Master's Thesis
석사 학위논문

Multi-modal Generality for Hierarchical Organization of Cognitive Control

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Department of
Brain and Cognitive Sciences

DGIST

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by

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A thesis submitted to the faculty of DGIST in partial fulfillment of the requirements for the degree of Master of Science in the Department of Brain and Cognitive Sciences. The study was conducted in accordance with Code of Research Ethics[1]

11. 20. 2019

Approved by

Professor Hyeon-Ae Jeon (Advisor)	(signature)
Professor Wookyung Yu (Co-Advisor)	(signature)

[1] Declaration of Ethical Conduct in Research: I, as a graduate student of DGIST, hereby declare that I have not committed any acts that may damage the credibility of my research. These include, but are not limited to: falsification, thesis written by someone else, distortion of research findings or plagiarism. I affirm that my thesis contains honest conclusions based on my own careful research under the guidance of my thesis advisor.

Multi-modal Generality for Hierarchical Organization of Cognitive Control

Taehyun Yoo

Accepted in partial fulfillment of the requirements for the degree of Master of Science.

11. 20. 2019

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MS/BS
201825005

유 태 현. Taehyun Yoo. Multi-modal Generality for Hierarchical Organization of Cognitive Control. Department of Brain and Cognitive Sciences. 2020. 32p.
Advisors Prof. Hyeon-Ae Jeon, Co-Advisors Prof. Wookyung Yu

Abstract

Cognitive control is a process that enables humans to behave adaptively depending on current goals. The architecture of cognitive control has been specifically investigated in the concept of hierarchy. Researchers have examined the processing of hierarchical structures using visual information only. However, parsing multisensory information is also possible in the process of cognitive control, and it still remains unclear how the hierarchy of cognitive control is processed with multisensory information. Here, we hypothesized that the hierarchy of cognitive control would be processed in the same way regardless of sensory modality of information-be it visual or multisensory. To address this question, we designed two behavioral experiments using visual and auditory stimuli, and adopted cued-trial switching paradigm where each cue signaled the task to be performed: ① Auditory cue-Visual target (A-V) experiment and ② Visual cue-Auditory target (V-A) experiment. The experiment consisted of three subordinate-experiments comprised of three levels of hierarchy (Response, Feature and Dimension), with varying levels of complexity defined as the number of alternatives (one, two, and four). Participants were asked to press buttons following the set of cue-relevant mappings. In results, accuracy data showed main effects in both level of complexity and hierarchy in both experiments (less accurate as the level of complexity and hierarchy increase). With respect to reaction times, we could also find main effects in both level of complexity and hierarchy. A significant interaction was observed in both experiments. Taken together, results showed that, in both A-V and V-A experiments, participants' performance worsened with longer reaction times as the level of hierarchy and complexity increased. In conclusion, we suggest that hierarchy of cognitive control is constructed independent of sensory modality of information.

Keywords: cognitive control; hierarchy; visual; auditory; multi-sensory;

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I. Introduction

Cognitive control is the ability to behave appropriately for achieving their goals based upon situations [1, 2]. It enables us to plan ahead and to use rules when we select relevant actions, overcoming competitors [2]. Notably, we constantly deal with information from various sources of different sensory modalities in the complex external environment. Consider a simple example of customer entering a bank. According to the rule, customer takes a number then waits for his turn, comparing other numbers that bank teller calls. Otherwise, he would be turned away. Therefore, processing multisensory information is critical in making proper behaviors along with cognitive control, and this ability is defined as multisensory cognitive control [3-5].

Specifically, human behavior is hierarchically organized in that higher-level action controls lower-level actions [6]. Imagine ‘making a cup of tea’. People usually decompose this superordinate task into some subtasks such as ‘putting teabag in teapot’ and ‘pouring tea into cup’ to carry out. Even these subtasks can be decomposed into more subordinate subtasks like ‘lifting teapot’, ‘moving teapot to cup’ and ‘tilting teapot until tea pours’. Likewise, parcellation of the main goal into smaller sub goals efficiently is a central feature of goal-directed behavior

[7]. In this respect, abstractness is defined based on a classing rule whereby more abstract representations generalize across a class or set of representations at subordinate levels [8]. In other words, action representation is defined as more abstract to the extent that it generalizes over specific instances.

However, previous studies elucidated the hierarchy of cognitive control only in relation to processing visual information [9-14], and thus it remains unclear whether it is generalized for processing multisensory information such as auditory stimuli. Therefore, we aimed to investigate if hierarchy of cognitive control would be processed in the same way regardless of sensory modality of information. To do this, we conducted a behavioral experiment where we manipulated the levels of both complexity and abstractness of representations using visual and auditory stimuli [8]. The behavior experiment was divided by sensory modality in the manner of presenting task into 2 experiments. The first was Auditory-Visual (A-V) experiment in which cue was presented as auditory stimuli and object was presented as visual stimuli. The second was Visual-Auditory (V-A) experiment in which cue was presented as visual stimuli and object was presented as auditory stimuli. We hypothesized that participants will show worse performance (i.e., longer reaction times) as the level of complexity and hierarchy increase in both experiments.

