blue 9 appeared in the middle of the screen which points out how many pictures they would see for the next episode. Below the number 6 or 9 "press a button to continue" was written in the same color as the number above (see figure 2.2). Each session started with 9-picture episode and continued with 6-picture. The episode length changed alternately in every following episode throughout the session. Additionally, in fixed-length episodes, there were cue numbers under each trial as 1, 2 or 3. It made it easier to discriminate which picture they were comparing with. For example, they were comparing the current number 2 picture with the previous number 2. There was no such cue in the variable-length condition.

In the variable-length sessions, participants did not know how many pictures they would see for each episode. At the beginning of the variable-length episode, only "press a button to continue screen" in red appeared in the middle of the screen without any number (see figure 2.2). In the variable length version; the shortest episode length was 9 pictures, and the longest episode length was 18 pictures. The number of pictures for each variable length episode was assigned randomly.

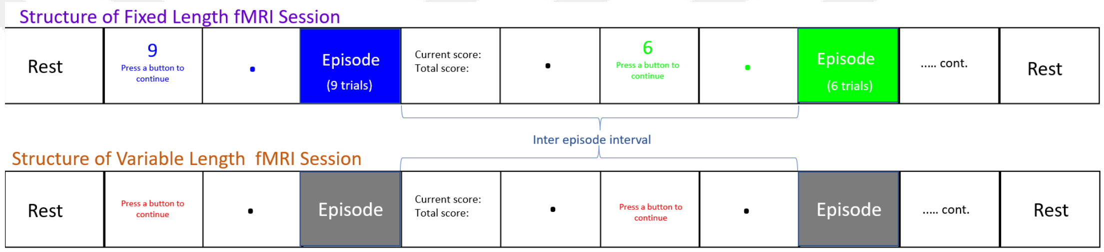

Figure 2.2: fMRI session structure for two types of conditions in the experiment. Above is a fixed-length session. Below is a variable-length session.

Each session started with 15 seconds rest period. The word "Rest" appeared in the middle of the screen. It disappeared after 15 seconds. Then, the first episode started with the "press a button to continue" screen (with a number above for fixed length episodes) (see figure 2.2). After the button press, a fixation point appeared. The duration of fixation points between episodes in the experiment was jittered 1 to 8 seconds. The fixation point was followed by the first trial of an episode. There was a fixation point between each trial which was jittered between 1 to 8 seconds (see figure 2.1).

At the end of each episode, feedback was given to participants as two types of scores in the middle of the screen. If the participant completed the task without any error, their current score would be +1; if they gave 1 wrong answer, their current score would be 0; if they made more than 1 error, their current score would be -1. The total score was the cumulative score of all the past episodes' score. The score screen stayed on the screen for 1 second followed by a fixation point. Then, the "press a button to continue" screen appeared. After the button press, another fixation point appeared and a new episode started. The experimental session continued in the same manner. At the end of the session, a rest screen appeared again and stayed on the screen for 1 minute.

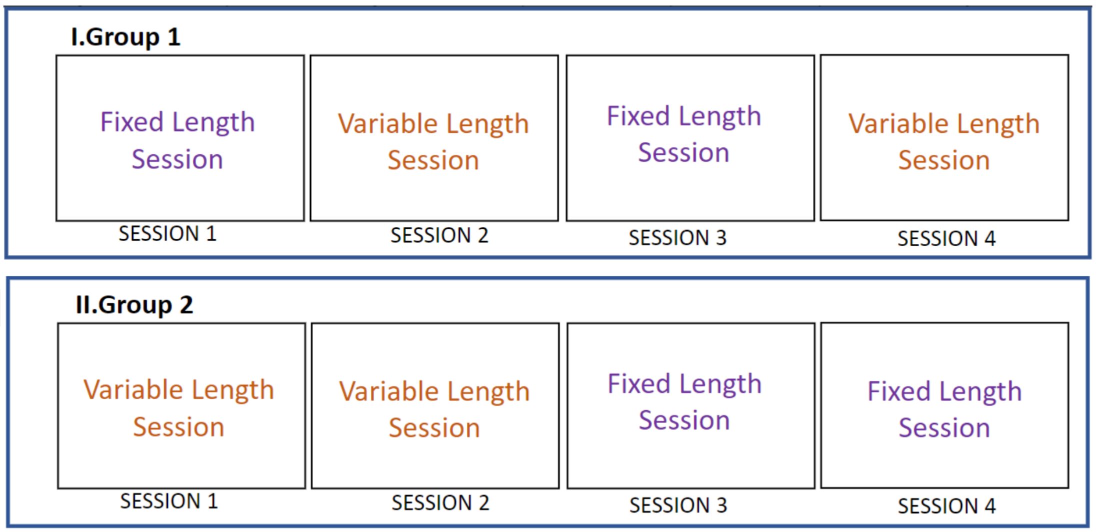

Figure 2.3: Order of the session types changed for different participants.

19 participants completed four 3-back sessions. The order of the sessions was fixed-length, variable-length, fixed-length, variable-length (see figure 2.3 first frame). Each session lasted approximately 12 to 16 minutes. It was a self-paced n-back task. The first 3 participants completed the 4 sessions as 1-hour long fMRI run. Because participants felt sleepy towards the end, we changed the design to 4 separate fMRI runs. The first 19 participants did 7 nine trials fixed-length episodes, 7 six trials fixed-length episodes in a session. Additionally, they completed 10 episodes of variable length for each of two variable-length fMRI sessions. These participants did practice of both fixed and variable-length episodes before the experiment.

