NEURAL ACTIVATION DURING DUAL-TASK PROCESSING WITH SIMULTANEOUS STIMULUS PRESENTATION

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Abstract

Despite extensive literature regarding response time cost in dual-task processing, the predominant procedures do not isolate task-processing from stimulus processing. The purpose of this study was to investigate the neural correlates of motor learning and dual-task processing using a procedure in which stimulus processing was held constant. Participants learned to make bimanual or unimanual hand responses to indicate the individual or associated pairs of stimuli in two types of tasks. In the independent task (two-set task), participants made a response with the left hand corresponding to the left image shown on the screen and a response with the right hand based on the right image, simultaneously. In the relational task (one-set task), the individuals respond with button-presses to the pair of images shown. Subjects performed an equal number of trials per condition and neural activation during each trial was recorded using fMRI. Preliminary behavioral results showed that there was a significant interaction between task condition and response type, as well as a greater response time-cost for bimanual responses in the independent condition. Imaging analysis suggests significantly greater neural activation in the inferior frontal sulcus (IFS) during the independent task ($p<0.01$). These preliminary results seem to support the behavioral findings of Schumacher et al. (2018) and implicate, at a neural activation level, a dissociation in the location of task-processing between the independent and relational tasks.

Introduction

The fields of attention and dual-task interference has experienced an evolution from the bottleneck theories of the 1980s and 1990s (Hazeltine, Ruthruff, & Remington, 2006; Hazeltine, Teague, & Ivry, 2002; McCann & Johnston, 1992; Pashler, 1994; Schubert, 1999; Schumacher et al., 1999; Van Selst & Jolicoeur, 1997) to theories of adaptive executive control (Meyer et al., 1995; Schumacher et al., 2001). Further, the field has shifted from assessing the Psychological Refractory Period (PRP) Effect - the slowing of RTs for the subsequent stimulus presented after a short period of time (Welford, 1952; Meyer & Kieras, 1997; Schumacher et al., 1999) - to the "task manipulation procedure" paradigm (Schumacher et al., 2018). The task manipulation procedure aims to assess the Task-file Representation hypothesis, which suggests that exposure to stimuli update existing representations, such that they become more abstract and lead to more complex resulting behaviors (Schumacher & Hazeltine, 2016).

Based on the merits and limitations of the extensive literature of behavioral paradigms for studying dual-task interference, the proposed study will further examine the "task manipulation procedure", debuted by Schumacher et al. (2018) and investigate the neural correlates of dual-task interference using this procedure. This procedure differs from others in its ability to isolate task-related interference by structuring the task such that participants complete them both simultaneously without preference to one or the other, in contrast to the PRP procedure that has been used exclusively to date (Schumacher et al., 2018). Similarly, this procedure eliminates the danger of demand characteristics, as the assumed "dual-task" trials (known as relational trials) in which two images are coded to one set of hand responses. These trials require the computational association of two images, but subjects only produce one manual response for the pair of images, which allows for the isolation of the structural location of the interference in the processing chain at either the perceptual processing or decision making/executing phase. Moreover, the temporal overlap with the presentation of two images at once for both single and dual-task trials increases the strength of this paradigm over others used previously in the literature. The aim of this study was to repeat this paradigm, culminating in a test session in the fMRI in order to determine the role of the interior frontal sulcus (IFS), shown first by Stelzel et al. (2006), in coordinating dual-task processing. It was hypothesized that there would be a significant interaction between condition and response on participant reaction time during the task, as seen in Schumacher's original behavioral study (2018) and that there would be significantly greater neural activation in the IFS during the independent task than the relational task.

Literature Review

The robust literature of the field of Cognitive Neuroscience is the result of decades of modulation between potential theories of human behavior and adjustment of those theories to fit new knowledge about the structure and function of the brain. This study contributed a refined account of the areas of the brain involved in single and dual-task processing, as well as the influence of bimanual and unimanual motor responses on dual-task cost.

In the early days of dual-task interference research, two opposing theories emerged that disputed the origin of the time cost – the increase in amount of time required to complete a task - observed when participants must complete two tasks nearly simultaneously. The first proposed that the reason for the delay was a bottleneck of the two streams of information. Only one stream of information could pass through the bottleneck at one time, so the other stream of processing must be postponed (Welford, 1952). The opposing perspective hypothesized that there is a limit to the attentional capacity of the human mind and can be divided between multiple tasks. Therefore, the first task or the task of greatest importance would receive a larger allocation of attention than the second task, and the response time for the second task will be slower than the first task (McCleod, 1977).