II. Methods

2.1 Participants

Twenty-eight native Korean speakers participated in the behavior experiment. Exclusion criteria were colorblindness and history of medical or psychiatric illness. All participants were all right-handed with normal or corrected-to-normal vision. Right handedness were verified using the Edinburgh Handedness Inventory [15]. None of them had history of neuropsychological disorder. Normal color and nonverbal auditory perception of participants were verified by the Ishihara test and Seashore Rhythm test, respectively [16-17]. They were examined with Visual and Auditory Digit Span test assessing the working memory [18-19]. The participants who passed all 3 neuropsychological tests performed behavior experiment. They were randomly divided into two halves, those participated A-V, and those participated V-A experiment. Data from two participants in V-A experiment were excluded for low accuracy (< 80%). Informed consent was obtained from every participant in accordance with procedures approved by Ethical Committee / internal review boards in DGIST. After experiment, they were asked to fill in questionnaire and then paid for their participations. Detailed summary of the participants is shown in Table 1.

	A-V experiment	V-A experiment
Age (years)	20.79 ± 1.48	20.33 ± 0.98
Gender (M/F)	5/9	5/7
Handedness (LQ)	All right-handed (89.08 ± 8.89)	All right-handed (85.30 ± 7.73)

Table 1. Demographics and neuropsychological characteristics of participants from the behavior experiment (mean ± SD). Abbreviations: LQ (Laterality Quotient)

2.2 Experimental design

2.2.1. Behavioral tasks

We conducted two behavior experiments, A-V experiment (Figure 2) and V-A experiment (Figure 3). Each experiment was subdivided into three mini-experiments depending on hierarchical level (Response, Feature, and Dimension). Each of three mini-experiments manipulated the competition at the highest levels by increasing the number of alternatives at the level (1, 2 and 4). The design of each mini experiment is described below.

<Response experiment>

Response experiment manipulated the competition among responses by varying the number of response buttons corresponding to the cues of each block.

Before each block, instruction informed participants of rule about the 4 cue-to-response mappings which were relevant for the block (Figure 2A, 3A). Each cue-to-response mapping appeared for 3s one at a time. Total of 4 cue-to-response mappings appeared with 1-s intervals. They were repeated one more time after 3s to make participants be well-informed of rule. In the block, 8 trials were presented. Each of 8 trials was composed of one cue (Figure 2B, 3B). They were presented for 2s one by one, separated by 1-s fixation period. Participants were instructed to press button for the trial based on the learned cue-to-response mappings.

Response competition was manipulated depending on the number of responses that participants could select on a given block informed by instruction. This manipulation resulted in 3 conditions varying competition (Figure 2A, 3A). In 1-Response block (R1), 4 cues mapped to only one response, in other words, there was no response conflict. In 2-Response block (R2), 4 cues mapped to two responses (2 cues mapped to one response and the other 2 cues mapped to another response) so that there was response conflict. Lastly, in 4-Response block (R4), each of 4 cues mapped to one of four responses producing the greatest response conflict. Competition at superordinate levels was minimal as each cue was always relevant to a given response. Additionally, we used 16 cues so there are different buttons to respond in different blocks in a condition. For example, in R1 condition, 4 cues mapped to one response in a block and other 4 cues mapped to other one response in another block.

<Feature experiment>

Feature experiment manipulated the competition among features by varying the number of features of objects corresponding to the cues of each block. The presented object varied along one dimension and the other features along the other dimensions were fixed.

Before each block, instruction informed participants of rule about the 4 cue-to-feature mappings which were relevant for the block (Figure 2C, 3C). Each cue-to-feature mapping appeared for 3s one at a time. Total of 4 cue-to-feature mappings appeared with 1-s intervals. They were repeated one more time after 3s to make participants be well-informed of rule. In the block, 8 trials were presented. Each of 8 trials was composed of one cue and one object (Figure 2D, 3D). They were presented for 4s one by one, separated by 1-s fixation period.

Participants were instructed to press button for the trial based on the learned cue-to-feature mappings. If the presented object had cue-relevant feature, they made a “positive” response. Otherwise, they made a “negative” response.

Feature competition was manipulated depending on the number of features that corresponded to the cues on a given block informed by instruction. This manipulation resulted in 3 conditions varying competition (Figure 2C, 3C). In 1-Feature block (F1), 4 cues mapped to only one feature, in other words, there was no feature conflict. In 2-Feature block (F2), 4 cues mapped to two features (2 cues mapped to one feature and the other 2 cues mapped to another feature) so that there was feature conflict. Lastly, in 4-Feature block (F4), each of 4 cues mapped to one of four features producing the greatest feature conflict. Competition at superordinate levels was minimal as each cue was always relevant to a given feature in one dimension. Likewise, competition at subordinate levels was maintained equivalent to R2 blocks of the response experiment as every block always involved two responses (positive and negative). Additionally, we used 16 cues so there are different features corresponding to the cues in different blocks in a condition. For example, in F1 condition, 4 cues mapped to one feature in a block and other 4 cues mapped to other one feature in another block.

<Dimension experiment>

Dimension experiment manipulated the competition among dimensions by varying the number of dimensions corresponding to the cues of each block.

Before each block, instruction informed participants of rule about the 4 cue-to-dimension mappings which were relevant for the block (Figure 2E, 3E). Each cue-to-dimension mapping appeared for 3s one at a time. Total of 4 cue-to-dimension mappings appeared with 1-s intervals. They were repeated one more time after 3s to make participants be well-informed of rule. In the block, 8 trials were presented. Each of 8 trials was composed of one cue and two objects (Figure 2F, 3F). They were presented for 6s in V-A experiment and 4s in A-V experiment, separated by 1-s fixation period. Participants were instructed to press button for the trial based on the learned cue-to-dimension mappings. If the features of two objects along cue-relevant dimension were matched, they made a “match” response. Otherwise, they made a “nonmatch” response.

