# THE ROLE OF SPATIAL AND NON-SPATIAL CONTEXT IN HIERARCHICAL DECISIONMAKING

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The Role of Spatial and Non-Spatial Context in Hierarchical Decisionmaking

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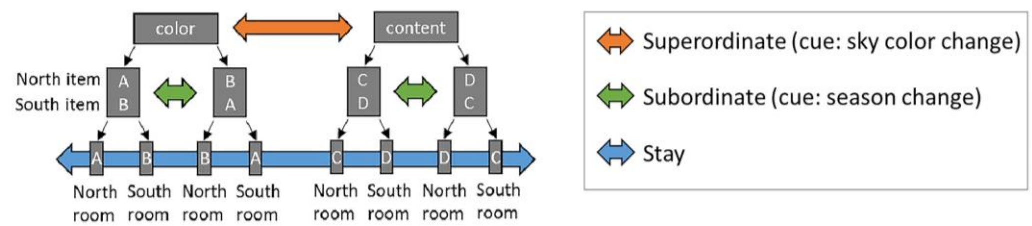
# CHAPTER 1 | INTRODUCTION

Decisionmaking is a vital aspect of cognition, dictating how we process the world we live in and navigate our surrounding environments. Considered a complex function and often dependent on memory, decisionmaking involves many areas of the brain such as the hippocampus acting as the locus of spatial memory and navigation (Brown et al., 2021; Merkow et al., 2015; Nee & Brown, 2013; Osorio-Gómez et al., 2023; Pacheco et al., 2017). Our brains employ various cognitive processes, including spatial navigation, to engage in decisionmaking based on the web of information around us. Recent research has shown that our brains organize information in hierarchies, where certain rules or contextual cues dictate the relationship of pieces of information to one another (that is, some hold more weight than others; Cellier et al., 2022; Reynolds & O'Reilly, 2009). These hierarchical models are still being studied, with some theories suggesting how they might function. For example, when faced with different decision scenarios, researchers have observed changes in brain activity, indicating shifts in hierarchical processing (Brown et al., 2021; Cellier et al., 2022; Pischedda et al., 2017). While multiple models have been proposed to explain the mechanism behind this process, particular recent research suggests that hierarchical organization varies across brain regions in non-spatial and spatial contexts in a way not seen before in similarly styled decisionmaking studies – specifically, the novel findings pertain to the hippocampus's sensitivity to levels of changing hierarchical rules(Brown et al., 2021). Thus, my thesis study aimed to compare how individuals process spatial and non-spatial information in memory-dependent decisionmaking.

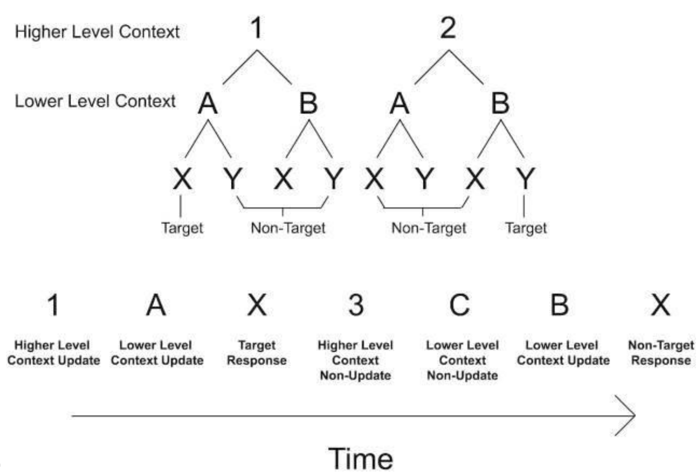
To even conduct a magnetic resonance imaging (MRI) study comparing how hippocampal and frontal engagement differ depending on whether the information for decisionmaking is spatial or non-spatial, a task design needed to be built where both decisionmaking scenarios simultaneously existed. As a result, we used a novel combination of methods from two notable works to investigate this: 1) a cognitive control task consisting of hierarchical static image sets in different simulated environments inspired by Brown et al. (2021), and 2) an AX-continuous performance task (AX-CPT) structure to create hierarchy within certain tasks informed by Nee and Brown (2013; see Fig. 1).

**Figure 1**

*Influential Task Designs Using Hierarchical Structure*




(a)




(b)

*Note*. Experimental task design schematics from (a) Brown et al.'s (2021) and (b) Nee and Brown's (2013) studies. Part (a) is adapted from "Evidence for a Gradient within the Medial Temporal Lobes for Flexible Retrieval under Hierarchical Task Rules," by T. Brown, 2021, *Hippocampus*, *31*(9), 1003–1019. Copyright 2021 by Wiley Periodicals LLC. Adapted with permission. Part (b) is reprinted from "Dissociable Frontal–Striatal and Frontal–Parietal Networks Involved in Updating Hierarchical Contexts in Working Memory," by D. Nee, 2013, *Cortex*, *23*(9), 2146–2158. Copyright 2012 by Derek Nee.

Gathering data in this human pilot study enabled me to see if the novel test conditions taxed cognition similarly Nee and Brown's (2013) purely non-spatial AX-CPT study. This was not only important to progressing toward an MRI goal but also interesting as a behavioral study because given both conditions occur in the same overarching task, differences in error rates and decisionmaking time could be compared when based on non-spatial and spatial streams of cues.

The significance of my research extends beyond the realm of theoretical exploration and holds implications for both clinical and non-clinical domains. By shedding light on the mechanisms behind decisionmaking dynamics, there is great potential to offer practical insights into attention deficit-related disorders inclusive of attention-deficit/hyperactivity disorder (ADHD) and guidance for personalized therapeutic interventions for neurological disorders such as Alzheimer's disease, which is projected to affect 153 million people worldwide by 2050 (Nichols et al., 2022). This research has potential to be a steppingstone toward developing new strategies for enhancing cognitive function and improving outcomes for individuals with abnormal neurological conditions.

# CHAPTER 2 | LITERATURE REVIEW

## Introduction

Humans must operate in a world of ever-changing environments, and adapting to varying conditions is critical to effective decisionmaking. For example, a person might decide what type of meal to prepare depending on what ingredients are available. However, that person may also change this decision to use the same ingredient types differently depending on the time of day – for instance, making a savory crepe for breakfast or a sweet crepe for dessert. In this scenario, choices between which ingredients to use are embedded between a higher-level context of the appropriate meal type to make. This illustrates how hierarchical decisionmaking involves prioritizing overarching rules or context which then influences more specific decisions.

Literature has repeatedly documented that various hierarchies are implemented by the brain in processing how new and old information is represented (Cellier et al., 2022; Pischedda et al., 2017; Reynolds & O'Reilly, 2009; Schumacher & Hazeltine, 2016). However, recent research suggests that hierarchical organization is associated with different regions of the brain depending on context (Brown et al., 2021; Nee & Brown, 2013). In particular, Brown et al.'s (2021) study utilized space as critical contextual cue and found gradients in the hippocampus alongside the prefrontal cortex (PFC). This is an interesting discovery that can help scientists understand how the brain adjusts to navigating spatial environments more reflective of the real world since hierarchical decisionmaking tasks are not typically designed with a spatial component in mind, and it is plausible that the hippocampus role could be influenced by how important spatial context is to one's decisionmaking hierarchy (Brown et al., 2021; Pacheco et al., 2017). Consequently, investigating the intersection of hierarchical decisionmaking and spatial navigation continues to be a growing area of needed research. To examine the effect of spatial navigation on hierarchical decisionmaking and potential underlying neural mechanisms, studies encompassing decisionmaking, spatial memory, neural mechanisms, hippocampus, and cognitive control tasks are reviewed here.

The purpose of the literature review is to establish the current state of knowledge in this field and synthesize what brain regions are believed to be involved in spatial decisionmaking while highlighting the historical oversight of the hippocampus's role in hierarchical decision-making when involving spatial components. This review will first outline the concept of hierarchical decisionmaking and the proposed neurological basis of spatial decisionmaking then present findings and interpretations of relevant studies in the field. Finally, the implications of understanding hierarchical decisionmaking in a spatial context and themes for future research are discussed.

## Hierarchical Decisionmaking Models

Hierarchical decisionmaking refers to the use of organizing contextual cues and actions based on their relative importance or priority and implementing a structured set of governing rules to guide decisionmaking, ranging from simple to complex tasks, using working memory (WM; Cellier et al., 2022; Pischedda et al., 2017; Sarafyazd & Jazayeri, 2019). Due to the complex nature of processing and internally representing information, theoretical models of hierarchical decisionmaking continue to evolve with time. Dynamic modeling approaches, which include hierarchical reinforcement learning and attentional state-space models, have become key tools in understanding how decisionmaking hierarchies are formed (Collins & Shenhav, 2022). These models propose that PFC regions work to dynamically filter task-relevant information, creating highly functional layers that can support task demands and update to adapt to new contexts which complement. Earlier computation models such as the work of Reynolds and O'Reilly (2009) proposing prefrontal cortex-basal ganglia interaction to be critical for updating contextual WM further contributed to the widely agreed-upon notion that cognitive control-related function is supported by the frontal cortex (Collins & Shenhav, 2022).