Many researchers attempted to develop experimental paradigms to evaluate one theory or another and further refine the proposed explanations for dual-task interference (McCann & Johnston, 1992; Meyer et al., 1995; Pashler, 1994). McCann & Johnston specifically examined the efficacy of both bottleneck and capacity theories in describing dual-task response costs when stimulus onset asynchrony (SOA), or the time between the appearance of each stimulus, decreases (1992). Tombu et al also investigated the efficacy of a bottleneck theory of attention, specifically the unified bottleneck hypothesis, which proposed that an excessive load in either perceptual encoding or response selection impacts the other because the two streams of information processing are interconnected. They aimed to assess this hypothesis and evaluate the neural correlates of dual-task processing with a time-resolved fMRI scan while participants completed a perceptual-encoding task and a decision-making task (2011). These researchers were specifically interested in assessing whether there was consistent activation in the ROIs that were previously associated with the response-selection bottleneck across both types of tasks, specifically the aSMFC, IFJ, IPS, and bilateral insula (2011). The perceptual-encoding task used in this study required participants to remember four unique (hard) or four identical (easy) consonants presented at the beginning of a trial and identify whether the probe letter at the end of the trial matched one of the four consonants. This task was immediately followed by an auditory-manual task with both short and long SOA. Tombu et al found that the ROIs were all most active with high demand task (short SOA), which is consistent with their hypothesis.

These experiments helped to distinguish between the concepts of attentional capacity and information processing; however, the procedure used in these studies were limited in their generalizability because the stimuli appeared sequentially each time, though humans typically encounter many types of stimuli that must be processed simultaneously. Other researchers have developed new procedures to address this limitation, requiring participants to respond to two stimuli of different modalities presented simultaneously (Hazeltine, Teague, & Ivry, 2002; Schumacher et al., 2001; Stelzel et al., 2006; Schumacher et al. 2016, Schumacher et al., 2018).

In 2006, Stelzel, Schumacher, and others continued to assess dual-task interference using a procedure with simultaneous onset of two stimuli of varying modalities, while also investigating the neural correlates of single-task and dual-task processing across two modalities. Their study found that the inferior frontal sulcus (IFS) was significantly more active during modality-incompatible dual tasks (Stelzel et al., 2006). Schumacher later addressed the inconsistent cognitive load in previous paradigms, where one stimulus must be identified, with one response, in single-task trials, but two stimuli must be identified, with two responses, in dual-task trials, with the task manipulation paradigm (2018).

The task manipulation paradigm (2018) consists of several repetitions of an independent and a relational task where participants must make the correct button presses that correspond to each of the two individual images (independent) or the pair of images (relational) shown on the screen (Schumacher et al. 2018). Both unimanual and bimanual button presses were required for some images in both the relational and independent tasks. Schumacher et al overcame the limitations of previous dual-task procedures and also demonstrated a significant difference between response time for unimodal responses during a bimanual task versus a unimanual task (2018).

Building off of Schumacher's most recent work, this study will examine the areas of activation in the brain during the computation of a singular or dual task with unimodal or bimodal hand responses. Since the development of the improved paradigm that eliminates the inconsistency in cognitive load, there has not been any investigation into the areas of brain activation during single or dual-task processing with unimodal or bimodal responses. Due to the aforementioned difference in cognitive load magnitude of the previous experiments in the literature, it is not clear whether the activation that was observed in prior studies can be attributed exclusively to dual-task processing, or simply to a greater magnitude of cognitive load. The proposed experiment would provide much-needed data about the structures of the brain that are active when dual-task processing is occurring, perhaps confirming the role of the IFS that was discovered previously (Stelzel et al. 2006) or implicating the role of the posterior lateral prefrontal cortex, that was found in recent experiment using transcranial direct current stimulation (tDCS) (Filmer, Mattingley, and Dux (2013).

Methods

Participants

Four individuals (age range 18-30, 3 female) participated in this experiment. This study was carried out in accordance with the recommendations of the Georgia Institute of Technology, Institutional Review Board. The protocol was approved by the Institutional Review Board. All participants gave written informed consent in accordance with the Declaration of Helsinki. Participation was voluntary. Participants were compensated with course credit. Before they began the first session, participants reviewed the task instructions [Appendix A].