Dimension competition was manipulated depending on the number of dimensions that corresponded to the cues on a given block informed by instruction. This manipulation resulted in 3 conditions vary competition (Figure 2E, 3E.) In 1-Dimension block (D1), 4 cues mapped to only one dimension, in other words, there was no dimension conflict. In 2-Dimension block (D2), 4 cues mapped to two dimensions (2 cues mapped to one dimension and the other 2 cues mapped to another dimension) so that there was dimension conflict. Lastly, in 4-Dimension block (D4), each of 4 cues mapped to one of four dimensions producing the greatest dimension conflict. Competition at subordinate levels was maintained equivalent to F2 blocks of the response experiment as every block always involved match decision between features of two objects along cue-relevant dimension and entailed two responses (match and nonmatch). Additionally, we used 16 cues so there are different dimensions corresponding to the cues in different blocks in a condition. For example, in D1 condition, 4 cues mapped to one dimension in a block and other 4 cues mapped to other one dimension in another block.

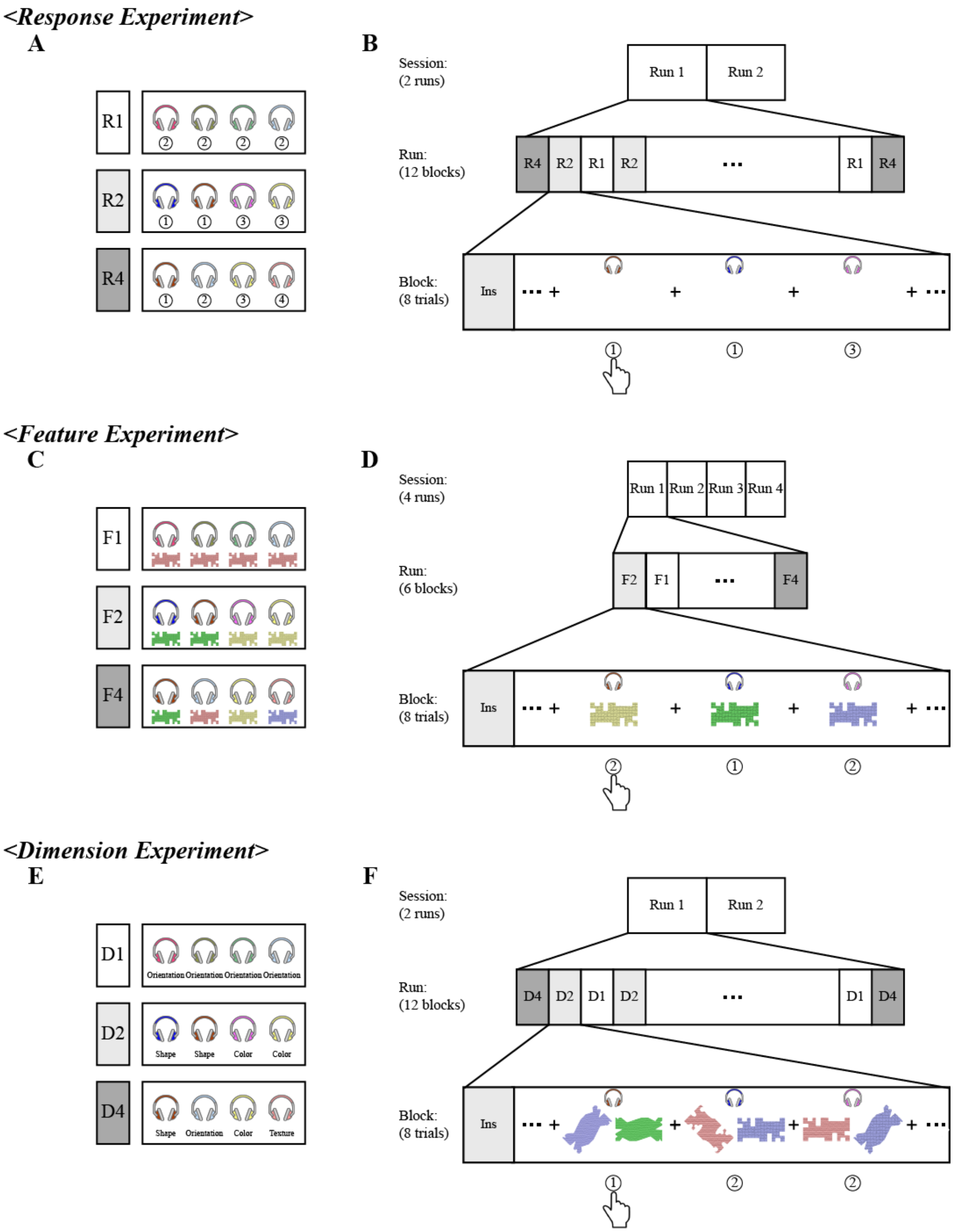

Figure 1. Experimental design of A-V experiment. (A) Instructions in Response experiment. Response competition varies by the number of responses that correspond to the colors on each block; On a given block, colors map to one (R1), two (R2), and four(R4) responses. (B) Trial sequences in Response experiment. Participants are instructed to press color-relevant-response button for each trial. Each number listed below ("①", "①", "③") indicates correct button for each trial. (C) Instructions in Feature experiment. The presented object varies along one dimension (color in this case) and the other features