Reynolds and O'Reilly (2009) found that compartmentalizing representations in different ways under constraints (i.e. a hierarchy) within the PFC led to faster learning and additionally reinforced the importance of the basal ganglia (BG) in its role of dynamically and selectively gating the contents of the PFC. The researchers' biologically inspired computational model was trained on a hierarchical AX-CPT paradigm and incorporated parallel loops of connectivity between the PFC and BG which enabled selective gating of WM content. When connectivity was manipulated, results supported that higher-order (referred to in their work as "outer-loop") contexts were placed in more distal areas of the PFC and could parallel to serving as long-term 'tags' used to inform more short-term goals and decisions made by the brain on a task-specific basis (Reynolds & O'Reilly, 2009).

Later, Schumacher and Hazeltine (2016) investigated the associations between hierarchical representations in the PFC during human response selection, particularly when it comes to processing abstract relationships of stimuli. Rather than solely relying on the current environment to dictate a response, researchers proposed a model self-titled *"task files"* reliant on PFC mechanisms that represent both perceptual features and abstract goals on hierarchical levels. Modeling representations in such a manner highlights the dimensionality of neural representation and has led to works that support both the existence and nonexistence of brain regions showing gradients when using hierarchical rule sets (Cellier et al., 2022; Pischedda et al., 2017). When adding a spatial component to hierarchical decisionmaking, it would be valuable to take into consideration the potential existence of a hierarchical gradient along with hierarchical rule sets.

**Spatial Memory & Navigation**

Building on our understanding of hierarchical representations in the PFC, we pivot to the critical role of recognition memory in shaping human responses to spatial environments. Human recognition memory plays a large role in the ability to recognize and recollect information about environments to navigate them (Merkow et al., 2015; Osorio-Gómez et al., 2023; Pacheco et al., 2017). Humans significantly recognize objects in spatial environments when encoding and retrieval contexts are congruent; that is, one is more likely to identify a novel object if they encounter it again under the same or similar context (e.g. same location, color, and/or shape) rather than a vastly different one (e.g. different location, color, and/or shape; Merkow et al., 2015; Pacheco et al., 2017). When congruent contextual information is no longer available, WM-guided behavior has been shown to be supported by functionally active and latent states; moreover, these functional states utilize hierarchies to guide flexible behavior needed to function (Muhle-Karbe et al., 2021). This sort of flexibility is crucial to mentally "maneuver" through quickly changing environments and hierarchical rule sets.

While many studies focus on the hippocampus as a locus for spatial navigation, it is important to note as Bauman and Mattingley (2021) have that brain regions that exist outside of the hippocampus appear to support navigation abilities including the parahippocampal cortex, retrosplenial cortex, dorsal striatum, and posterior parietal cortex (Merkow et al., 2015; Osorio-Gómez et al., 2023; Pacheco et al., 2017). In fact, combined lesions of the perirhinal, postrhinal, and entorhinal cortices – all extrahippocampal regions in the medial temporal lobe (MTL) – in rat models have been found to impair contextual discrimination (Burwell et al., 2004). In hierarchical decisionmaking tasks, such contextual discrimination processes may be important because the brain must recognize subtle differences in environments or situations, therefore implying that memory-based spatial decisionmaking beyond the hippocampus may involve a larger network than previously thought. Discoveries like this have contributed to a better understanding of contextual navigation circuitry in humans.

**Integration of Spatial & Hierarchical Decisionmaking in Neural Circuits**

Rules that people use to guide decisions are hierarchical, with "lower-order" rules nested within "higher-order" ones. Manipulating these rules in memory-dependent decisionmaking changes brain engagement, but consensus on underlying neural mechanisms is lacking (Brown et al., 2021; Nee & Brown, 2013; Sarafyazd & Jazayeri, 2019). Bicanski and Burgess (2018) demonstrated how spatial experiences from an egocentric perspective connect with MTL representations via the retrosplenial cortex as an intermediary of sorts. Sarafyazd and Jazayeri (2019) ultimately incorporated theories from Bicanski and Burgess's (2018) work by observing the dorsomedial frontal cortex (DMFC) and anterior cingulate cortex (ACC) in monkeys and found hierarchically organized neural circuits contributing to adaptive decisions. Specifically, monkeys tasked with multiple hierarchically organized decisions were confirmed to update their beliefs in line with underlying rule switches, and the updating of beliefs was characterized by the ACC acting directly downstream of the DMFC (Sarafyazd & Jazayeri, 2019).

Moving from hierarchical decisionmaking principles, the involvement of the DMFC and ACC in shaping neural circuits for adaptive decisions as observed by Sarafyazd and Jazayeri (2019) becomes an integral transition. This leads to the exploration of hierarchical context in human WM by Nee and Brown (2013), highlighting the hierarchical organization within the PFC in human the human brain. A traditional AX-CPT paradigm with number and letter cues – representing higher-level and lower-level contexts, respectively – was employed; the higher-level context was established by a number cue (“1” or “2”), which subsequently dictated a response for a lower-level context letter cue series (“A-X” for 1 or “B-Y” for 2; see Fig. 1b). Their investigation of hierarchical context bolstered the ongoing theory that the PFC exhibits hierarchical organization based on how abstract (higher-level) or concrete (lower-level) information is, enabling the brain to be flexible in making an action plan in response to information. Using two levels of hierarchy, researchers specifically found a frontostriatal association gradient with higher-level context being associated with the anterior PFC while lower-level context being associated with the posterior PFC.

The anterior-to-posterior gradient within the PFC that Nee and Brown’s research supported was further investigated in a spatial task context by Brown et al. (2021), who found that different hierarchical task rule levels resulted in distinguishable hippocampal activity and hippocampal-prefrontal functional interconnectivity. This is notable, as past studies involving hierarchical decisionmaking tasks have shown more activity in prefrontal and parietal regions, but not the hippocampus (Nee & Brown, 2013; Schumacher & Hazeltine, 2016). While both studies’ task designs involved an AX-CPT structure, Brown et al. (2021) utilized environmental contextual cues for decisionmaking as opposed to arbitrary symbolic cues used in Nee and Brown (2013; see Fig. 1). One theory for the differing findings is that introducing a contextual spatial condition leads to a split of reliance between the MTL and PFC, indicating a potential role of scene-sensitive regions in guiding hierarchical decisions (Brown et al., 2021). Fully understanding these nuances will contribute to unraveling how spatial and non-spatial contexts guide decisionmaking, a focal point of our research.

## Applications & Implications

Practical applications in cognitive neuroscience exist, given that our decisions may be affected differently than others by health factors like aging, neurodegenerative diseases, and neurological disorders (Nichols et al., 2022; Samanez-Larkin & Knutson, 2015; Schott et al., 2007). Deficits of WM in healthy individuals of all ages with ADHD impact distractibility, particularly in academic settings (Fried et al., 2019). When focusing on university students alone, Gorohovsky and Magen (2022) found that those with ADHD had reduced accuracy for the orientation or appearance (token) of objects compared to a non-ADHD cohort yet potentially processed scene representations and objects together as a novel finding. Knowing that WM encompasses both spatial and contextual memory, better understanding the hierarchy of memory function will better equip educators and those in the medical and scientific field to understand attention-related disorder mechanisms. Our research aims to contribute to this understanding by exploring the intricate interplay between hierarchical decisionmaking and spatial memory in neural circuits, providing insights for targeted interventions and personalized therapeutic approaches.

## Conclusion

This review has highlighted the intricate relationship between hierarchical decisionmaking and spatial memory within neural circuits with room for further exploration in the field. Studies such as Burwell et al. (2004) challenged the exclusive role of the hippocampus in spatial navigation, to which this thesis also does in seeking to elucidate whether the hippocampus is involved in non-navigation decision-making. Simulated models additionally displayed the connectivity of parietal and retrosplenial cortices with the MTL in representing spatial experiences (Bicanski & Burgess, 2018). Sarafyazd and Jazayeri (2019) demonstrated hierarchical reasoning in the frontal cortex, uncovering adaptive decisionmaking circuits, and the anterior-to-posterior gradient within the PFC explored by Nee and Brown (2013) was extended by Brown et al. (2021) in a spatial context revealing hippocampal activity may be different depending on task specifics and may also follow such a gradient seen in the PFC. The current understandings of neural mechanisms reveal a lapse in certainty over when and how the hippocampus is – and is not – involved in memory-based decisionmaking, though. One intriguing possibility may be something about the significance of spatial information as a contextual trace. Addressing this gap in research could offer practical insights into attention-related disorders and potentially further guide personalized therapeutic interventions, and thus further work is needed in navigating the dynamic landscape of decisionmaking.