9 participants completed 4 fMRI sessions (see figure 2.3 second frame). The first two sessions were variable length, last two sessions were fixed length. They completed 10 variable-length episodes in a session and 16 fixed-length (8 nine trials, 8 six trials) episodes in a session. This group of participants had known only about variable length conditions. These participants did only the practice of variable length before the experiment. After they completed two variable-length sessions in the fMRI machine, the fixed-length condition was explained via fMRI speaker.

2.3 Procedure

Before the experiment, the task was introduced to participants briefly and a practice session held on a computer screen. Participants were instructed to compare the current picture on the screen with the 3 previous one throughout the experiment. The practice part took around 15 minutes. For the practice part, participants gave their responses by pressing 1 and 2 on the keyboard by their right index and right middle finger respectively. 1 indicates yes, 2 indicates no response. Participants repeated the practice part until they completed 2 episodes without any errors.

In the fMRI room, earplugs were given to participants to lessen their exposure to the loud noise of the scanner during the scan. Participants laid down in the fMRI machine on their backs. Foam paddings were used to minimize head motion. They were placed under the head and around the ears in the head coil. Another foam pad was placed under the knees. A mirror was placed above the head coil. Participants saw the screen behind the fMRI machine via this mirror. All stimuli were displayed at the center of the screen. The mirror location was arranged according to screen visibility to participants. Participants gave their responses via a button box with their right index and middle finger in the fMRI machine. The index finger indicates yes "this picture is same with 3-back one", middle finger indicates "no, it is not the same picture". Each fMRI run consisted of one of the conditions only (variable-length or fixed-length). The experimental task started after the acquisition of 10 dummy scans. Since the fMRI machine was adjusted not to save images of dummy scans, they were not included in the general linear model (GLM) to allow for T1 equilibration effects.

2.4 Apparatus

All fMRI scans were conducted at National Magnetic Resonance Research Center (UMRAM) in Bilkent University by using 3T Siemens TimTrio MR scanner with a

32-channel phased array head coil. The features of MR compatible stimuli screen were 800x600 pixel, 32-inch LCD screen with a 60 Hz refresh rate (For some participants the brand of the screen was TELEMED; For the rest of the participants it was TROYKA MED). Responses of the participants were collected with a fiber optic button box (Current Design, fORP 904 fMRI trigger and response system). The experimental stimuli were prepared and run on MATLAB, Psychophysics Toolbox (The Mathworks, Natick, MA). Before the experimental fMRI run, T1-weighted anatomical image acquired (TR=2600 ms, TE=2.92 ms, flip angle=8°, FoV read=256 mm, FoV phase=87.5%, 176 slices with 1×1×1 mm3 resolution). For each experimental run, T2-weighted EPI acquisition sequence were applied (TR=2000 ms, TE=30 ms, flip angle=78°, 64 x 64 matrix, FoV read=192 mm, 32 slices with a thickness of 3.0 mm, 3×3×3 mm3 resolution).

2.5 Analysis

2.5.1 Behavioral Data Analysis

2.5.1.1 Accuracy

2X6 repeated measures ANOVA was conducted (N = 29) There were no data exclusions for this analysis. In this analysis, 4 to 9 trials of variable length and fixed length long episodes were included. Short episodes were not included because it is not our research interest in this analysis line. So, in the rest of the text fixed length is referred to as 'fixed length: long episodes' The analysis was done using Jamovi 2.2.5. The results were checked in MATLAB.

2.5.1.2 Reaction Times

2x9 repeated measures ANOVA was conducted (N = 29) to examine the reaction time differences between trials and episode types. There were no data exclusion for this analysis 1 to 9 trials of variable length and fixed length long episodes were included. The analysis was done using Jamovi 2.2.5. The results were checked in MATLAB R2021a.

2.5.2 FMRI Data Analysis

fMRI analysis was done using SPM 12, using automated analysis pipelines [31].

2.5.2.1 Data Exclusion Criterias

To obtain reliable BOLD activity in response to modeled experimental events, we excluded most of the incorrect trials and slow reaction times. Slow reaction times were calculated for each participant individually as their average reaction time from their all responses to trials plus 3 standard deviations. Their reaction time of the first 3 trials was not included in to slow reaction time calculation since slower reaction times were expected in the beginning of each episode. Slow reaction times were excluded because it might be the case that during the slow RT trials participants might lose focus and they were not able to complete the trial properly.

In all episode types, we excluded the whole episode if participants had 1 slow reaction time in the episode. In fixed length short (6 trials) episodes, if the participant did more than 1 error, we excluded the whole episode. We excluded only the incorrect trial response from the episode if participants did 1 error and there was no slow reaction time in the episode.

In long (nine trials) episodes, we excluded the whole episode if participants did more than 2 errors. We excluded only the incorrect trial response from the episode if participants did 1 or 2 errors and there was no slow reaction time in the episode.

In variable length episodes, we excluded the whole episode if participants did more than 3 errors. We excluded only the incorrect trial response from the episode if participants did 1 or 2 errors and there was no slow reaction time in the episode.

2.5.2.2 Preprocessing

Before statistical analysis, data was preprocessed by SPM12 GUI. First, EPI volumes were slice-time corrected using the last slice (slice 32) as a reference and then realigned into a standard orientation using the last volume as the reference. These realigned volumes then were normalized into the Montreal Neurological Institute (MNI) space and spatially smoothed using an 8 mm full-width half-maximum Gaussian kernel. During the normalization stage, voxels were resampled to a size of $2 \times 2 \times 2$ mm. The time course of each voxel was high pass filtered with a cutoff period of 90 s.

2.5.2.3 First Level Analysis

Statistical analysis was conducted using GLMs. Each trial position of each episode type were modeled with separate event regressors. Each of them modeled as stimulus to response time. They convolved with a single basis function modeling the canonical hemodynamic response (HRF). Movement parameters were included as covariates of no interest. Parameter estimates for each regressor were calculated from the least-squares fit of the model to the data.