along the other dimensions are fixed. Feature competition varies by the number of features that correspond to the colors on each block; On a given block, colors map to one (F1), two (F2), or four(F4) features. (D) Trial sequences in Feature experiment. Participants are required to press "positive" button if presented object has color-relevant feature or "negative" button if it has other features. Each number listed below ("②", "①", "②"; "①"-positive, "②"-negative) indicates correct button for each trial. (E) Instructions in dimension experiment. Dimension competition varies by the number of dimensions that correspond to the colors on each block; On a given block, colors map to one (D1), two (D2), or four(D4) dimensions. (F) Trial sequences in Dimension experiment. Participants are instructed to press "match" button if presented objects have same feature along color-relevant dimension or "nonmatch" button if it they had different features each other. Each number listed below ("①", "②", "②"; "①"-match, "②"-nonmatch) indicates correct button for each trial. Abbreviations: Ins (Instruction); R (Response); F (Feature); D (Dimension)

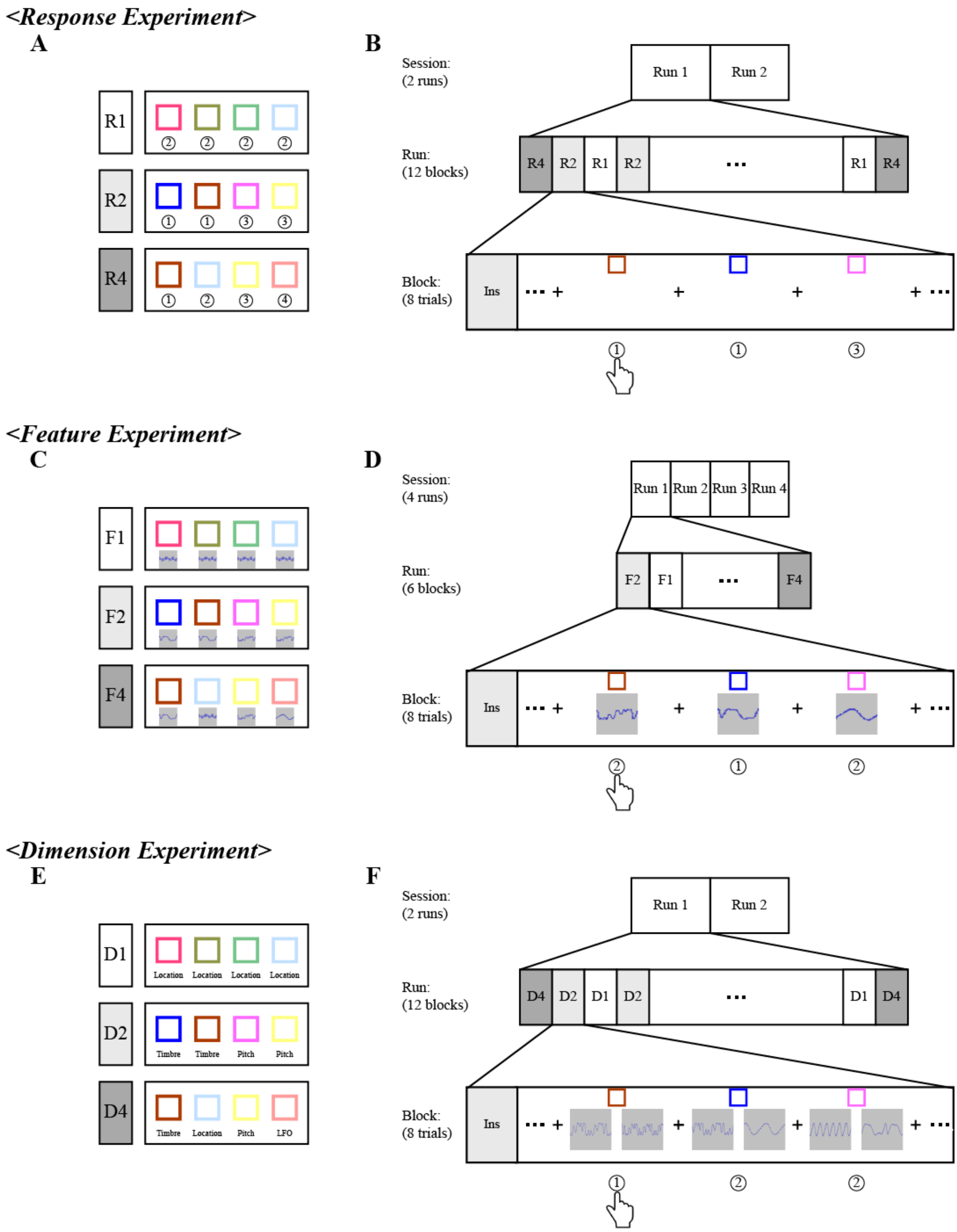

Figure 2. Experimental design of V-A experiment. (A) Instructions in Response experiment. Response competition varies by the number of responses that correspond to the colors on each block; On a given block, colors map to one (R1), two (R2), and four(R4) responses. (B) Trial sequences in Response experiment. Participants are instructed to press color-relevant-response button for each trial. Each number listed below ("①", "①", "③") indicates correct button for each trial. (C) Instructions in Feature experiment. Each object is described with its waveform. The presented object varies along one

dimension (timbre in this case) and the other features along the other dimensions are fixed. Feature competition varies by the number of features that correspond to the colors on each block; On a given block, colors map to one (F1), two (F2), or four(F4) features. (D) Trial sequences in Feature experiment. Participants are required to press “positive” button if presented object has color-relevant feature or “negative” button if it has other features. Each number listed below (“②”, “①”, “②”; “①”-positive, “②”-negative) indicates correct button for each trial. (E) Instructions in dimension experiment. Dimension competition varies by the number of dimensions that correspond to the colors on each block; On a given block, colors map to one (D1), two (D2), or four(D4) dimensions. (F) Trial sequences in Dimension experiment. Participants are instructed to press “match” button if presented objects have same feature along color-relevant dimension or “nonmatch” button if it they had different features each other. Each number listed below (“①”, “②”, “②”; “①”-match, “②”-nonmatch) indicates correct button for each trial. Abbreviations: Ins (Instruction); R (Response); F (Feature); D (Dimension)