# CHAPTER 3 | METHODS AND MATERIALS

## Participants

Six pilot participants were recruited for this experiment from the Georgia Institute of Technology through the Memory, Affect, and Planning (MAP) Laboratory and Cognitive Neuroscience at Tech Research Laboratory (CoNTRoL). Participants spent between 100 and 150 minutes completing the experiment. No participants were excluded from the analyses. Four were female, zero were left-handed, and three identified as Asian, two as White, and one as Black/African American. Eligible recruited participants ranged in age from 18 to 21 years and were all in good health with normal (or corrected) vision and without a history of neurological disorders.

Although this sample is small, the goal for my thesis was to develop the paradigm and then pilot the task in this group to establish early on whether more changes are needed before running the full experiment in an MRI environment. For example, could participants with our target demographics learn the task, and do they show a similar behavioral profile to the AX-CPT participants in the inspirational fMRI study for this design (despite the significant changes we made to embed that paradigm structure in a virtual environment)?

## Materials

### *Hardware*

The technical setup for the experiment consisted of a computer system with a minimum Core i7-13700 at 2.10 GHz with 16 GB of RAM. Participants were situated in front of the computer screen and had access to a standard keyboard and mouse.

*Software*

E-Prime 3.0 (version 3.0.3.80) was used to present and conduct experimental tasks, and it also provided automatic data storage to log individual participant's performance data during the study (Psychology Software Tools, 2016). The obtained data was collected on the computer the participant performed the experiment on to be then stored on an electric database hosted on the Georgia Tech Dropbox storage space (certified by the Georgia Tech cyber security group for Category III data security) and subsequently exported to JASP (version 0.19.1) after binning for processing and analysis (JASP Team, 2024).

*Virtual Environments*

One primary virtual environment (VR) was used in this experiment consisting of a clearing surrounded by various trees, shrubbery, and mountains in the background. In the clearing, three mailboxes were set up in concordance with three of the four cardinal directions (north, south, and east; see Fig. 2). Imagery from this environment was replicated during three different times of day (noon, sunset, and night), and depending on the given task, the mailbox also had additional non-spatial details including color, content, and exterior ornamental mirror shape (see Fig. 3). The model for this VR was initially created in Unreal Engine 4 (version 4.27) and then exported as static JPG images for use in E-Prime with exception to one introductory video taken from an egocentric point of view.

**Figure 2**

*Cardinal Directions of VR Training Phase*

(a) (b) (c)

*Note*. Three VR cardinal directions shown to participants during the study's training phase. Part (a) depicts the north direction and surroundings with no mountains in the background. Part (b) depicts the south direction and surroundings with a large mountain in the background**.** Part (c) depicts the east direction and surroundings with a small mountain in the background**.**

**Figure 3**

*Temporal and Non-Spatial Details of VR Training Phase*


(a) (b) (c)

*Note*. Temporal conditions of noon, sunset, and night in addition to non-spatial details of mailbox color, content, and exterior mirror shape shown to participants during the study's training phase. Part (a) depicts noon with non-spatial details of a red mailbox, travel magazine, and rectangular mirror. Part (b) depicts sunset with non-spatial details of a blue mailbox, newspaper, and circular mirror. Part (c) depicts night with non-spatial details of a yellow mailbox, garden magazine, and oval mirror. Each of the non-spatial detail options (red, blue, or yellow mailbox; travel magazine, newspaper, or garden magazine; rectangular, round, or oval mirror) were interchangeable and could be combined with different temporal conditions.

## Procedure

At the beginning of this one-day study after giving informed consent, all participants were asked to provide demographic information including age, sex, handedness, education, and quality of the prior night's sleep (see Appendices A and B). Participants were then given two additional questionnaire forms including a health screening form and Santa Barbara Sense of Direction (SBSOD) Scale form (see Appendices C and D). Once participants were comfortably situated in an isolated testing room, they were asked to perform tasks in two phases for the experiment in E-Prime 3.0: one training phase and one experimental navigational phase (described in detail below). To ensure participants associated the test images – which manipulated spatial cues – to have meaning, participants were first trained on the layout of the space before proceeding to the main task (i.e., facilitate learning that North and East images had a meaningful spatial relationship and are not random, disconnected images of boxes in unrelated forest backgrounds).

The training phase comprised three modules aimed to familiarize the participant with the 1) temporospatial orientation used throughout the study, 2) correct/incorrect response expectations for the spatial portion of the experimental phase, and 3) correct/incorrect response expectations for the non-spatial portion of the experimental phase. All of the training modules provided immediate on-screen feedback ("correct" or "incorrect") based on the participant's response input during each trial. Data from the training phase were not analyzed and used purely for practice purposes to discourage any confounding effects of learning during the primary experimental navigation phase.

The primary experimental navigation phase consisted of two modules (described in detail below) aimed at measuring participants' navigational decisionmaking strategy and execution. The two experimental modules mimicked training phase modules 2 and 3 but without feedback and had more trials. The inclusion of irrelevant nontarget stimuli throughout in varying context cue levels (i.e., east direction, red mailbox, circular mirror, and garden magazine) of both the training and experimental phases was established to be non-update controls where participants would not update their WM(Nee & Brown, 2013).

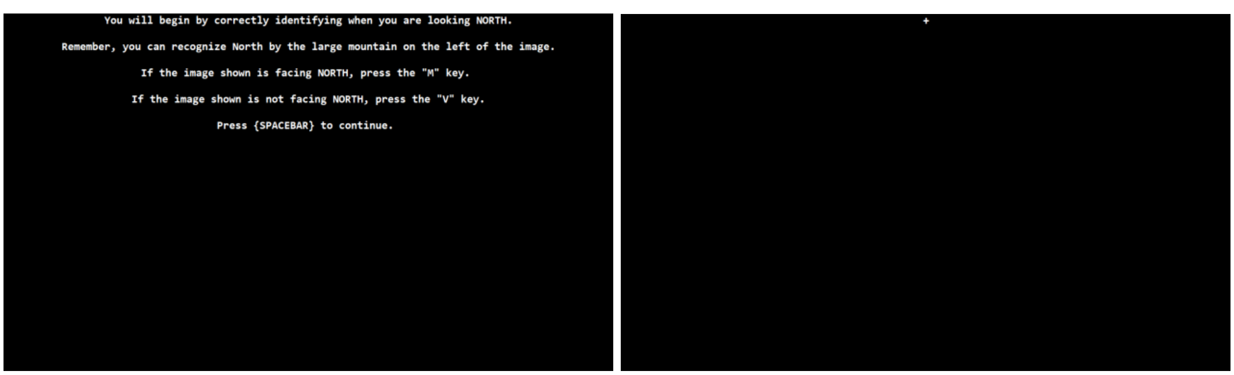
## Experimental Design

### *Training Phase*

The training phase was used to familiarize participants with the VR that the study utilized along with applicable response keys (“M” and “V”) used. In the first “Orientational and Directional Training” training module, participants were exposed to an introductory video that panned through the VR from an egocentric point of view during noon, then sunset, and finally at night. In this way, participants were exposed to the temporospatial conditions they could expect to encounter throughout the study. After the video concluded, participants were directed to correctly identify east, south, and north, respectively, using the “M” key to indicate a correct pairing between the image shown and the governing instruction prompt given or “V” key to indicate an incorrect pairing between image and prompt. Immediate on-screen feedback was provided based on input (see Fig. 4). If a participant did not respond within 2000 ms, their input was marked incorrect. One trial set consisting of 12 trials each for north, south, and east was presented with a 1000 ms fixation point before each trial and consistent inter-trial interval (ITI) of 2000 ms for a total of 36 trials spanning the three tested directions (PhenX Toolkit, n.d.).

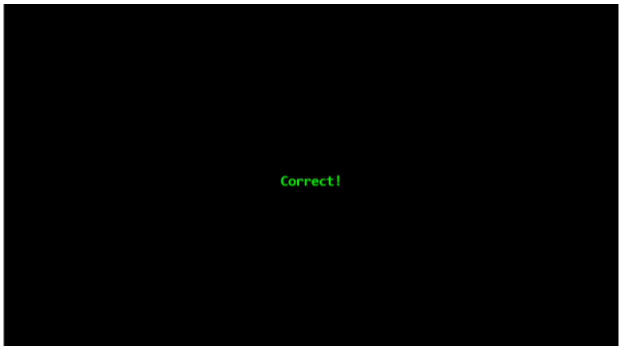
**Figure 4**

*“Orientational and Directional Training” Module Task Example*



(a) (b)

**Figure 4 (continued)**




(c) (d)

*Note*. Example task procedure for the “Orientational and Directional Training” module. Part (a) includes a direction prompt for identifying the NORTH direction. Part (b) includes a fixation point shown before the image. Part (c) includes a blank mailbox facing a certain direction during varying times of day which is shown for 2000 ms before a black response screen is shown. Part (d) includes on-screen feedback depending on the participant’s response.