2.5.2.4 Region of Interest Analysis

Regions of Interest (ROIs) corresponding to the 10 MD regions were constructed using the MarsBaR toolbox for SPM. These ROIs were created as spheres of 10 mm radius at the following regions and coordinates (in MNI space): anterior cingulate cortex (ACC; 0 31 24), pre-supplementary motor area (pre-SMA; 0 18 50), bilateral inferior frontal sulcus (IFS; central coordinate $\pm$ 41 23 29), bi-lateral intraparietal sulcus (IPS; $\pm$ 37 56 41) and bilateral anterior insula extending into frontal operculum (AI/FO; ± 35 18 3) all taken from [32]; bilateral anterior prefrontal cortex ROIs (APFC; 27 50 23 and 28 51 15) were taken from [29]. ROI analysis was done using SPM 12 under MATLAB (2021a). Each beta value of each regressor for each participant was obtained. 2x8 (Episode type X trial positions) ANOVA was done by using these values on MATLAB. The same analysis was done on Jamovi 2.2.5 to check the results. In the ANOVA analysis episode type has two levels as variable-length and fixed-length long episodes. Trials 1 to 8 were modeled for both episode types. Trial 9 was not included in the analysis. Because it is known that activation related to the last trial in a task that has trial series significantly higher than other trials in the series [4]. Since our main interest is to see the differences between episode types, we didn't include the last trials not to interfere it with our main results.

2.5.2.5 Whole Brain Analysis

2x8 (Episode type X trial positions) Anova was conducted for whole-brain analysis. Two episode type were contrasted for each trial position. Analysis was done by SPM 12 under MATLAB (2021a)

2.5.2.6 Finite Impulse Regressors Analysis

In another GLM model, we used finite impulse regressors model. So that, we were able to the see time course of activity throughout the episodes. Furthermore, hemodynamic response can be observed without assumptions about the shape of neural activity. Each episode type was modeled according to its length. Fixed length short episode modeled as 25 two seconds, fixed length long episode modeled as 35 two seconds, variable length modeled as 55 two seconds. Analysis was done by SPM 12 under MATLAB (2021a) The analysis was done for each ROI mentioned above. After obtaining beta values of the model 2X35 (episode type 2 levels: fixed long episode and variable length episode; 35 time bins. each consisting of 2 seconds) repeated measures ANOVA was done. In a second ANOVA, we compared fixed length short vs long episode as 25 time bins 2X25 (episode type

2 levels: fixed long episode and short episode; 25 time bins. each consisted of 2 seconds) repeated measures ANOVA was done.

Chapter 3

Results

3.1 Behavioral Results

3.1.1 Accuracy

The mean accuracy of the fixed length condition was 98.25 % (SD = 1.25), the mean accuracy of variable length was 97.13 % (SD = 1.1911) (see figure 3.1).

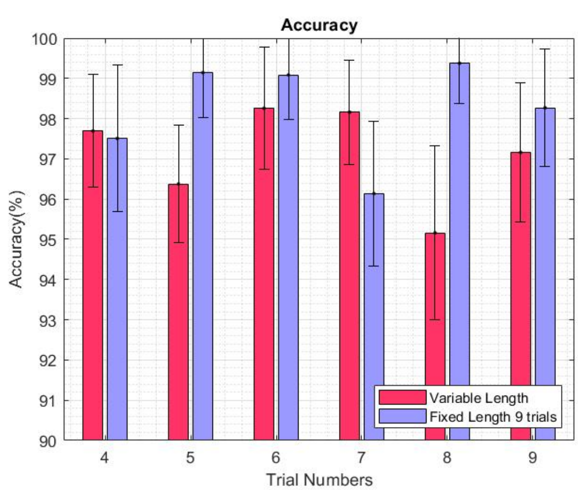

Figure 3.1: accuracy percentages of trial positions for fixed length and variable length episodes

Repeated Measures ANOVA

Within Subjects Effects

	Sum of Squares	df	Mean Square	F	p
trials	112	5	22.3	0.888	0.490
Residual	4650	185	25.1		
episodes	122	1	122.3	4.552	0.040
Residual	994	37	26.9		
trials ✻ episodes	467	5	93.4	3.724	0.003
Residual	4638	185	25.1		

Figure 3.2: Repeated measures 2X6 ANOVA table for accuracy percentages. Episode types 2 Level: fixed,variable; trial positions 6 level: trial 4 to 9)

Repeated measures ANOVA (2X6 Episode types 2 Level: fixed, variable; trial positions 6 level: trial 4 to 9) revealed that there is a significant main effect of episode type on accuracy. It shows that accuracy percentage of fixed length condition significantly higher than variable length condition (see figure 3.2). Significant interaction effect between episode types and trial positions. So, accuracy of trial positions effected by episode type.

3.1.2 Reaction Time

The mean values of reaction times can be seen in figure 3.3. Repeated measures ANOVA (2X9 Episode types 2 Level: fixed, variable; trial positions 9 level: trial 1 to 9) showed that there is a significant main effect of episode type on reaction time. It shows that reaction times of variable length conditions are significantly higher than fixed length conditions(see figure 3.4). There was no significant interaction effect between episode types and trial positions.