Stimuli

This study replicated the stimuli specifications Schumacher et al. (2018) for grayscale face and place images. For the independent condition, three randomly selected faces from the set were assigned to a middle-finger response, an index-finger response or no response on the same hand. Right and left-hand assignments for face or place images were counterbalanced across four sub-groups of participants. For the relational condition, each possible pair of 3 face and 3 place images was assigned to a middle-finger response, an index-finger response or no response using both hands.

Behavioral Procedure

The experiment consisted of two sessions in a “mock” magnetic resonance imaging scanner and one session in a 3T magnetic resonance imaging scanner, within one week of each other. Informed consent and magnetic resonance safety screening was obtained prior to session 1 and again prior to session 3. Before beginning each session, participants were reminded that they would complete two conditions and shown an example of each. On the screen, one stimulus (face or place) appeared to the left of a centered, fixation cross and a second stimulus appeared simultaneously to the right of the fixation (face or place, opposite category of stimulus 1). The stimulus array was viewed at 2.5° x 14° visual angle in the “mock” scanner and magnetic resonance imaging scanner. Participants responded to stimuli using the index and middle fingers of both hands to press buttons to indicate the learned responses. During the first two sessions, participants completed one practice cycle and four cycles. Each cycle consisted of four blocks of 18 relational trials per block and two blocks of 18 independent trials per block.

During the relational (1-set) task participants were instructed to respond with the correct hand response that corresponds to the pair of images on the screen. During the independent (2-set) task, participants were instructed to respond with their left hand to the image positioned left of the fixation cross and with their right hand to the image on the right of the fixation cross. After each incorrect trial, the correct mapping was shown on the screen. Participants received feedback about their left and right accuracy and mean reaction time after each block. In session 1 and 2, the practice sessions, there was a consistent inter-trial interval of 1000ms and each image appeared on the screen for 2000ms. In order to qualify to participate in the 3rd session, participants were required to exceed 80% overall accuracy for both the independent and relational tasks by the end of the second practice session.

During the third session, participants completed one relational practice block and one independent practice block followed by six test cycles during a functional magnetic resonance imaging (fMRI) scan. Participants received feedback about their left and right accuracy and mean reaction time after each block. In session 3, stimuli appeared on the screen for 2000ms and the inter-trial interval alternated randomly between 2000ms, 4000ms, and 8000ms, in order to account for anticipation effects in BOLD signal.

fMRI Procedure

All images were acquired at the Georgia Institute of Technology with a Siemens Magnetrom TrioTrim MRI Scanner and 12-channel head coil, and cushions were used to stabilize participants and reduce head motion. A structural T1-weighted MPRAGE anatomical scan (slice thickness = 1.0 mm, flip angle = 9°). was acquired at the beginning of the session, followed by six functional runs. Each of the runs were acquired using a whole-brain single-shot, gradient-echo, echo-planar (echo time=30ms, field of view = 192-mm, flip angle = 90°, repetition time = 2000ms). Individual functional volumes consisted of 36 axial-slices with 3-mm thickness and 1-mm gap.

Data Processing: Behavioral

Data from trials where an incorrect response was recorded or where a response occurred within 200ms were removed. Mean reaction time was calculated for bimanual and unimanual responses across independent and relational trials for session 3 only. A two-factor within-subjects ANOVA was performed to assess the interaction between Condition (Independent v. Relational) and Response (Unimanual v. Bimanual).

Data Processing: Imaging

Anatomical images were used to create group level mean neural activation at a corrected q-value of 0.01 was mapped onto a standard anatomical brain mask using Analysis of Functional

NeuroImages (AFNI) software, an open-source program, funded by NIH and accessible for research purposes (Cox, 2019). Data were segmented, spatially normalized onto a standard MNI atlas space and corrected for motion.

Results

It was hypothesized that task-representation would affect dual-task cost, as well as neural activation in the frontal lobe, specifically in the IFS. Response time data from session 3 was analyzed to ensure that the same effect was found in this investigation as Schumacher et al. originally saw in the first iteration of this paradigm (2018). The Huynh-Feldt correction was used for all comparisons because the data violated the assumption of sphericity.