In the second “Spatial Training Sequential” module, participants were given a task mirroring the actual experimental test with two caveats: the training module was half the length of the actual test, and the training module included instant on-screen feedback which the actual test omitted. Participants were given a series of images that compounded on the scene they viewed (time of day, direction, and mailbox contents) and to which they were instructed to only identify compounded scenes as correct by pressing the “M” key that included 1) the time of day being NOON, the direction being NORTH, and mailbox contents being a TRAVEL MAGAZINE or 2) the time of day being SUNSET, the direction being SOUTH, and mailbox contents being a NEWSPAPER (see Fig. 5). For any incorrect compounded scenes that did not align with either noon > north > travel magazine OR sunset > south > newspaper, participants were instructed to press the “V” key. In the event a participant did not respond within 2000 ms, the response period timed out and input was marked as incorrect. The order of which scenes were compounded was randomized, and a 1000 ms fixation point before trials with a consistent ITI of 2000 ms was present between 72 total trials. Halfway through the module (36-trial mark), a direction screen with the same initial directions was shown to give participants an optional break and resume when they would like.

**Figure 5**

*Spatial Compounded Scene Instance Example*

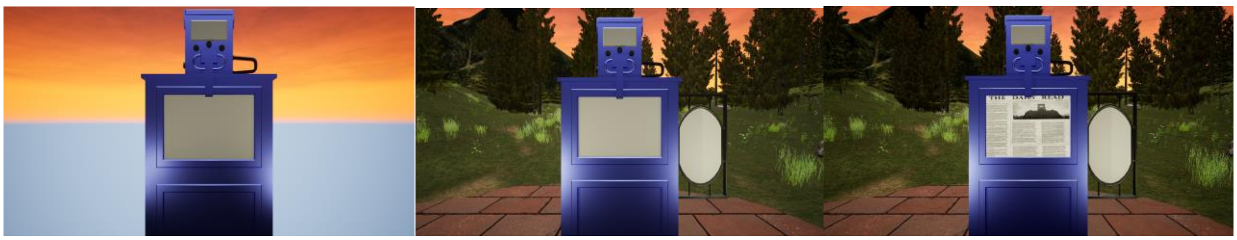

(a) (b) (c)

*Note*. Example procedure for the spatial condition's compounded scene instance in a correct condition. Part (a) includes no scene but only noon temporal information shown for 2000 ms. Part (b) populates additional north direction information shown for 2000 ms along with extraneous mirror shape information. Part (c) includes additional travel magazine mailbox content information as the final compounded scene which is shown for 4000 ms. After the allotted time, participants are shown a black response screen.

In the third and final "Non-Spatial Training Sequential" module, participants were again given a task mirroring the actual experimental test with the same two caveats described in the "Spatial Training Sequential" module. Participants were again given a series of images compounded on the scene they viewed, but this time correct attributes were dependent upon mailbox color, ornamental mirror shape, and mailbox content rather than temporospatial components. Specifically, they were prompted to identify compounded scenes that included 1) a YELLOW mailbox, RECTANGULAR mirror shape, and mailbox contents being a TRAVEL MAGAZINE or 2) BLUE mailbox, OVAL mirror shape, and mailbox contents being a NEWSPAPER as correct by pressing the "M" key (see Fig. 6). For any incorrect scenes that did not align with either yellow mailbox > rectangular mirror > travel magazine OR blue mailbox > oval mirror > newspaper, participants were instructed to press the "V" key. In the event a participant did not respond within 2000 ms seconds, the response period timed out and input was marked as incorrect. The order of which scenes were compounded was randomized, and a 1000 ms fixation point before trials with a consistent ITI of 2000 ms was present between 72 total trials. Halfway through the module (36-trial mark), a direction screen with the same initial directions was shown to give participants an optional break and resume when they would like.

**Figure 6**

*Non-Spatial Compounded Scene Instance Example*



(a) (b) (c)

*Note*. Example procedure for the non-spatial condition's compounded scene instance in a correct condition. Part (a) includes no scene but blue mailbox information shown for 2000 ms. Part (b) populates additional oval mirror shape information shown for 2000 ms along with extraneous orientation information. Part (c) includes additional newspaper mailbox content information as the final compounded scene which is shown for 4000 ms. After the allotted time, participants are shown a black response screen.

*Experimental Navigation Phase*

In between the training phase and experimental navigation phase, participants were offered a brief five-minute break. After completing the training phase, participants then completed the actual experiment in the experimental navigation phase, which consisted of two modules ("Spatial Sequential" and "Non-Spatial Sequential," respectively) that were identical in layout and design to the "Spatial Training Sequential" and "Non-Spatial Training Sequential" modules of the training phase (see Figs. 5 and 6). However, both of the final experimental test modules were twice the length of their corresponding training modules. As a result, the "Spatial Sequential" module consisted of four 36-trial sets in length (148 individual total trials) with three total optional breaks at the 25%, 50%, and 75% completion marks. Similarly, the "Non-Spatial Sequential" module consisted of four 36-trial sets in length (148 individual total trials) with three total optional breaks at the 25%, 50%, and 75% completion marks. Additionally, on-screen feedback for the participants after each trial was omitted on whether their input response was correct or incorrect to not influence future responses.

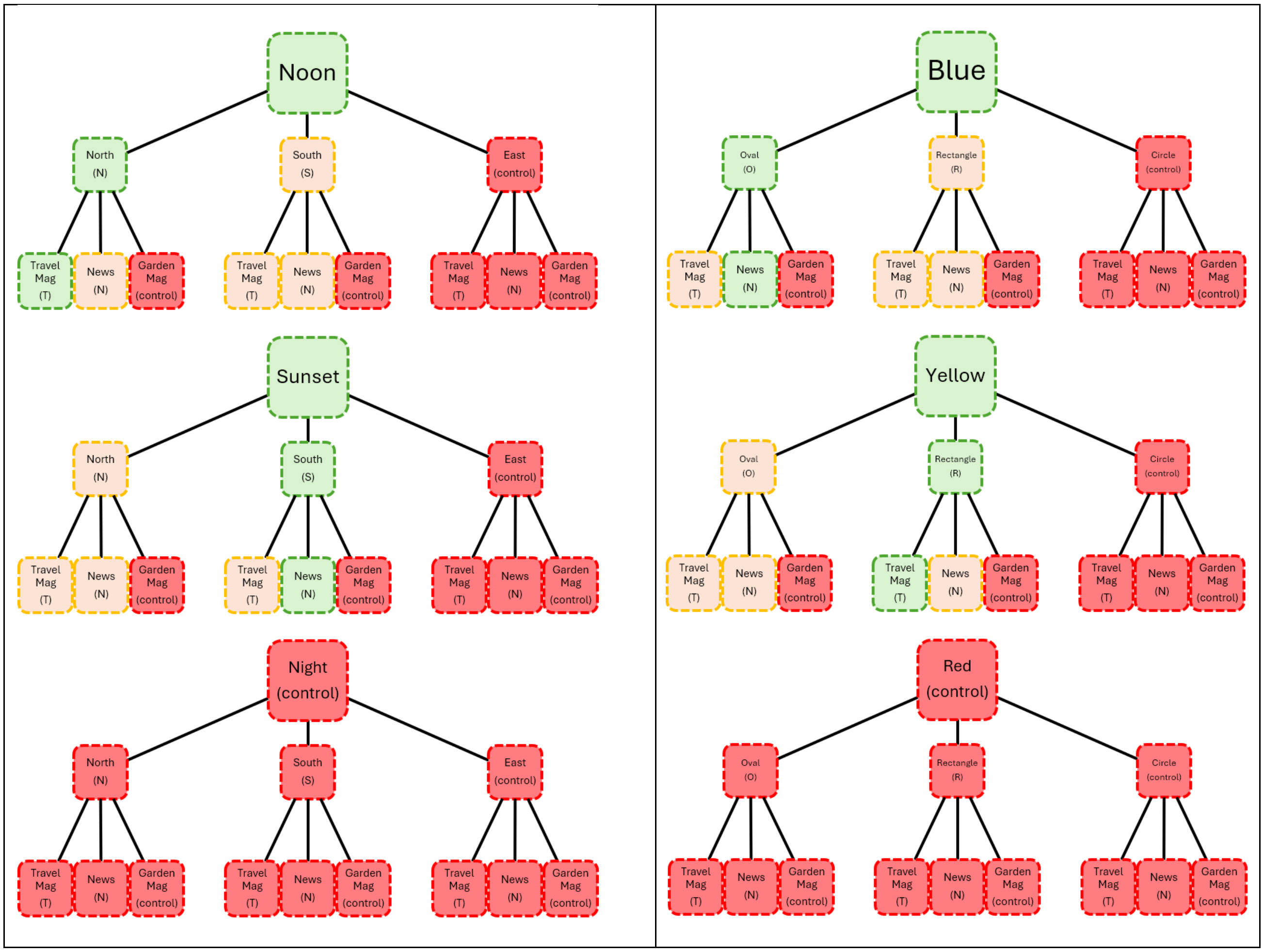
### *Modified AX-CPT Paradigm*

In a traditional AX-CPT paradigm, participants are required to maintain upper and lower-level contexts in their WM and update their decision accordingly when a change within a context occurs (Nee & Brown, 2013). Additionally, participants are only temporarily exposed to context cues one at a time. In this experiment of a modified AX-CPT paradigm, both upper-level and lower-level context cues were visible throughout the trials, but presentation of the cues on each trial into sequences was staggered so that evidence towards participants' correct response (what the current context is) emerged over time each trial and therefore emulates Nee and Brown's (2013) interpretation of hierarchy. It was assumed that participants' WM storage and updating were still strongly emphasized as participants were mainly directed to focus on the new stimulus being presented at each level while keeping the previous contexts stored (see Fig. 7).