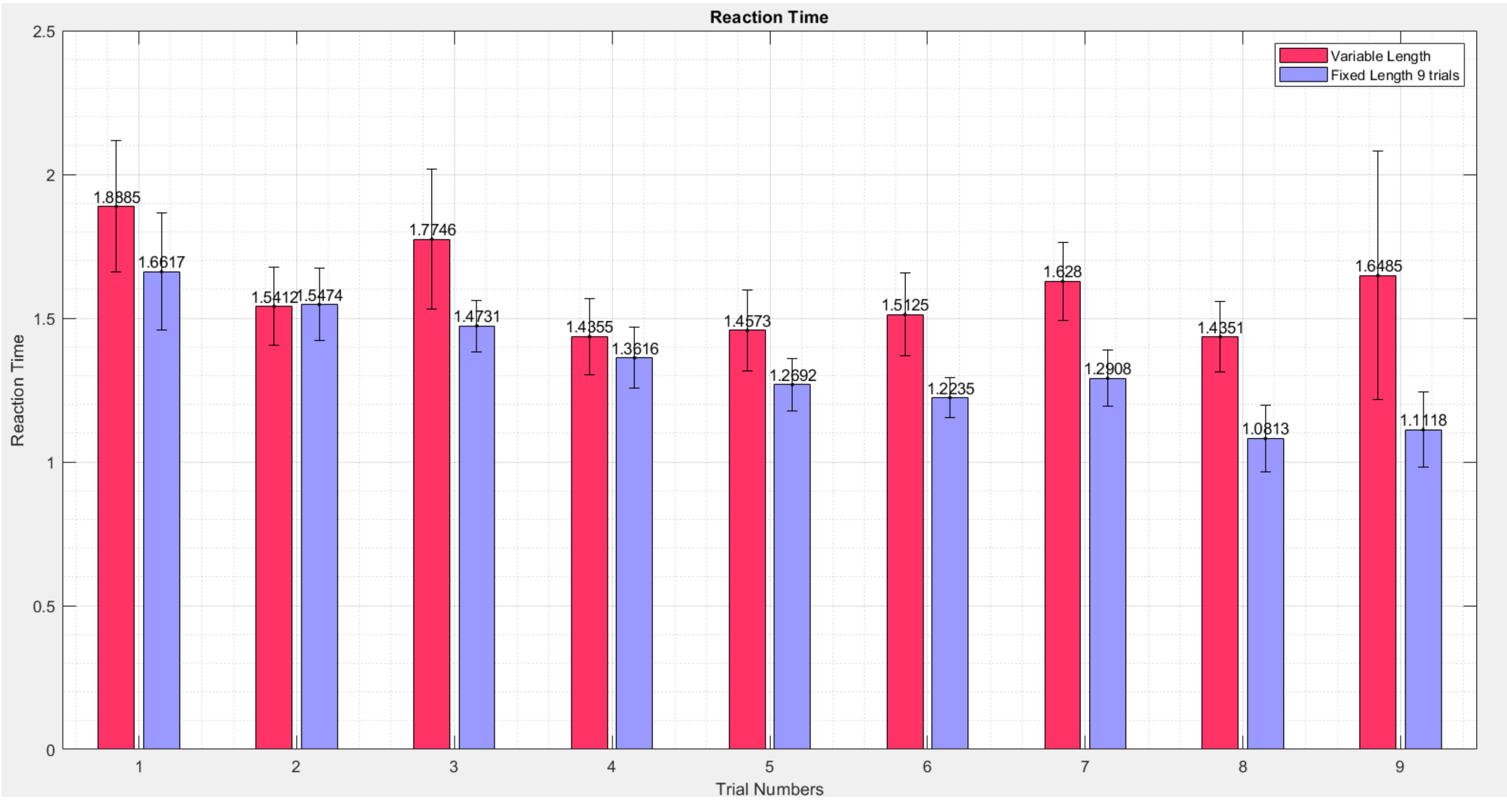

Figure 3.3: Average reaction times of trial positions in fixed length and variable length episodes

Behavioral results indicate that cognitive control demands of variable length are higher than the fixed length condition since the variable length condition has higher reaction times and less accuracy percentage than the fixed length condition. High reaction time indicates high task demands simply because it took more time to process, make a decision and apply the decision. Low accuracy indicates high task demands simply because it shows that participants couldn't keep the items in their working memory in variable length conditions as good as in fixed length condition.

Within Subjects Effects

	Sum of Squares	df	Mean Square	F	p
episode	7.37	1	7.370	8.47	0.007
Residual	23.50	27	0.870		
trials	15.90	8	1.987	4.31	< .001
Residual	99.50	216	0.461		
episode ✻ trials	2.71	8	0.338	1.15	0.334
Residual	63.81	216	0.295		

Figure 3.4: Average reaction times of trial positions in fixed length and variable length episodes

3.2 FMRI Results

3.2.1 Region of Interest Results

Repeated measures 2X8 (episode type: 2 Level: fixed and variable, trial positions: 1 to 8) ANOVA was used. Results showed that there is a significant main effect of episode in ACC ($F(1,27) = 7.25$, $p < 0.03$), right anterior prefrontal cortex (L-aPFC) ($F(1,27)=4.43$, $p < 0.05$), SMA ($F(1,27) = 11.07$, $p < 0.01$), left inferior frontal sulcus(IFS-L) ($F(1,27) = 9.48$,$p < 0.01$), Intraparietal Sulcus-Left(IPS-L) ($F(1,27) = 15.40$, $p < 0.001$), left insula ($F(1,27) = 6.64$, $p < 0.03$), Inferior Frontal Sulcus-Right(IFS-R) ($F(1,27) = 13.19$, $p < 0.01$), Intraparietal Sulcus-Right(IPS-R) ($F(1,27) = 25.92$, $p < 0.0001$), right insula ($F(1,27) = 5.42$, $p < 0.05$). Additionally, there is an interaction effect between episode types and trial positions in IFS-L ($F(7,189) = 2.48$, $p < 0.03$), IPS-L ($F(7,189) = 3.30$, $p < 0.01$), IFS-R ($F(7,189) = 2.60$, p ¡ 0.03), IPS-R ($F(7,189) = 5.37$, $p < 0.0001$). You can see the activity pattern in figure 3.5.