2.2.2. Experimental paradigm

Hierarchical design, also called nested design is defined as a research design in which level of one factor are hierarchically subordinate to another level. Figure 3A, B depict one condition (complexity 2) of each three mini-experiments of which highest level represented is different, from response level to dimension level in A-V and V-A experiment, respectively. This figure illustrates the process resolving conflict from superordinate to subordinate level the step by step. Hence, the tree data structure in this experimental design is organized hierarchically.

This design allowed to vary competition of each four mini-experiments parametrically at the respective four hierarchical levels keeping competition at subordinate level constant and at superordinate levels minimal. More specifically, in response experiment, competition at superordinate levels was minimal as each cue was always relevant to a given response. In feature experiment, competition at superordinate levels was minimal as each cue was always relevant to a given feature. Competition at subordinate levels was constant as there are always two alternatives, “positive” and “negative”. In dimension experiment, competition at superordinate levels was minimal as each cue was always relevant to a given dimension.

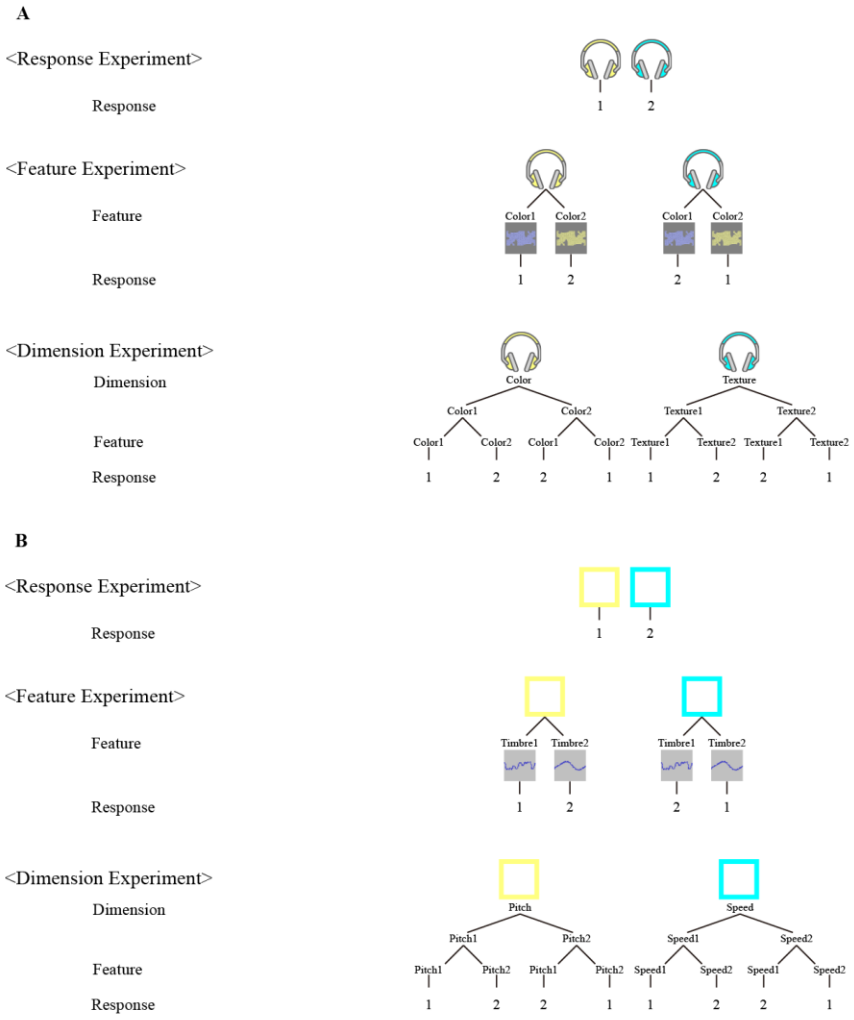

Figure 3. Hierarchical Design in A-V and V-A experiment. The figure illustrates conditions which have two alternatives at the highest level of each experiment (R2, F2 and D2 conditions) in (A) A-V experiment (B) V-A experiment. The hierarchical level is derived from abstractness in which superordinate level are more abstract than subordinate level so that the former includes the latter.

2.3 Stimuli

<A-V experiment>

In A-V experiment, we used 16 auditory cues as pure tones characterized by their different tones and frequencies. Loudness of each cue was controlled by Adobe Audition® CC. The volume was set individually for each participant to a comfortable level. Visual objects consisted of 256 items (4 shapes X 4 orientations X 4 colors X 4 textures). They were made by using the Adobe Illustrator® CC software. The shapes was so ambiguous that they did not resemble any easily verbalizable known objects.