**Figure 7**

*Modified AX-CPT Schematic*

(a) (b)




*Note*. Diagram outlining the modified AX-CPT task. Hierarchies were dependent on which condition – (a) spatial or (b) non-spatial – was being tested. Participants responded to varying mailbox content ("travel mag," T or "news," N) based on either a spatial or non-spatial hierarchical context. In the spatial condition, correct target responses were dependent on both higher-level time-of-day ("Noon" or "Sunset") and lower-level cardinal direction ("North," N or "South," S) contexts. Participants associated a target response to mailbox content T when it was preceded by N under the "Noon" context; an alternative associated target response was to mailbox content N preceded by S under the "Sunset" context. In the non-spatial condition, correct target responses were dependent on both higher-level mailbox color ("Blue" or "Yellow") and lower-level mirror shape ("Oval," O or "Rectangle," R) contexts. Participants associated a target response to mailbox content N when it was preceded by O under the "Blue" context; an alternative associated target response was to mailbox content T preceded by R under the "Yellow" context. Participants associated a non-target response with any other hierarchical context combinations in both spatial and non-spatial conditions. Irrelevant stimuli ("Night; East; Circle; Garden Mag") were included to act as controls for higher- and lower-level context updating; in these instances, participants were directed to withhold these details from their WM.

*Ethics*

The Georgia Tech Institutional Review Board approved this experiment (H23024). Before the experiment was conducted, written informed consent was obtained from all participants. Participants were compensated with two "SONA Systems" course credits if self-elected, and any participants that prematurely aborted the experiment received one "SONA Systems" course credits.

*Dual Use Research of Concern (DURC)*

This study was not subject to consideration as DURC.

**Data Analysis**

*Attrition*

Zero participant data samples were omitted from analysis due to either attrition or intentional exclusion.

*Statistics*

A paired samples t-test was used to analyze behavioral data. To test the effective manipulation of data, lower-order contexts and their subsequent target/non-target responses pairs were compared against higher-order contexts (Noon or Sunset; North or South). As each participant had individual results, paired t-tests were used to further analyze this behavioral data. Normality was not tested due to the pilot sample size being so small that these assumptions (while critical) cannot be controlled for at this stage, and due to the fact that statistical inferences are not being used to draw conclusions beyond feasibility of the running the design in its current form in a full study.

### *Data Availability*

Upon reasonable request, access to the de-identified data of this study may be provided by contacting Dr. Thackery I. Brown. Data can normally be requested as soon as within a year after publication of the data.

### *Code Availability*

Source code is available upon reasonable request by contacting Zoë Altizer.

JASP (version 0.19.1) available from: https://jasp-stats.org/download/

Unreal Engine (version 4.27) available from: https://www.unrealengine.com/en-US/download

E-Prime 3.0 (version 3.0.3.80) available from: https://support.pstnet.com/

*License: Georgia Tech License*

## Reporting

This study complies with the Center for Open Science's Materials, Design, Analysis, and Reporting (MDAR) Framework and MDAR checklist found at https://osf.io/bj3mu/.

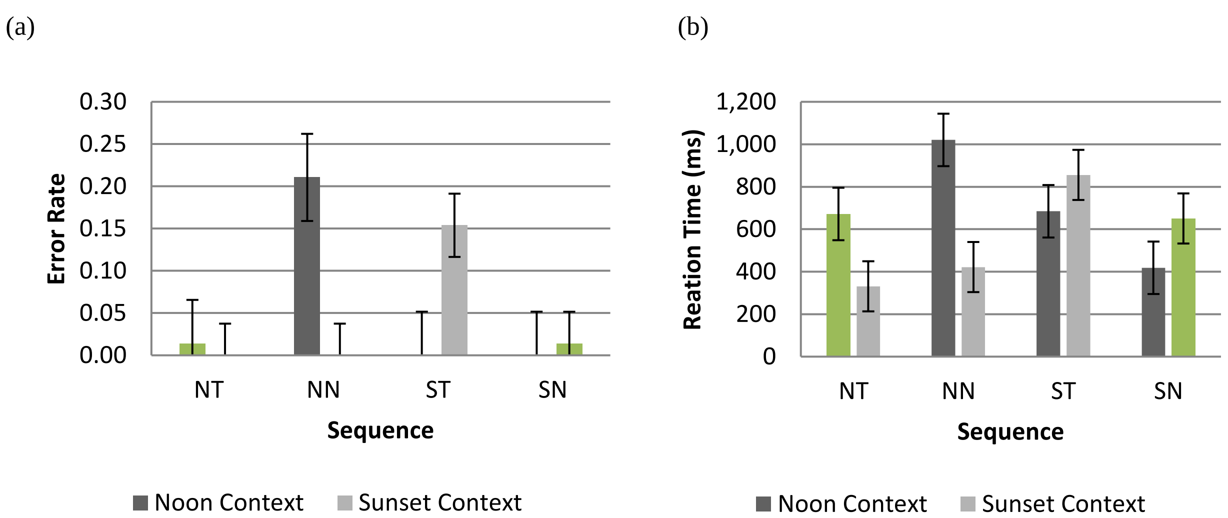
# CHAPTER 4 | RESULTS

## Behavioral Data

These behavioral data were examined to investigate the relationship between spatial processing and hierarchical decision making in an AX-CPT task(Nee & Brown, 2013). Subject accuracy was at ceiling (mean accuracy = 96.5% in non-spatial condition, 97.5% in spatial condition), which suggests that participants understand the directions given to them and maintained proper contexts throughout their WM (see Figs. 8 and 9). The purpose of evaluating reaction times was to see if there were comparable differences to those observed in the original AX-CPT paper (see Discussion below).

**Figure 8**

*Spatial Condition Behavioral Data*

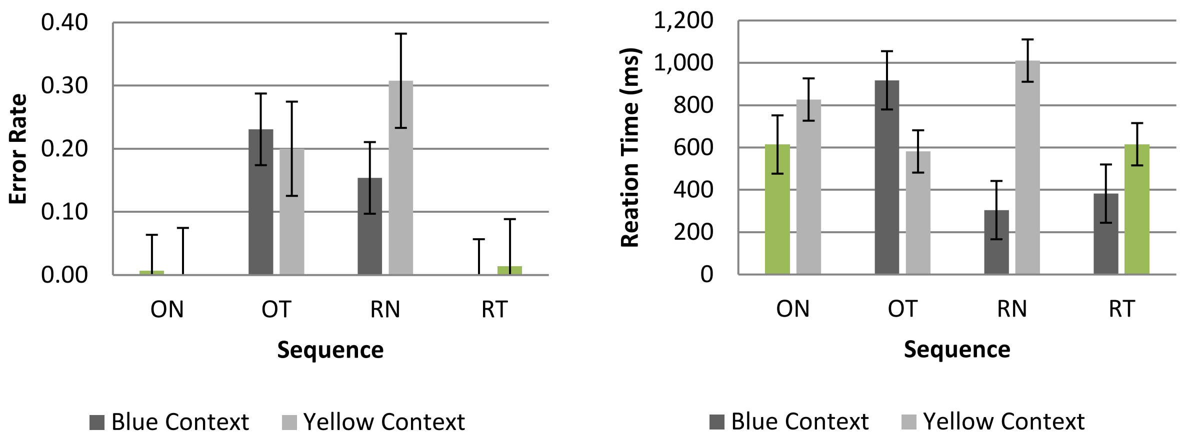



*Note*. Behavioral data for the spatial testing condition. Part (a) depicts error rates, while part (b) depicts reaction time in milliseconds. Target sequences are highlighted in green for ease of visualization. Higher error rates on Sunset-ST and Noon-NN sequences may indicate participants used higher and lower-level contexts to predict the upcoming target sequence and were slightly slowed and less accurate when their prediction was inconsistent with the sequence presented. Error bars indicate SEM.