Results showed that, except left-aPFC, the activity in the multiple demand regions are higher in fixed length condition than in variable length condition. This results indicate activation in the frontopariatel regions is higher for low task demand condition than high task demand condition.

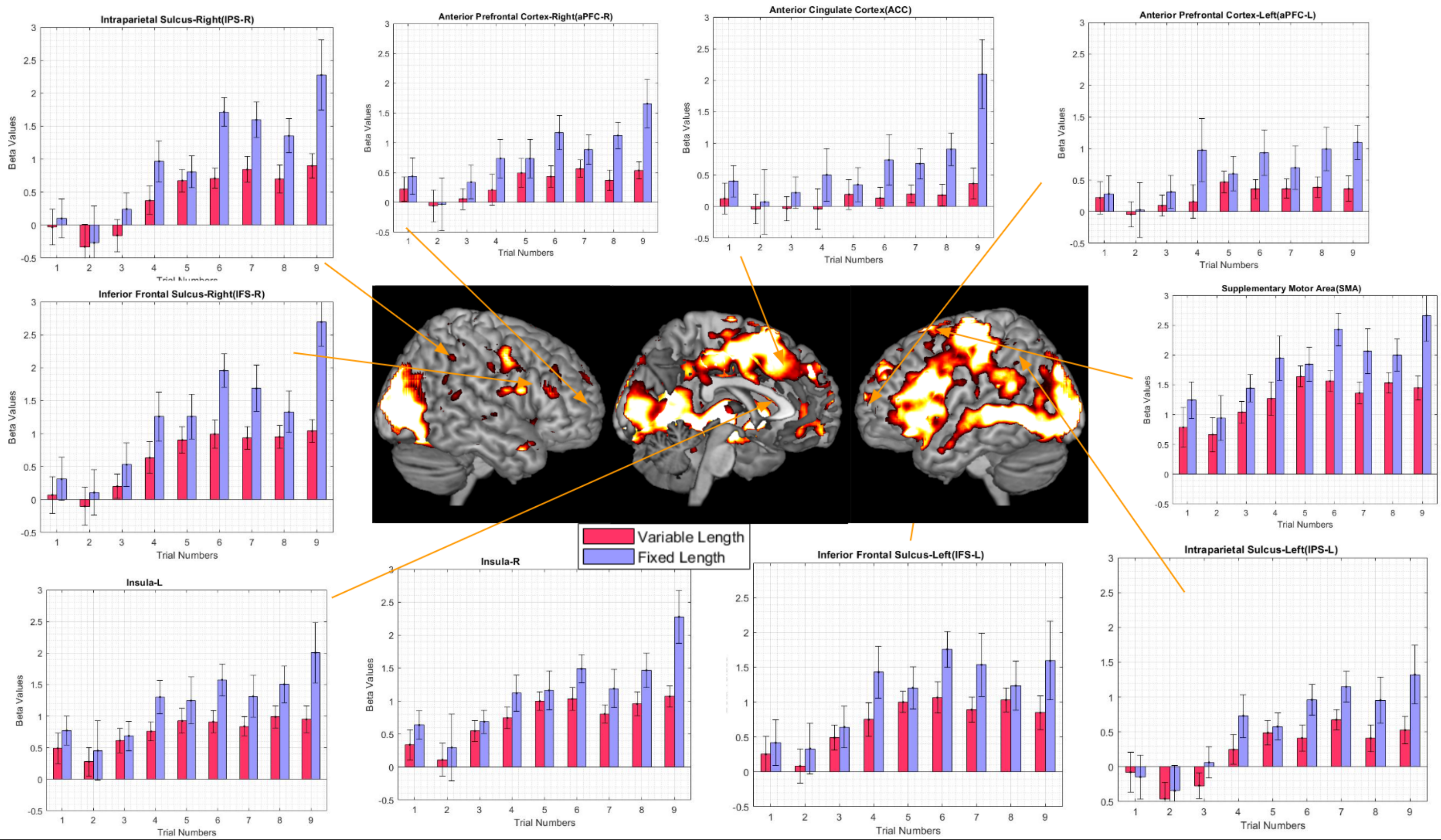

Figure 3.5: Multiple demand regions. Bar graph of each region. Blue bars represent variable-length trials, pink bars represent fixed-length trials. Whole brain render shows interaction effect between episode types and trial positions in many regions. F values are between 4 to 8 which lighten up black to red to yellow.

3.2.2 Finite Impulse Regressors Analysis

The ANOVA results of fixed versus variable length are follows. There are significant main effect in aPFC-L ($F(1,27) = 5.46$, $p < 0.05$) and SMA ($F(1,27) = 5.11$, $p < 0.05$).Both in aPFC-L and SMA activation is higher in variable length condition. There are significant interaction effect between episode type and time bins of the episode in ACC ($F(34,918) = 3.64$, $p < 0.001$), aPFC-R ($F(34,918) = 1.53$, $p < 0.001$), SMA ($F(34,918) = 3.22$, $p < 0.001$), IFS-L ($F(34,918) = 2.96$, p <0.001), IPS-L ($F(34,918) = 2.56$, $p < 0.001$), insula-L ($F(34,918) = 1.57$, $p < 0.05$), IPS-R ($F(34,918) = 2.08$, $p < 0.001$), insula-R($F(34,918) = 1.50$, $p < 0.05$). Episode type affects level of activity in different time bins in those regions (see figure 3.6).