Behavioral Data

Response time was evaluated for session 3. The response time data indicate a dual task cost during the independent conditions, as participants were much slower to complete bimanual responses (95.92s ± 1.64) than unimanual responses (56.07s ± 15.64) (Figure 1). In the relational condition, the mean response time for bimanual responses (90.45s ± 7.08) was marginally greater than unimanual responses (50.95s ± 14.01) (Figure 1). A two-way, within-subjects ANOVA yielded a significant interaction $F(1,7) = 28.885$, $p < .001$.

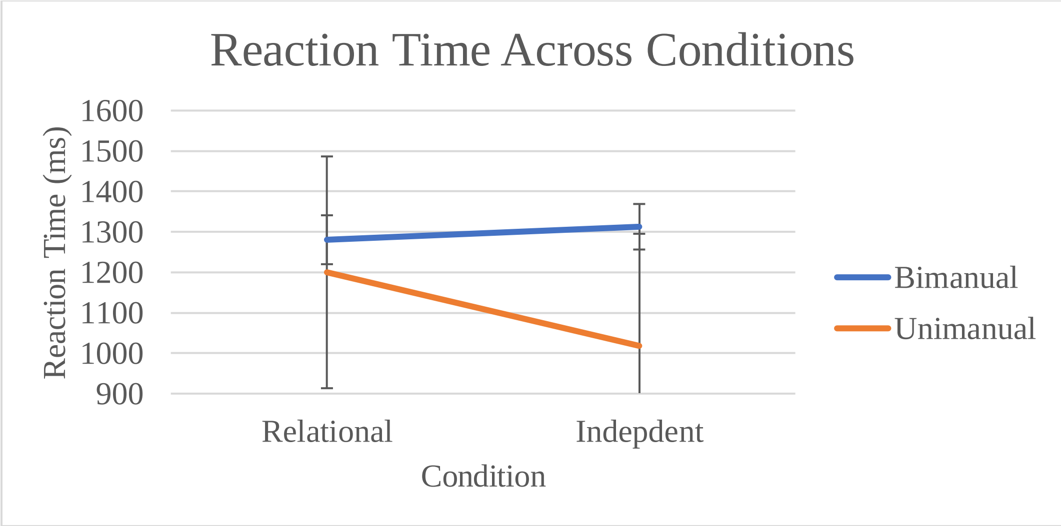


Figure 1. Mean Response Time Across Conditions. The graph shows the mean Response Time across conditions and response type (Bimanual, Unimanual) during Session 3 with error bars

indicating standard deviation for each condition and response type. Error bars indicate standard deviation.

Neural Activation Data

Individual activation maps (Appendix B) for each of the four pilot subjects showed generally increased activation in frontal lobe regions during the independent task over the relational task. The activation maps also showed a slight increase in activation in the superior parietal lobe during the relational task over the independent task.

Analysis of group level neural activation during the independent task that was significantly different from the relational task ($p<0.01$) yielded the images in Figure 4.

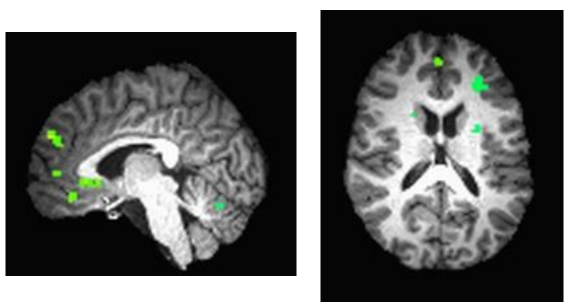


Figure 2. Neural Activation Areas for Independent v. Relational Task. Images depict areas of neural activation in the Independent task that are significantly different ($p=0.01$) from activation areas during the Relational task, specifically IFS, precuneus, and ACC.

Discussion

Condition and motor response significantly affected response time, in the case of the independent task when subjects made bimanual responses. This is consistent with other studies that show an increase in response time when two motor responses are executed in response to two separate tasks and the presentation of two stimuli. This particular procedure rules out the possible effect of number of stimuli presented on the time it takes a participant to process the task and make a response in both the single and dual task conditions.

Preliminary neural activation analysis showed an increase in frontal lobe activation while subjects performed the independent task and an increase in superior parietal lobe activation when subjects performed the relational task. While frontal lobe activation supports the hypothesis of this study, the occurrence of superior parietal lobe activation was unexpected. Upon collecting functional MRI data from many other subjects, statistical analyses will be performed to determine if the difference in parietal lobe activation during the relational task is significant.