**Figure 9**

*Non-Spatial Condition Behavioral Data*

(a) (b)




*Note*. Behavioral data for the non-spatial testing condition. Part (a) depicts error rates, while part (b) depicts reaction time in milliseconds. Target sequences are highlighted in green for ease of visualization. Higher error rates on Yellow-RN and Yellow-RT sequences, for example, may indicate participants used higher and lower-level contexts to predict the upcoming target sequence and were slightly slowed and less accurate when their prediction was inconsistent with the sequence presented. Error bars indicate SEM.

Higher-level contexts (Blue, Yellow; Noon, South) were collapsed to promote simplicity and better comparisons across context changes. Adopting classic formatting methods used in traditional AX-CPT tasks, the shorthand of “ON” and “RT” in the non-spatial condition along with and “NT” and “SN” in the spatial condition refer to the target responses (within the higher-level context of “Blue” or “Yellow” and “Noon” or “Sunset,” respectively; Brown et al., 2021; Nee & Brown, 2013). In a similar vein for example, the sequence “ON” in the non-spatial condition refers to both “Blue-O-N” and “Yellow-O-N” while “SN” in the spatial condition refers to both “Noon-S-N” and “South-S-N.”

*Spatial Condition*

Mean reaction times for the response period were 672 ms (Noon-NT), 1020 ms (Noon-NN), 684 ms (Noon-ST), 418 ms (Noon-SN), 331 ms (Sunset-NT), 422 ms (Sunset-NN), 856 ms

(Sunset-ST), and 651 ms (Sunset-SN). When comparing NT sequence trials, North context condition reaction times were not significantly higher than South context condition reaction times ($p > 0.05$). When comparing NN sequence trials, North context condition reaction times were significantly higher than South context condition reaction times ($p < 0.05$). When comparing ST sequence, North context condition reaction times were not significantly lower than South context condition reaction times ($p > 0.52$). When comparing SN sequence trials, North context condition reaction times were not significantly lower than South context condition reaction times ($p > 0.05$).

### *Non-Spatial Condition*

Mean reaction times for the response period were 614 ms (Blue-ON), 917 ms (Blue-OT), 304 ms (Blue-RN), 382 ms (Blue-RT), 827 ms (Yellow-ON), 581 ms (Yellow-OT), 1011 ms (Yellow-RN), and 615 ms (Yellow-RT). When comparing ON sequence trials, Blue context condition reaction times were non-significantly lower than Yellow context condition reaction times ($p > 0.67$). When comparing OT sequence trials, Blue context condition reaction times were significantly higher than Yellow context condition reaction times ($p > 0.05$). When comparing RN sequence trials, Blue context condition reaction times were significantly lower than Yellow context condition reaction times ($p < 0.05$). When comparing response time sequence trials, Blue context condition reaction times were significantly lower than Yellow context condition reaction times ($p < 0.05$).

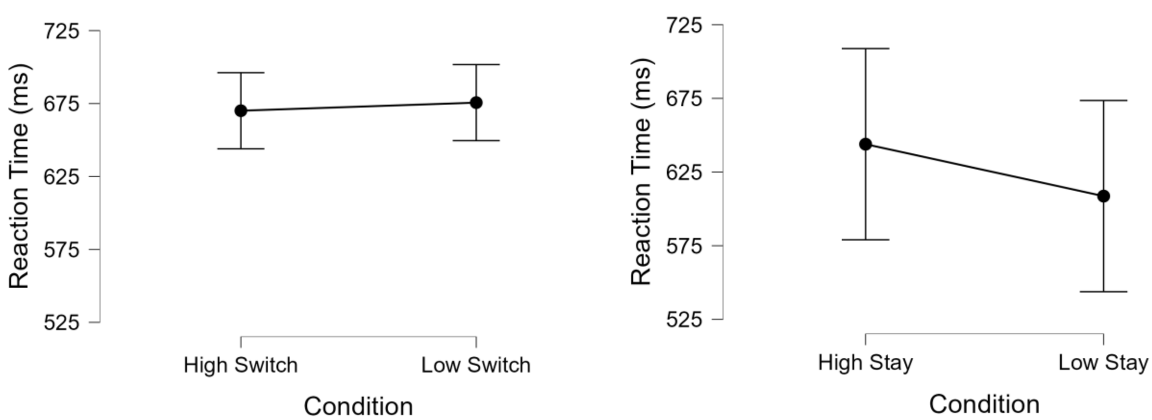
## Higher- and Lower-Level Context Update Interactions

These data represent impacts of context loss on behavior. In this task, when participants were presented a new response scenario (in the form of a switch in higher- or lower-level context) from trial to trial, reaction times could change reflecting "switch costs" where participants are uncertain and are adjusting to new overarching rules. To test for these costs, paired t-tests were used to compare the average reaction times of each target or non-target response in the spatial and non-spatial conditions, grouped by respective higher-level context (see Figs.10 and 11). In spatial trials, high switch reaction times had a mean of 670.07 ms which was non-significantly lower than low switch reaction times with a mean of 675.62 ms ($p > 0.71$). Low stay reaction times had a mean of 608.66 ms which was non-significantly lower than high stay reaction times with a mean of 643.91 ms ($p > 0.36$).

**Figure 10**

*Change in Reaction Time between Spatial Higher- and Lower-Order Contexts*

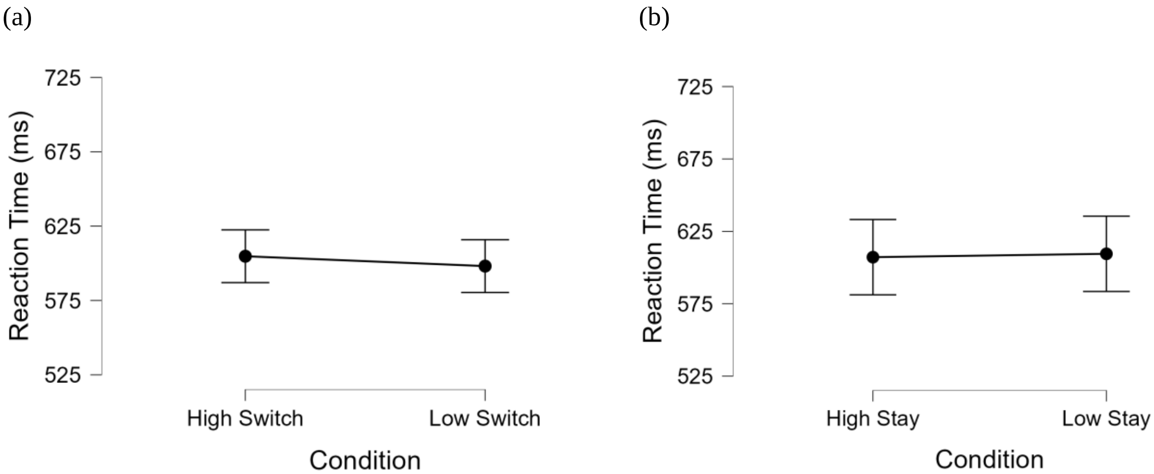
(a) (b)




*Note*. Comparing reaction times between higher- and lower-order contexts in the spatial condition. Part (a) depicts reaction time changes where context switches between trials were present, and part (b) depicts reaction time changes where context switches between trials were not present. A high switch was considered when the higher-order context (i.e., time of day) changed between trials. Similarly, a low switch was considered when the lower-order context (i.e., cardinal direction) changed between trials. A high stay was considered when the higher-order context (i.e., time of day) stayed the same between trials. Similarly, a low stay was considered when the lower-order context (i.e., cardinal direction) stayed the same between trials.

**Figure 11**

*Change in Reaction Time between Non-Spatial Higher- and Lower-Order Contexts*




*Note*. Comparing reaction times between higher- and lower-order contexts in the non-spatial condition. Part (a) depicts reaction time changes where context switches between trials were present, and part (b) depicts reaction time changes where context switches between trials were not present. A high switch was considered when the higher-order context (i.e., mailbox color) changed between trials. Similarly, a low switch was considered when the lower-order context (i.e., mirror shape) changed between trials. A high stay was considered when the higher-order context (i.e., mailbox color) stayed the same between trials. Similarly, a low stay was considered when the lower-order context (i.e., mirror shape) stayed the same between trials.

Overall, evidence for switch costs in either version of the task were not seen, suggesting that people did not get into “cognitive sets” and might instead evaluate for context changes on every trial in this AX-CPT variant (see Discussion below).