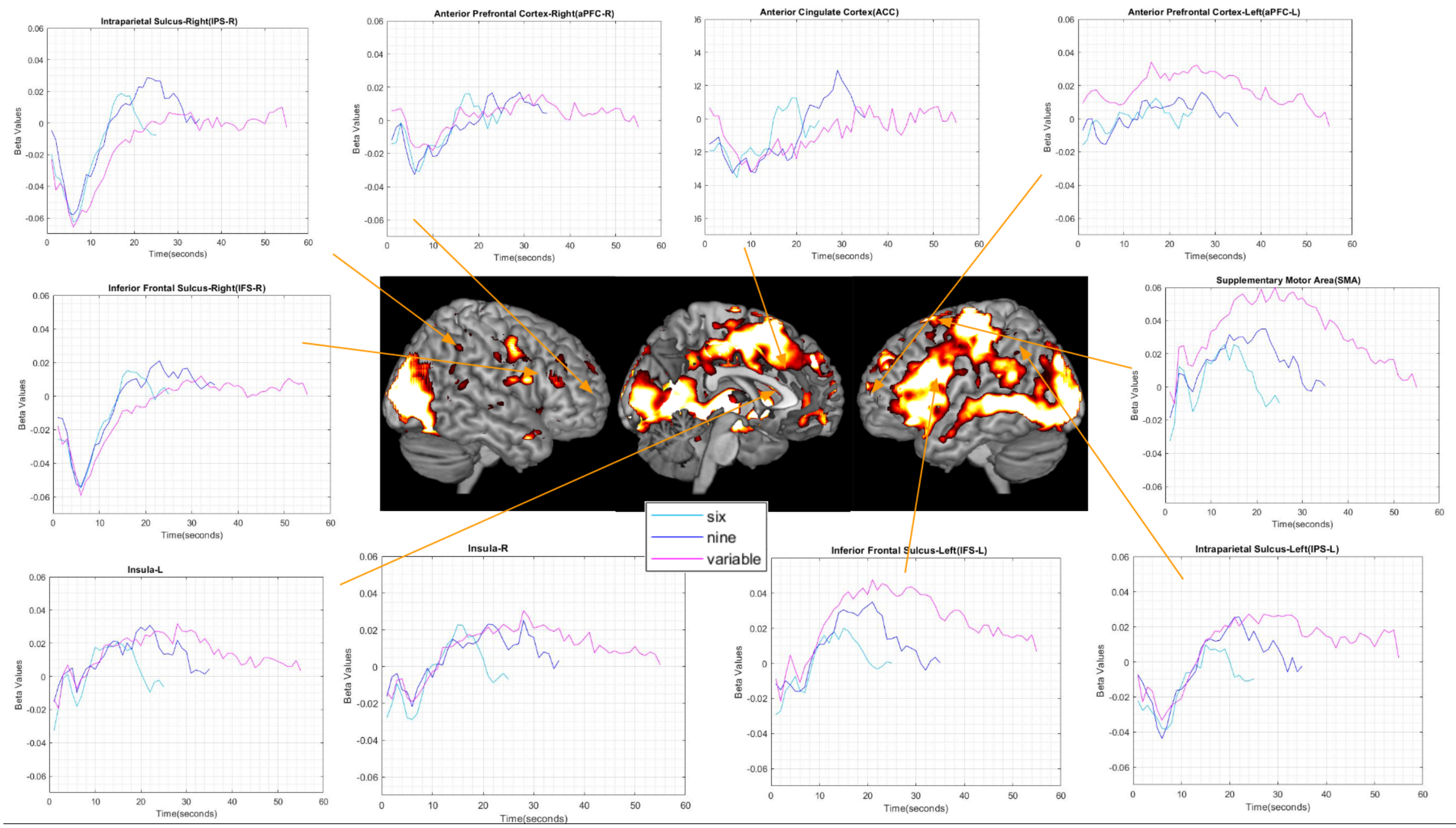

Figure 3.6: FIR results of multiple demand regions. light blue: fixed length short episodes, dark blue: fixed length long episode, pink: variable length episodes. Whole brain render shows interaction effect between episode types and trial positions in many regions. F values are between 4 to 8 which lighten up black to red to yellow.

The ANOVA results of fixed long versus short length are follows. There are significant main effect in SMA ($F(1,27) = 20.39$, $p < 0.001$), IFS-L ($F(1,27) = 15.02$, $p < 0.001$), IPS-L ($F(1,27) = 21.19$, $p < 0.001$), insula-L ($F(1,27) = 10.35$, $p < 0.05$), IPS-R ($F(1,27) = 5.75$, $p < 0.03$), insula-R($F(1,27) = 5.06$, $p < 0.05$). There are significant interaction effects between episode type and time bins of the episode in ACC ($F(24,648) = 3.67$, $p < 0.001$), aPFC-R ($F(24,648) = 2.09$, p

<0.003), SMA ($F(24,648) = 4.20$, $p < 0.001$), IFS-L ($F(24,648) = 4.21$, $p < 0.001$), IPS-L ($F(24,648) = 4.58$, $p < 0.001$), insula-L ($F(24,648) = 4.39$, $p < 0.001$), IPS-R ($F(24,648) = 4.59$, $p < 0.001$), insula-R($F(24,648) = 3.66$, $p < 0.001$). Episode type affects level of activity in different time bins in those regions (see figure 3.6).

As it is seen in figure 3.6 there is apparent initial deactivation at the beginning of episode IPS-R, IPS-L, ACC, IFS-R, aPFC-R. The activation gradually increased beginning to end of the episode. The increase is sharper in the fixed-length condition. When we compare the activity pattern of fixed-length long and short episode, it is notable that peak activity are at the end of the episodes. So, the highest activity in short episodes appears earlier than in long episodes. Moreover, peak activity at the end of the episodes is always higher in a long episode in the IPS-R, IPS-L, ACC, IFS-R, aPFC-R, insula-L, SMA, IFS-L.