Group level neural activation analysis shows significant activation of the inferior frontal sulcus (IFS), precuneus and anterior cingulate cortex (ACC) (Figure 3), which is also shown in previous neural activation analyses during task-switching (IFS: Stelzel, Basten & Fiebach, 2011; Stelzel, 2006). There is a strong chance of type I error in these statistics because of the small sample size (N=4). In forthcoming data collection, reliable statistical analyses will be conducted with a larger sample size.

One limitation of this paradigm is the inconsistency in inter-trial interval between practice sessions 1 and 2 and test session 3. In order for the two practice sessions to prepare the participants as best as possible for the test session in the MRI scanner, it would be wise to adjust the procedure to include a jittered inter-trial interval between 2000ms, 4000ms and 8000ms.

This pilot-study has confirmed that there is a significant interaction between condition and response type, which affects participant response time while completing this task. There is also significant activation in regions of the pre-frontal cortex only in the independent task, which is consistent with the prediction that, despite holding stimulus presentation constant in this task, there are different regions of activation when participants complete two-tasks at once, regardless of whether they are executing one or two motor responses. Further data collection is ongoing to continue the preliminary research that was conducted in this study. The forthcoming findings will help narrow the field of cognitive neuroscience and dual-task interference research towards a more defined understanding of the functional differences in neural processing while humans are “multitasking”.

Works Cited

Cox, R. W. (2019) AFNI: Analysis of Functional NeuroImages (Version: AFNI_19.1.04). Available from: https://afni.nimh.nih.gov/

Filmer, H. L., Mattingley, J. B., & Dux, P. E. (2013). Improved multitasking following prefrontal tDCS. *Cortex, 49*(10), 2845-2852. doi:10.1016/j.cortex.2013.08.015

Hazeltine, E., Ruthruff, E., & Remington, R. W. (2006). The Role of Input and Output Modality Pairings in Dual-Task Performance: Evidence for Content-Dependent Central Interference. *Cognitive Psychology, 52*(4), 291-345. doi:10.1016/j.cogpsych.2005.11.001

Hazeltine, E., Teague, D., & Ivry, R. B. (2002). Simultaneous Dual-Task Performance Reveals Parallel Response Selection After Practice. *Journal of Experimental Psychology: Human Perception and Performance, 28*(3), 527-545. doi:10.1037/0096-1523.28.3.527

McCann, R. S., & Johnston, J. C. (1992). Locus of the Single-Channel Bottleneck in Dual-Task Interference. *Journal of Experimental Psychology: Human Perception and Performance, 18*(2), 471-484. doi:10.1037/0096-1523.18.2.471

McLeod, P. (1977). Parallel processing and the psychological refractory period. *Acta Psychologica., 41*(5), 381-396.

Meyer, D. E., Kieras, D. E., Lauber, E., Schumacher, E. H., Glass, J., Zurbriggen, E., . . . Apfelblat, D. (1995). Adaptive executive control: Flexible multiple-task performance without pervasive immutable response-selection bottlenecks. *Acta Psychologica, 90*(1), 163-190. doi:10.1016/0001-6918(95)00026-Q

Meyer, D. E., & Kieras, D. E. (1997). A Computational Theory of Executive Cognitive Processes and Multiple-Task Performance: Part 2. Accounts of Psychological Refractory-Period Phenomena. *Psychological Review, 104*(4), 749-791. doi:10.1037/0033-295X.104.4.749

Pashler, H. (1994). Graded Capacity-Sharing in Dual-Task Interference? *Journal of Experimental Psychology: Human Perception and Performance, 20*(2), 330-342. doi:10.1037/0096-1523.20.2.330

Schubert, T. (1999). Processing Differences Between Simple and Choice Reactions Affect Bottleneck Localization in Overlapping Tasks. *Journal of Experimental Psychology: Human Perception and Performance, 25*(2), 408-425. doi:10.1037/0096-1523.25.2.408

Schumacher, E. H., Cookson, S. L., Smith, D. M., Nguyen, T. V. N., Sultan, Z., Reuben, K. E., & Hazeltine, E. (2018). Dual-Task Processing With Identical Stimulus and Response Sets: Assessing the Importance of Task Representation in Dual-Task Interference. *Frontiers in Psychology, 9*. doi:10.3389/fpsyg.2018.01031