# CHAPTER 5 | DISCUSSION

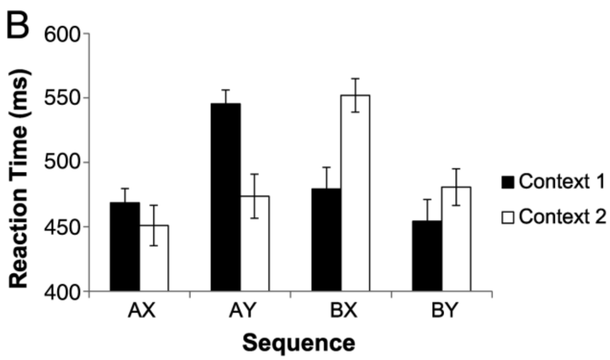
This study sought to explore the relationship between hierarchical decisionmaking and spatial memory within the brain, in particular examining how individuals process spatial and non-spatial information in WM-dependent tasks. Central to the goal that my research supports was the question of how hierarchical organization in the brain processes hierarchical task contexts, and in particular establishing a paradigm to test for novel patterns of engagement of brain regions such as the hippocampus depending on the spatial or non-spatial nature of the context changes. By combining insights from hierarchical decisionmaking models and spatial memory task mechanisms, this work aimed to further progress in shedding light on specific neural circuits that support complex decisionmaking processes shaped by contextual cues.

**Behavioral Data Validates Novel Task Design**

The behavioral data overall suggest promising direction aligning with prior research, which validates this novel task design indicating impacts of context loss on behavior (Nee & Brown, 2013). When qualitatively compared, the overall pattern of behavioral reaction time data in both the spatial and non-spatial conditions (see Figs. 8 and 9) is similar to Nee and Brown's (2013) original AX-CPT design (see Fig. 12). In the spatial condition, the slower reaction times of "NN" sequence trials relative to "SN" sequence trials align with the similar performance seen in the original study of non-significant slowed "AY" trial reaction performance relative to "BY" trial reaction performance. Likewise, the slower reaction times of "ST" sequence trials relative to "SN" sequence trials align with reaction time performance observed in "BX" trials relative to "BY" trials in the original study. In the non-spatial condition, the slower reaction times of "OT" sequence trials relative to "RT" sequence trials align with the similar performance seen in the original study of non-significant slowed “AY” trial reaction performance relative to “BY” trial reaction performance. Likewise, the overall slower reaction times of “RN” sequence trials relative to “RT” sequence trials align with reaction time performance observed in “BX” trials relative to “BY” trials in the original study.

**Figure 12**

*Behavioral Results from Previous Research*




*Note*. Behavioral reaction time results from Nee and Brown’s (2013) study. Reprinted from "Dissociable Frontal–Striatal and Frontal–Parietal Networks Involved in Updating Hierarchical Contexts in Working Memory," by D. Nee, 2013, *Cortex, 23*(9), 2146–2158. Copyright 2012 by Derek Nee.

The abnormal increase in reaction time of the Yellow-ON sequence relative to the target Blue-ON sequence, however, differs from the trend observed in Nee and Brown’s (2013) results. It is possible this was due to participants spending more time on the given contextual information before rejecting that the stimuli do not match with their ruling prompt. Additionally, all non-spatial cues were inevitably buried in space, thus participants could be spending more time detecting target from non-target in the non-spatial scenarios compared to the spatial counterpart scenarios. Such observations contribute to the nuanced nature of how individuals process spatial and non-spatial information in memory-dependent decisionmaking.

**Changing Spatial and Non-Spatial Hierarchical Contexts does not Influence Reaction Time**

Results did not demonstrate typical expected behavioral switch costs when taking the hierarchical task structure into consideration for both spatial and non-spatial test conditions (see Figs. 10 and 11). This suggests that when moving from one context to another (applicable to both higher- and lower order contexts) between trials in our paradigm, the change in contexts did not result in a straightforward speed-accuracy tradeoff. At surface level, it would appear that participants interpreted higher-order and lower-order context levels as equal magnitudes of change in terms of selecting responses, which would call into consideration the hierarchical nature of the task design. Hierarchical dependencies are not a straightforward matter, however, and prior work supports this notion (Baumann & Mattingley, 2021; Burwell et al., 2004; Pischedda et al., 2017).

A valid, alternate explanation for these null reports is that contexts were changing so often that participants were anticipating every trial as a “switch,” thus negating major evidence for switch costs. In other words, participants were always monitoring for a context change and thus did not settle into a particular “response set” or pattern of responding. If this likelihood is the case, it means the lack of switch costs does not necessarily mean the hierarchical structure is not represented; it might just mean participants are continually evaluating the context state at both levels of the hierarchy before responding. Such null switch cost reports support the overall ambiguity of switch costs due to complex hierarchical dependencies as additionally addressed in the previous AX-CPT work of Nee and Brown (2013). While the original task design that inspired this study did not focus on switch costs, these data nevertheless aid in our understanding of participant experience.

## Limitations

The scope of this study was mainly limited due to its nature as a behavioral pilot, with a small sample size and no neural data at this time. This lends great opportunity to be expanded to more populations beyond healthy young adults in future work. An additional limitation was the distribution of how many control trials participants encountered. The number of encounters a participant encountered was randomized (occurrence weights varied each time E-Prime ran the test programs), so a participant could receive four control trial conditions in a given experimental phase while another participant could have received three. While there was a nonzero chance that participants would not see any control trial conditions at all and it is not clear how this difference across subjects would make a difference in the results, it would be good practice to minimize in any subsequent studies investigating hierarchical decisionmaking involving spatial and non-spatial contexts. Information from previous methodologies on this matter is limited, though.

## Future Directions

The findings of my thesis offer an early validation of the task design and its capacity to simulate hierarchical decision-making within realistic spatial contexts. Although this pilot study was limited to behavioral data, it lays the groundwork for transitioning to a full-scale neuroimaging experiment. Future work can incorporate fMRI to explore how hippocampal engagement differs between spatial and non-spatial conditions. By expanding the sample size and including more diverse populations, subsequent studies can clarify the roles and interactions of hippocampal and prefrontal systems in hierarchical reasoning. Ultimately, this line of research holds promise for developing targeted interventions to address deficits in decision-making associated with aging and neurological disorders.

# APPENDIX A

| FOR OFFICE USE ONLY |
| --- |
| Study ID: __________ |
| Testing date+time:______________ |
| P ☐ E ☐ |

**Date:**___________________

**MAP Lab Information Form**

**Name**: _________________________ **Participant ID:** _______________

**E-mail address:**___________________ **Phone number**:__________________

**Years of Education**: _____ **Age**: _______ **Sex**:_______ **Handedness**:_______

**How many hours did you sleep in the last ____ hours:** ______

**What time did you wake up this morning:** ______

**Race (circle one)**: [] American Indian/Alaskan [] Asian [] Pacific Islander

[] Black/African American [] White [] Hispanic/Latino

[] More than one race (please designate which by circling all that apply)

**Is English your first language? (circle one):** [] Yes [] No

**If no, at what age did you start learning it?:** ____________

**Are you Bilingual?** [] Yes [] No

**Do you have normal (or corrected to normal) vision?(circle one):** [] Yes [] No

**If you are participating in an fMRI or EEG study, would you be able to wear contacts for the experiment?** [] Yes [] No

**Are you colorblind? (circle one):** [] Yes [] No

**Do you have normal (or corrected to normal) hearing?(circle one):** [] Yes [] No

## How would you rate your general health?

[] Poor [] Fair [] Good [] Excellent

**1.** Are you **currently** taking <u>any medications</u>? **Y** **N**

________________________________________________________________

**2.** Do you have a pacemaker, vagus nerve stimulator, or other electrical implant?
**Y** **N**

**3.** Do you have a history of head trauma? **Y** **N**

**4.** Have you ever had a seizure? **Y** **N**

**5.** Do you have any speech, sensory, or motor impairments or a learning disability? **Y** **N**

**6.** Have you ever been diagnosed with a psychiatric illness, or seen anyone for emotional or psychiatric problems? **Y** **N**

**7.** Have you ever been on any anti-depressant, neuroleptic, or sedative medications? **Y** **N**
Are you currently taking? **Y** **N**

**8.** Do you have a history of cardiac or other general health-related problems? **Y** **N**

**Please respond to the following specific health conditions – write N/A if condition is not applicable**

- Respiratory Problems?
  + Medications?________________________________________
- Heart Disease?
  + Medications?________________________________________
- High Blood Pressure?
  + Medications?________________________________________
- Low Blood Pressure or Anemia?
  + Medications?________________________________________
- Diabetes?
  + Medications?________________________________________
- Sickle Cell Anemia?
  + Medications?________________________________________
- Parkinson's/Alzheimer's?
  + Medications?________________________________________
- Stroke?
  + Medications?________________________________________
- ADD/ADHD?
  + Medications?________________________________________
- Multiple Sclerosis?
  + Medications?________________________________________
- Arthritis (problems with hands or back)?
  + Medications?________________________________________

- Other health problems we haven't mentioned?