3.2.3 Whole Brain Analysis

Results showed that there was a significant interaction between episode types and trial positions in many brain regions ($F(7,736) = 3.52$, $p < 0.0001$ (family-wise corrected)). The whole brain results were consistent with the ROI and FIR results (see figures 1.2 and 3.6). This consistency indicates that selecting multiple demand regions as ROI is reasonable.

Values on the statistic map are F values are between 4 to 8 that correspond to black to yellow. Activity was more spread in the left hemisphere compared to the right hemisphere (see figure 1.2). In addition to MD regions, there were interaction effect in occipital lobe, basal ganglia, DMN regions such as posterior cingulate cortex (PCC), precuneus, left temporal parietal junction.

Chapter 4

Discussion

We would like to investigate the pattern of activation in MD regions in response to program loads. It has been shown that higher MD activity is observed when increasing cognitive load by increasing cognitive control demands [21, 23, 22, 14]. We know that task-related programs have a cognitive load as well. Longer tasks require larger programs. Because of this, the program load of a longer task would be higher than the program load of the same but shorter task [1, 8].

Based on previous fMRI studies about task-related programs, we chose our region of interest as MD regions. The whole brain analysis showed MD regions activity as well. Since we can observe MD activity without any predetermined voxel cluster as well, whole brain analysis validates our region of interest selections.

We would like to investigate whether the cognitive load of programs and the cognitive load of control demands of tasks can be classified in the same cognitive load cluster. To be able to answer this question, we compared activity for "high program loads, high cognitive control demands" versus "low program loads, low cognitive control demands". Observing different kinds of activity patterns in MD in response to these two types of cognitive load indicates that two cognitive loads are categorically different. In fact, we found that even though variable-length condition has higher cognitive control than fixed-length condition, its activity in MD regions was lower than fixed-length condition during task execution.

Our experimental task was a sequential working memory task. Since it consisted of substeps to complete a task episode it can be considered hierarchical. The previous studies that involved "task-related programs" used rule-switch tasks [1, 6, 8]. In some previous experiments that related to task programs, trial order information of the episode was given at the beginning of episodes [6]. This initial information made episodes as one entity. In some other experiments, the only thing that makes the trials as an episode was the making participants think that a certain amount of trials builds up an episode [1]. So, even giving biased information about the episode leads to program construction. In those experimental designs, each trial was a subtask. In our experiment, every 3 trials can be considered a subtask. This structure of task episode adds a layer to the hierarchical organization of the task execution. In this way, compare to rule-switch tasks, task trials become dependent on each other. Even though cognitive control manipulation was done by adding cue numbers to each trial, we manipulated the cognitive control demands not only within a trial but also within an episode since the trials are dependent on each other. Since the program load manipulation itself is within an episode, trials that are dependent on each other should be an appropriate task design to compare two types of load. In this way, we can investigate different kinds of cognitive load not only within a trial but also within an episode. Furthermore, we kept the number of N in the n-back task same in two conditions to be able to compare trial by trial pattern of activation.

Behavioral results demonstrated that cognitive control demand manipulation among experimental conditions worked. Because reaction times of fixed-length episodes were significantly lower than the reaction times of variable-length conditions. Moreover, the accuracy of fixed-length condition higher compare to variable-length condition. Both reaction time and accuracy indicate that the task execution of variable-length episode relatively has more cognitive control demands than fixed-length episodes.

The 3-back task is an extended task that consists of sequential steps. So, overarching programs that subsume the task episode would be constructed at the beginning of task execution. There were several indicators of task-related program construction and execution. Firstly, as seen in the Reaction time bar graph (figure 3.3) first trial reaction time is the highest within both conditions. Similar kinds of results were also observed in the literature [6, 1]. The highest reaction time at the beginning of the episode stem from the time needed to construct task related program that subsumes the task episode [1]. It is known that this reaction time difference in the first trial is not a result of higher cognitive control or attention demands. Because this was tested by making each episode trial identical in their cognitive load. Furthermore, the only thing that makes the first trial as first is that participants were biased to construct the trials in a specific order. [8, 4]. Moreover, the reaction time of the first trial of longer task is higher than the first trial of shorter same task in their experiment[1]. Even though RT of the first trial between two conditions was not significant, we saw that the first reaction time of variable length was higher than the fixed length condition So, manipulation of the program load manifested itself in reaction time results.

Secondly, significant increase in MD regions' activity at the end of the episode points out the episode completion. This is an indication of construction of overarching task-related programs at the beginning of episode since the task completion also construction of program boundaries.

In the current study we see robust activation in the fixed length 9 trials but we don't observe it in the 9th trial of the variable length (see figure 3.5). It is because, in the variable length, episode boundaries that complete the task were unknown. It can be argued that the information related to episode length at the beginning of the episode, makes it able to create more concrete task-related programs.

There are findings in the literature that supports the assumption of robust activity indicator of program completion. Desrochers et al. [7] showed that activity gradually increases first to last trial in RLPFC and it is highest for the last trial. Similarly, Farooqui and Manly [8] observed the highest activation on the last trial of episodes in MD regions. Even though they change the episode length, they observe the same results.