<V-A experiment>

In V-A experiment, we used 16 visual cues as squares characterized by their different colors. Auditory objects consisted of 256 items (4 timbres X 4 locations X 4 pitches X 4 periods of LFO). They were made by using the FL studio 12 software with the purpose of being constructed so artificially and unfamiliarly that they were not verbalized. Loudness of each item was controlled by Adobe Audition® CC (-14.00 LUFS) [20]. The volume was set individually for each participant to a comfortable level.

2.4 Procedure

We conducted behavioral experiment for 3 days to reduce fatigue effect. Day 1: Participants was verified with several neuropsychological tests. After this, they were trained and practiced experiment. Day 2: Participants performed half of the behavioral experiment. The order was counterbalanced across participants. Day 3: Participants performed the remaining of the behavioral experiment. The order was counterbalanced across participants. After closing the experiment, participants were asked to fill in a brief questionnaire about strategies they used.

Response experiment consisted of 2 runs in total (Figure 1B, 2B). Participants performed one run for each day. In each run, they performed 96 trials comprised of 12 blocks. Blocks were randomized and counterbalanced for 3 conditions. Feature experiment consisted of 4 runs in which feature competition was manipulated along distinct dimension, respectively (Figure 1D, 2D). Participants performed two runs for each day. In each run, they performed 48 trials comprised of 6 blocks. Blocks were randomized and counterbalanced for 3 conditions. Dimension experiment consisted of two experiments in total (Figure 1F, 2F). Participants performed one run a for each day. In each run, they performed 96 trials comprised of 12 blocks. Blocks were randomized and counterbalanced for 3 conditions.

2.5 Preliminary experiment

Before behavior experiment, we carried out a preliminary experiment to confirm that the features along each dimension of an object were defined well so that each stimulus was distinguished from the others. We adopted ABX test paradigm which requires participants to identify detectable differences between two different objects on each sensory modality (i.e., visual and auditory ABX) [21]. For each trial, two different stimuli (A and B) were presented for 2s with 0.5-s interval sequentially followed by one stimulus (X) that was randomly same with A or B (Figure 4). The participants were then instructed to identify X as either A or B by pressing button. A and B had different features along one dimension and same feature along the other dimensions. Seven and four undergraduate or graduate students from the DGIST, who did not take part in the behavior experiment, participated the visual and auditory ABX test, respectively.

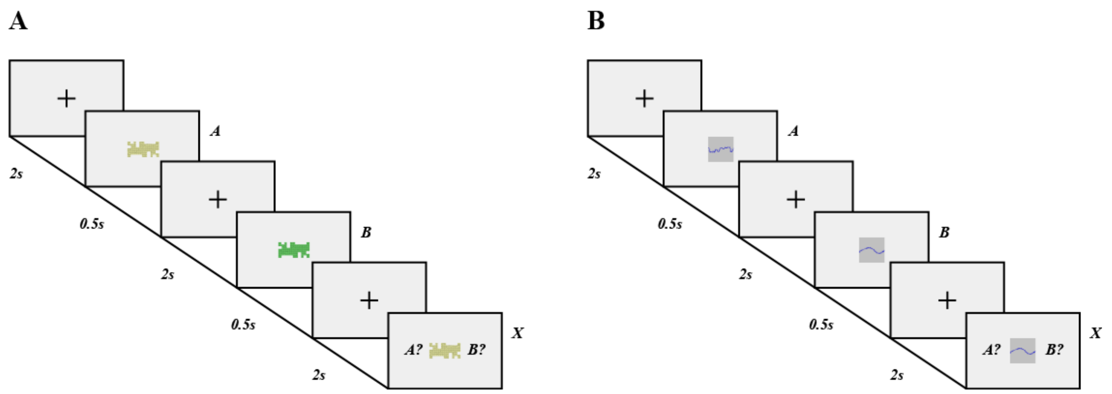

Figure 4. Schemes of ABX test for (A)visual and (B)auditory modalities. Participants are presented three objects (i.e., A, B and X which is same as either A or B). They are then instructed to choose a button based on the identification of X as either A or B.

III. Results

3.1 Accuracies and RTs in the preliminary experiment

To confirm that each target which was used in behavior experiment in both sensory modalities was much distinguishable from the others, we conducted a preliminary experiment. We verified that each object was well distinguishable as the accuracy of each dimension was much higher than chance level. Detailed summary of the results is shown in Table 2 and 3.

Visual ABX test	Shape	Orientation	Color	Texture
Accuracy (%)	97.7	96.0	99.2	97.7
RT (ms)	584.8	581.5	522.7	558.3

Table 2. Accuracy and RT in visual ABX test. The numbers represent the mean accuracy and reaction time for each dimension in visual ABX test.

Auditory ABX test	Timbre	Location	Pitch	Speed
Accuracy (%)	89.7	98.8	98.2	98.5
RT (ms)	940.6	774.0	953.6	1174.4

Table 3. Accuracy and RT in auditory ABX test. The numbers represent the mean accuracy and reaction time for each dimension in auditory ABX test.

3.2 Accuracies and RTs in the behavior experiment

After confirming the distinction between objects, we carried out the behavioral experiment. For accuracy data, in both experiments, we found main effects in both level of complexity [①A-V: $F(2, 156)=130.13$, $p<.001$; ②V-A: $F(2, 132)=22.223$, $p<.001$] and hierarchy [①A-V: $F(3, 156)=358.17$, $p<.001$; ②V-A: $F(3, 132)=317.186$, $p<.001$] (Fig. 5A, B). A significant interaction was observed in both experiments [①A-V: $F(3, 156)=17.17$, $p<.001$; ②V-A: $F(3, 132)=2.793$, $p<.05$].