Schumacher, E. H., & Hazeltine, E. (2016). Hierarchical Task Representation: Task Files and Response Selection. *Current Directions in Psychological Science*, *25*(6), 449-454. doi:10.1177/0963721416665085

Schumacher, E. H., Lauber, E. J., Glass, J. M., Zurbriggen, E. L., Gmeindl, L., Kieras, D. E., & Meyer, D. E. (1999). Concurrent Response-Selection Processes in Dual-Task Performance: Evidence for Adaptive Executive Control of Task Scheduling. *Journal of Experimental Psychology: Human Perception and Performance, 25*(3), 791-814. doi:10.1037/0096-1523.25.3.791

Schumacher, E. H., Seymour, T. L., Glass, J. M., Fencsik, D. E., Lauber, E. J., Kieras, D. E., & Meyer, D. E. (2001). Virtually Perfect Time Sharing in Dual-Task Performance: Uncorking the Central Cognitive Bottleneck. *Psychological Science, 12*(2), 101-108. doi:10.1111/1467-9280.00318

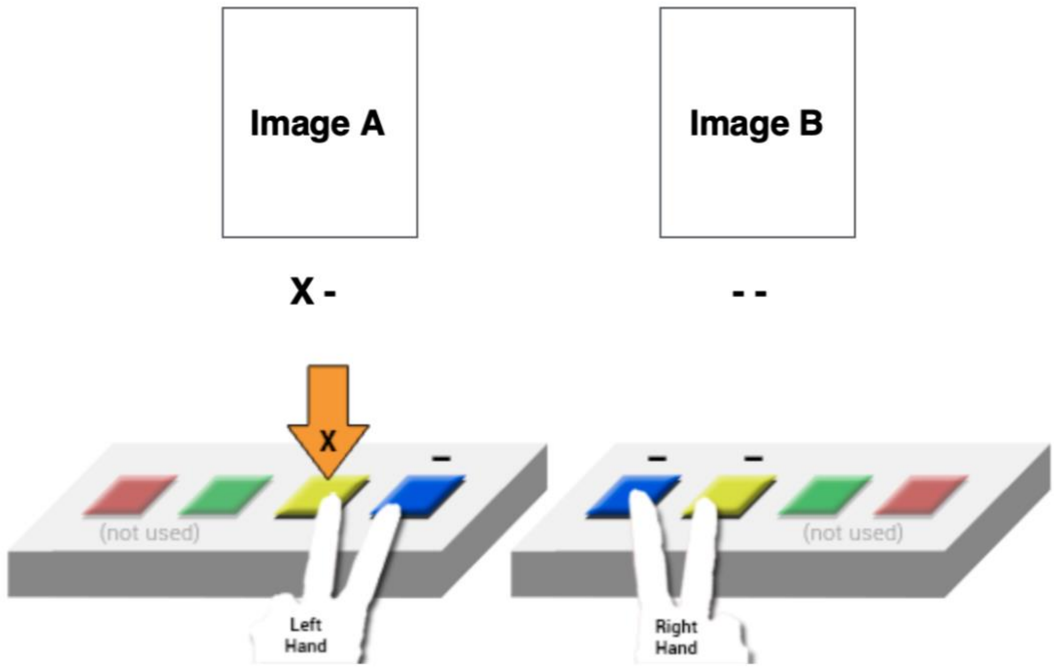
Stelzel, C., Schumacher, E., Schubert, T., & D'Esposito, M. (2006). The neural effect of stimulus-response modality compatibility on dual-task performance: an fMRI study. *Psychological Research, 70*(6), 514-525. doi:10.1007/s00426-005-0013-7

Stelzel, C., Basten, U., & Fiebach, C. J. (2011). Functional Connectivity Separates Switching Operations in the Posterior Lateral Frontal Cortex. Journal of Cognitive Neuroscience, 23(11), 3529-3539. doi:10.1162/jocn_a_00062

Welford, A. T. (1952). The 'Psychological Refractory Period' and the Timing of High Speed Performance—a Review and a Theory. *British Journal of Psychology. General Section, 43*(1), 2-19. doi:doi:10.1111/j.2044-8295.1952.tb00322.x

Appendix A: Task Instructions

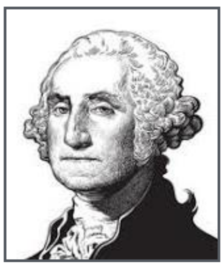
In this experiment you will be learning to make button presses based on pairs of images. You will make the key presses using the index and middle fingers of each hand only.