Our FIR results showed initial deactivation at the beginning of episodes in IPS-R, IPS-L, ACC, IFS-R, aPFC-R. The activation gradually increased towards the end of the episode. Especially in the fixed length condition this increase had a peak activation approximately at the end of the episodes in the IPS-R, IPS-L, ACC, IFS-R, aPFC-R, insula-L, SMA, IFS-L. There was also gradual increase in activation for the variable length condition but it does not have a peak as distinct as in the fixed length condition. The peak at the end of the episode in the fixed length condition might be an indicator of episode completion. It can also reflect the end of program execution. Firstly, in spite of the episode length, we see the peak activity at the end of the episode. Secondly, the highest activity at the end of the episode always higher in longer task episode. Thirdly, the reason why we don't see similar peak activity for the variable length condition is that there were no information about when the episode ends. The result is quite consistent with the fir analysis results in Farooqui et. al.(2012) [8] see figure 1.15. In their experiment trials were independent from each other. In our experiment, executing trials in the episode requires remembering the previous trials. So, the cognitive control strategies for episodes from these experiments were slightly different. However, these differences don't seem to affect the pattern of activity throughout the episode. In both studies activity pattern in bilateral IPS, bilateral IFS, ACC, right insula has similar kind of initial deactivation and gradual increase in the activation towards the end of the episode. It can be argued that the pattern of activity throughout the episodes with different cognitive control strategies were same with the previous experiment because the pattern of activity stems from program load. Since the task-related programs subsume the whole episode, we see a similar activation pattern in task completion.

Our study was a visual working memory task. One future direction might be testing task-related programs in other modalities such as using auditory working memory task. Additionally, in our study participants most likely coded stimuli verbally. Instead of this, a visual working memory task that consists of different visual patterns or orientations can be used to test effect of program load on MD regions. Furthermore, to be able to generalize our findings about the effect of program loads on MD regions, this hypothesis should be tested with different task paradigms that vary in their cognitive control demands and program loads. Even though in our study cognitive control demands manipulation was successful, maybe the difference was not enough to override activity stem from program loads. As a future direction, investigating a task design with high cognitive control demands' difference and low program load difference between conditions might be interesting.

The current study shows that program loads affect activity in MD regions in opposite directions compared to cognitive control demands. While cognitive control demands are positively correlated with MD regions' activity, program load is negatively correlated with the MD regions' activity. Task-related program constructed at the beginning of the episode. As a result, the reaction time of first trial was always the highest. Since the ending boundary hadn't known by the participants in variable episodes, we didn't observe a sharp peak at the end of the episode. In such wise, giving program-related information before episode execution impact the pattern of activation in some MD regions.

Chapter 5

Supplementary Materials

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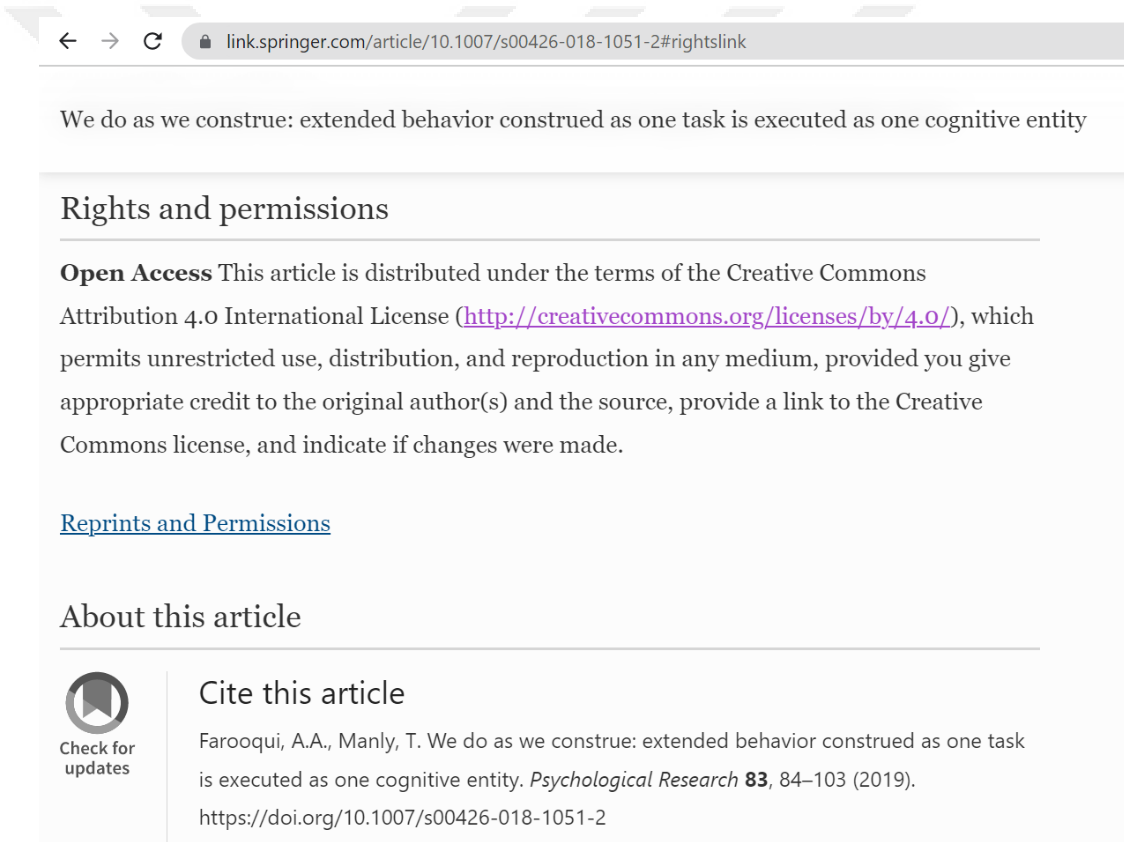
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We do as we construe: extended behavior construed as one task is executed as one cognitive entity

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