Regarding RT, we also observed main effects in both level of complexity [①A-V: $F(2, 156)=22.202$, $p<.001$; ②V-A: $F(2, 132)=7.093$, $p<.01$] and hierarchy [①A-V: $F(3, 156)=15.651$, $p<.001$; ②V-A: $F(3, 132)=98.783$, $p<.001$] (Fig. 5C, D). A significant interaction was observed in A-V experiment only [①A-V: $F(2, 156)=2.429$, $p<.05$; ②V-A: $F(2, 132)=1.370$, ns].

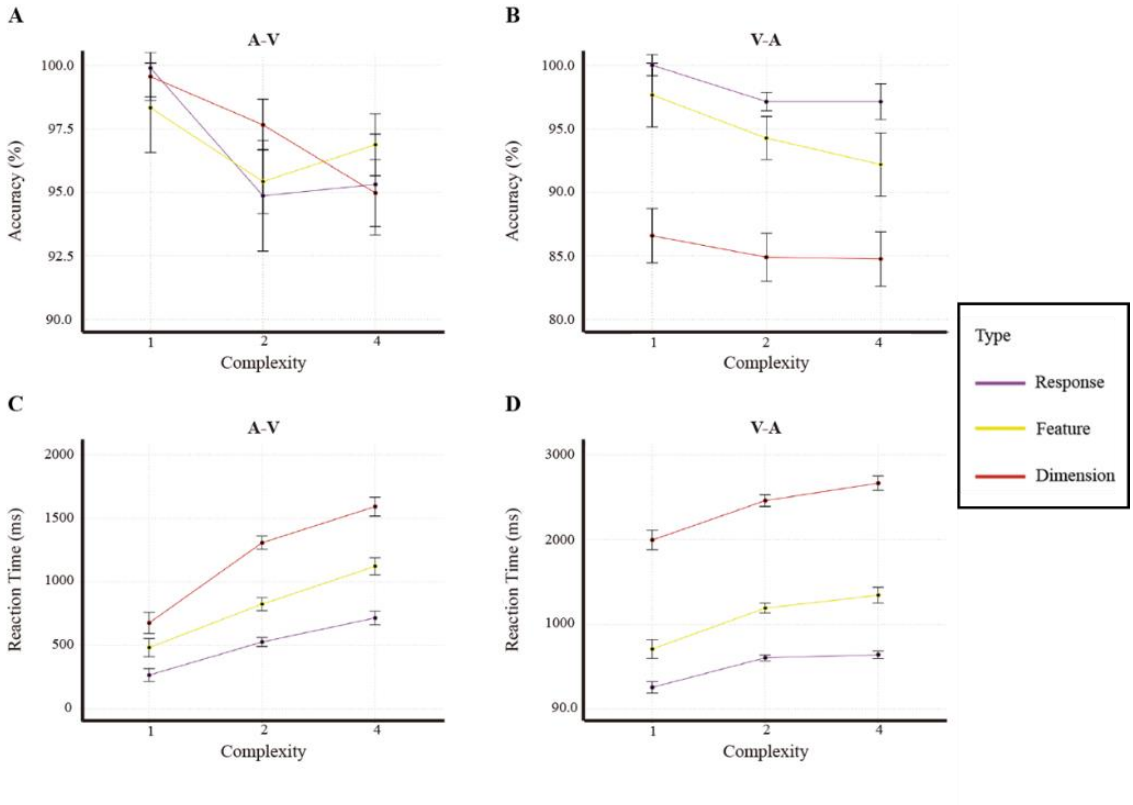

Figure 5. Accuracies and RTs of A-V and V-A experiment. The graphs depicts the mean accuracy and reaction time in both A-V and V-A experiments. The accuracy for each dimension is measured in (A) A-V experiment and (B) V-A experiments. The RT for each dimension is also measured in (C) A-V and (D) V-A experiments. X axis denotes complexities while Y shows accuracy in (A) and (B) and RT in (C) and (D).

IV. Discussion

Our study explored the multi-modal generality for hierarchical organization of cognitive control. We showed that RT was slower as the level of complexity and hierarchy increased in both experiment. By minimizing and fixing the effects of working memory in both experiments [22-25], we verified the existence of hierarchical processing across sensory modalities where higher level of processing influences lower level of processing to facilitate appropriate behaviors. Overall, our findings suggest the claim that architecture of cognitive control is structured hierarchically as a computational model regardless of sensory modality of information whereby sensory information is transformed into a conceptual representation that is essential for goal-directed behavior [26-27].

4.1 Hierarchy of cognitive control using multisensory information

According to information theory, cognitive control is mainly illustrated as a computational model, such that there is a control mechanism that allows the computational allocation of resources to process information related to goal [26-27]. In this framework, information should be encoded as conceptual representation so that it is easily accessible regardless of sensory modality [28]. The present study suggests the architecture of cognitive control is structured hierarchically as a computational model regardless of sensory modality of information.