You will be alternating between two sets or blocks, ***Independent*** blocks and ***Relational*** blocks:

- ***INDEPENDENT***
  In this block type, the left image will indicate the left hand response and the right image will indicate the right hand response. You must still make both responses at the same time, but you do not need to consider the combination of images for the correct pair of responses. You must make both hand responses at the same time.

  Ex. If the correct hand response for an image of George Washington is to select the left middle finger, then you will make this response each time you see George Washington's image, no matter which image is shown on the right.



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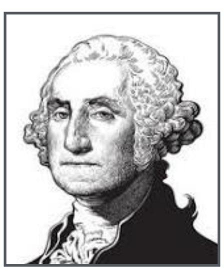

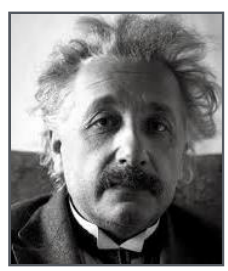

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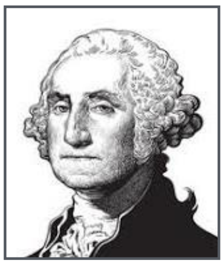
- ***RELATIONAL***
  In this block type, the *combination* of images will indicate the correct left hand response

and right hand response. Neither image alone will tell you anything about either response. You must make both hand responses at the same time.

Ex. The correct hand response for an image of George Washington paired with Winston Churchill is to press your left middle finger. The correct response will be different for an image of George Washington paired with Albert Einstein.



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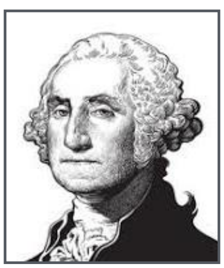

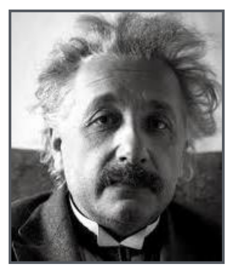

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Appendix B: Individual Pilot Subject Activation Maps

The following images are individual neural activation maps for each of the four pilot subjects in this study. The colors indicate areas of high activation, T-values that are either more positive or more negative than a threshold T-value at p=0.05, uncorrected. Warm colors indicate activation during the independent task and cool colors indicate activation during the relational task. Image processing and scale information from AFNI (Cox, 2019).

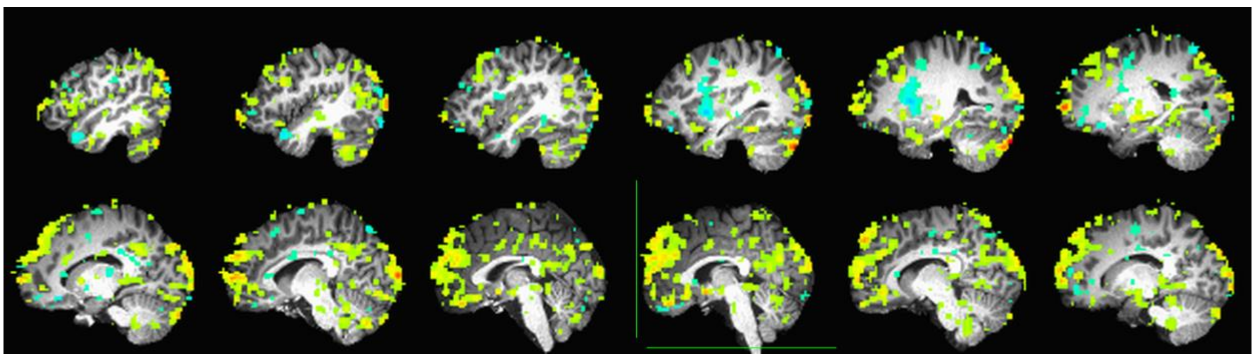

Image A. Subject 04 Sagittal Montage of activation during the Independent v. Relational Task