The design of this experiment manipulated control demands by varying two factors, (1) the hierarchical level of representations to be selected and (2) the difficulty of selection via complexity, thereby making it possible to entail conflict resolution at each level in a sense. Further, the present study counterbalanced for the complexity conditions at each hierarchical level to investigate the hierarchical effects. We also minimized the influence of working memory that is known to be important for cognitive control to examine the effects [22-25]. To this end, we presented the set of cue-relevant mappings in the same format which is presented in the instruction followed by each block of every mini-experiments. Additionally, we made stimuli distinguishable but ambiguous so that they did not resemble any easily verbalizable known objects. It prevented participants from utilizing semantic relationships that could work as a confounding factor [29]. Therefore, by ruling the influence of other factors out, the complexity and hierarchy effects remained as the only distinction between conditions. Accordingly, disparities in behavioral measurements between the conditions may be interpreted as computational delays induced by the hierarchy of cognitive control.

Concerning complexity, conflict processing posits that the amount of informational uncertainty that should be reduced for appropriate behavior was proportional to the number of alternatives from which participants must choose one, and this effect induced prolonged RTs and increased error rate in higher- than lower-uncertainty [27, 30-32]. In this regard, differences in RTs between two conditions that have different number of alternatives in both A-V and V-A experiments may be explained by conflict processing. On the contrary to RT data, we did not find this tendency in accuracy data in A-V experiment. This could be interpreted as ceiling effect, such that the accuracies of all conditions cluster toward the high end and they were influenced by the conflict processing no longer [33].

Based on the definition of hierarchy, processing hierarchies requires that superordinate levels asymmetrically reflect subordinate processing, allowing information to be inherited from higher to lower levels [34]. Our RT data suggests that there are more recruiting cognitive systems in higher level experiments, and it may be interpreted as hierarchy effects based on the experimental design of both A-V and V-A experiment. Taken together, our results support the architecture of cognitive control is structured hierarchically as a computational model regardless of sensory modality of information so that the sensory information is processed in the same way.

4.2 Influence of sensory modality on cognitive control

Involving sensory information, research has shown that vision is more dominant than any other senses suggesting 'Visual Dominance Theory', such that processing of visual information seems to dominate the processing of information from the other modalities [35-36]. Our results support this theory in that performance measured by RT and accuracy was better in the A-V experiment in which participants performed task with visual targets than V-A experiment in which participants performed task with auditory targets. We also observed the RT of Dimension experiment is much higher than Response and Feature experiment in V-A experiment compared to in A-V experiment. It is caused by auditory masking effect in which one auditory target hinders participants to parse the other auditory target and vice versa so that participants became unsure about targets with ambiguity [37].

These results can be explained by ‘Signal Detection Theory (SDT)’ [38-39]. SDT is the method which is mainly used to measure how we make decisions under conditions of uncertainty [39]. It is known that cognitive control is facilitated by perceptual confidence which relies on the estimation of reliability for perceived stimuli [40]. As vision is more accurate and reliable than the other senses, processing visual target may enhance cognitive control more easily [36]. Accordingly, differences in behavioral measurements between both A-V and V-A experiments may be interpreted as computational delays influenced by the sensory modality of information.

4.3 Hierarchical organization of prefrontal cortex

It is widely known that the human prefrontal cortex (PFC) plays an important role in cognitive control [41-45]. Accordingly, the architecture of cognitive control has been studied for investigating functional organization of PFC [46-53]. More recently, models of functional organization of PFC are proposed to subserve the hierarchy of cognitive control [7-12]. These models validate hierarchical organization of PFC along its rostro-caudal axis whereby posterior-to-anterior regions of PFC process progressively higher-order control [34, 54-55]. Specifically, caudal frontal regions are engaged for concrete action representation, and rostral frontal regions are engaged for abstract action representation [11]. However, previous studies elucidated the hierarchical organization only when dealing with visual information, and therefore, it will be critical to further examine the multi-modal generality of hierarchical organization in PFC remains to be investigated using fMRI experiment.

V. Conclusion

Given that participants' performance worsened with longer reaction time as the level of hierarchy and complexity increased in both A-V and V-A experiments, we suggest that hierarchy of cognitive control is constructed independent of modality of information. To the best of our knowledge, it's the first approach for multimodal extension in hierarchical processing. Also, this study has higher ecological validity in that the experimental design dealt with the processing multisensory information. Finally, the results suggest the need of further investigation on the neural underpinnings of multisensory hierarchical processing. Thus, the functional resonance imaging (fMRI) experiment with this design may contribute to identifying hierarchical organization of PFC in processing multisensory information.

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요 약 문

다중감각 정보를 처리할 때에 있어서

인지 통제의 보편적 위계 구조

인지 통제란, 인간은 이루고자 하는 목표에 부합하게끔 행동하는 능력을 말한다. 인지 통제는 다양한 구조를 통해 처리되는데, 대표적으로 상황에 따라 달라지는 상위 목표에 따라 행동이 조절되는 위계 구조가 있다. 하지만 이전 연구는 인지 통제의 위계 구조에 대해 단일감각 정보를 다룰 때에만 살펴봤다는 한계가 있다. 이에, 본 논문은 다중감각 정보를 처리할 때에 있어서 인지 통제의 위계 구조를 다루고 있다. 이를 확인하기 위해 처리하는 정보의 감각적 양상과 목표의 상위 관계를 다르게 조작하여 실험을 구분하였다. 그 결과, 참가자들은 처리하는 정보에 따라 조절되는 행동의 상위 목표와 복잡성에 따라 행동학적 결과가 유의한 결과를 보임을 확인하였다. 더불어, 감각적 정보의 양상에 상관없이 행동적 결과의 추세는 유사함을 확인하였다. 본 연구의 결과와 의의는 논의에서 상세히 다루었다.

핵심어: 인지 통제, 위계 구조, 다중감각