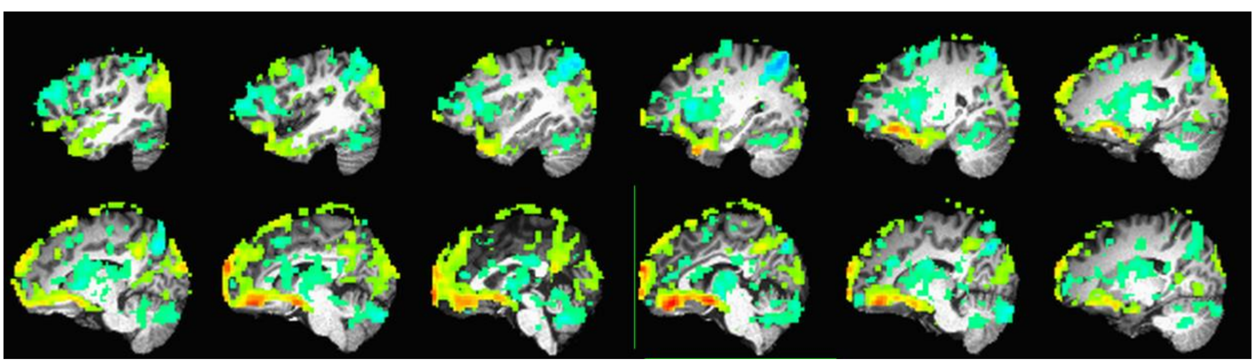

Image B. Subject 05 Sagittal Montage of activation during the Independent v. Relational Task

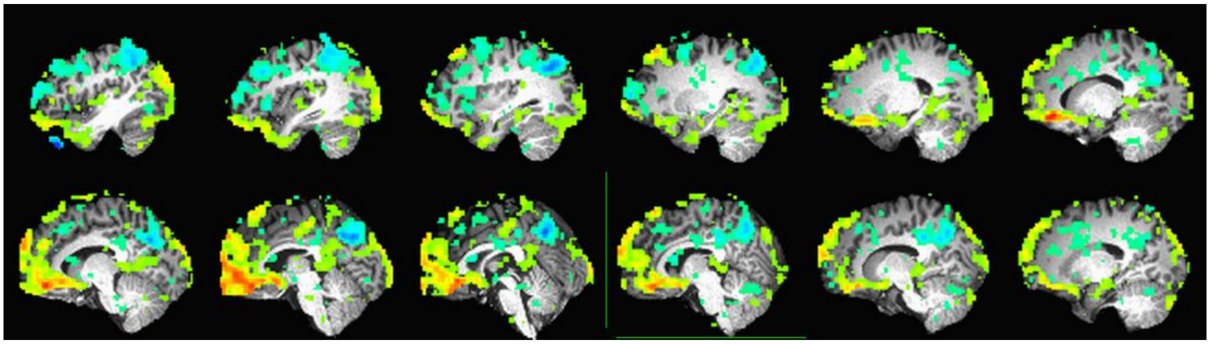
Image C. Subject 98 Sagittal Montage of activation during the Independent v. Relational Task

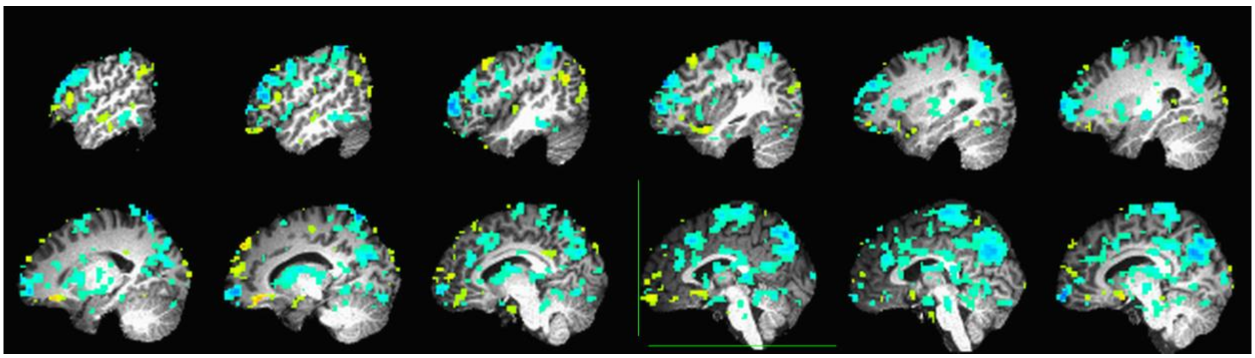
Image D. Subject 99 Sagittal Montage of activation during the Independent v. Relational Task