  ________________________________________________

# APPENDIX B

| FOR OFFICE USE ONLY |
|---|
| Study ID: __________ |
| Testing date+time:_____________ |
| P ☐ E ☐ |

**Date:**__________________

**MAP Lab Supplemental Demographics**

**Participant ID:** _______________

**Years of Education**: _____ **Age**: _______ **Sex**:_______ **Handedness**:_______

**How many hours did you sleep in the last ____ hours:** ______
**Was this sleep restful (circle one)? Yes - No**
**Was this sleep different than normal (circle one)? More - Less**
**What time did you wake up this morning:** ______

Are you currently using hormonal birth control? **Yes - No**

When was the start date of your last menstrual period? ____ - **Currently - N/A**

(note, your answers are confidential and these questions are to help interpret the memory measures, which can relate to hormone levels, where applicable)

**If this study is a multi-day study, did you think about the task when you weren't performing the task with us in the lab?**
**Yes - No**

- If yes, how frequently?

  ______________________

- In what detail (briefly describe what you thought about or remembered)?

  ______________________________________________________________
  ______________________________________________________________
  ______________________________________________________________
  ______________________________________________________________

# APPENDIX C

**GSU/GT Center for Advanced Brain Imaging**
**831 Marietta St, Atlanta GA 30332, USA**
**Phone (404) 385-8619 Fax (404) 385-8620**
www.cabiatl.com

**HEALTH SCREENING FORM**

| | | |
|---|---|---|
| **Name** | | **Phone Number** |
| **Date of Birth** | **Age** | **Gender** |

**Ethnic Category:**
[ ] American Indian/Alaska Native [ ] Asian
[ ] Black/African American [ ] Hispanic/Latino
[ ] Native Hawaiian/Other Pacific Islander [ ] Caucasian

**HANDEDNESS**

What hand do you normally use? (Put "+" in the column if you usually use that hand, "++" if you always use that hand, or one "+" in each column if you use both hands equally.)
Experimenter: Score 1 for L++, 2 for L+, 3 for + in each column, 4 for R+, and 5 for R++ (> = 20 ok).

| Activity | Left | Right |
|---|---|---|
| Writing a message | | |
| Drawing a picture | | |
| Using a toothbrush | | |
| Throwing a ball | | |
| Using a pair of scissors | | |

Do you have any immediate family members who write with their left hand? [ ] No [ ]Yes

**EYESIGHT**

| | | |
|---|---|---|
| Indicate which you use:<br>[ ] Glasses<br>[ ] Bifocals<br>[ ] Reading glasses<br>[ ] Contacts<br>[ ] None (normal vision) | If you know your prescription, please write it here.<br><br>*Left*<br><br>*Right* | Is the prescription for one eye much stronger than the other?<br>[ ] No [ ] Yes<br>Do you have astigmatism?<br>[ ] No [ ] Yes<br>Are you color blind?<br>[ ] No [ ] Yes |

**LANGUAGE / EDUCATION**

| | | |
|---|---|---|
| Is English your first language?<br>[ ] No [ ] Yes<br>If not, what language is? | List all other languages that you speak: | Starting with elementary school, how many years of education have you had? |

**GENERAL HEALTH**

| | |
|---|---|
| How would you rate your general health?<br>[ ] Poor [ ] Fair<br>[ ] Good [ ] Excellent | List any serious medical conditions that you have had, and list all of your current medications. |

**For Experimenter Use Only**:
Principal Investigator__________
Experimental ID__________
Subject ID__________
Screen Date__________
MRI Date & Time__________

June 2020

# APPENDIX D

SANTA BARBARA SENSE-OF-DIRECTION SCALE
Sex: F M Today's Date:_______________
Age:_______ V. 2

This questionnaire consists of several statements about your spatial and navigational abilities, preferences, and experiences. After each statement, you should circle a number to indicate your level of agreement with the statement. Circle "1" if you strongly agree that the statement applies to you, "7" if you strongly disagree, or some number in between if your agreement is intermediate. Circle "4" if you neither agree nor disagree.

**Questions to reverse code in bold.**

1. I am very good at giving directions.
strongly agree 1 2 3 4 5 6 7 strongly disagree

**2. I have a poor memory for where I left things.**
strongly agree 1 2 3 4 5 6 7 strongly disagree

3. I am very good at judging distances.
strongly agree 1 2 3 4 5 6 7 strongly disagree

4. My "sense of direction" is very good.
strongly agree 1 2 3 4 5 6 7 strongly disagree

5. I tend to think of my environment in terms of cardinal directions (N, S, E, W).
strongly agree 1 2 3 4 5 6 7 strongly disagree

**6. I very easily get lost in a new city.**
strongly agree 1 2 3 4 5 6 7 strongly disagree

7. I enjoy reading maps.
strongly agree 1 2 3 4 5 6 7 strongly disagree

**8. I have trouble understanding directions.**
strongly agree 1 2 3 4 5 6 7 strongly disagree

9. I am very good at reading maps.
strongly agree 1 2 3 4 5 6 7 strongly disagree

**10. I don't remember routes very well while riding as a passenger in a car.**
strongly agree 1 2 3 4 5 6 7 strongly disagree

**11. I don't enjoy giving directions.**
strongly agree 1 2 3 4 5 6 7 strongly disagree

**12. It's not important to me to know where I am.**

strongly agree 1 2 3 4 5 6 7 strongly disagree

**13. I usually let someone else do the navigational planning for long trips.**
strongly agree 1 2 3 4 5 6 7 strongly disagree

14. I can usually remember a new route after I have traveled it only once.
strongly agree 1 2 3 4 5 6 7 strongly disagree

**15. I don't have a very good "mental map" of my environment.**
strongly agree 1 2 3 4 5 6 7 strongly disagree

# APPENDIX E

## MDAR Author Checklist

**For all that apply, please note where in the manuscript the required information is provided.**

**Materials:**

| Newly created materials | indicate where provided: page no/section/legend) | n/a |
|---|---|---|
| The manuscript includes a dedicated "materials availability statement" providing transparent disclosure about availability of newly created materials including details on how materials can be accessed and describing any restrictions on access. | Methods and Materials | |

| Antibodies | indicate where provided: page no/section/legend) | n/a |
|---|---|---|
| For commercial reagents, provide supplier name, catalogue number and RRID, if available | | x |

| DNA and RNA sequences | indicate where provided: page no/section/legend) | n/a |
|---|---|---|
| **Short novel DNA or RNA including primers, probes:** Sequences should be included or deposited in a public repository. | | x |
| | | |

| Cell materials | indicate where provided: page no/section/legend | n/a |
|---|---|---|
| **Cell lines:** Provide species information, strain. Provide accession number in repository **OR** supplier name, catalog number, clone number, **OR** RRID. | | x |
| **Primary cultures:** Provide species, strain, sex of origin, genetic modification status. | | x |

| Experimental animals | indicate where provided: page no/section/legend) | n/a |
|---|---|---|
| **Laboratory animals or Model organisms:** Provide species, strain, sex, age, genetic modification status. Provide accession number in repository **OR** supplier name, catalog number, clone number, **OR** RRID. | | x |
| **Animal observed in or captured from the field:** Provide species, sex, and age where possible. | | x |

| Plants and microbes | indicate where provided: page no/section/legend) | n/a |
|---|---|---|
| **Plants:** provide species and strain, ecotype and cultivar where relevant, unique accession number if available, and source (including location for collected wild specimens). | | x |
| **Microbes:** provide species and strain, unique accession number if available, and source. | | x |

| Human research participants | indicate where provided: page no/section/legend) or state if these demographics were not collected | n/a |
|---|---|---|
| If collected and within the bounds of privacy constraints report on age, sex and gender or ethnicity for all study participants. | Methods and Materials | |

## Design:

| **Study protocol** | **indicate where provided: page no/section/legend)** | **n/a** |
|---|---|---|
| If study protocol has been pre-registered, provide DOI. For clinical trials, provide the trial registration number **OR** cite DOI. | | x |

| **Laboratory protocol** | **indicate where provided: page no/section/legend)** | **n/a** |
|---|---|---|
| Provide DOI **OR** other citation details if detailed step-by-step protocols are available. | | x |

| **Experimental study design (statistics details)** | | |
|---|---|---|
| **For in vivo studies:** State whether and how the following have been done | **indicate where provided: page no/section/legend. If it could have been done, but was not, write not done** | **n/a** |
| Sample size determination | | x |
| Randomisation | | x |
| Blinding | | x |
| Inclusion/exclusion criteria | | x |

| **Sample definition and in-laboratory replication** | **indicate where provided: page no/section/legend** | **n/a** |
|---|---|---|
| State number of times the experiment was replicated in laboratory. | | x |
| Define whether data describe technical or biological replicates. | | x |

| **Ethics** | **indicate where provided: page no/section/legend** | **n/a** |
|---|---|---|
| **Studies involving human participants:** State details of authority granting ethics approval (IRB or equivalent committee(s), provide reference number for approval. | Methods and Materials | |
| **Studies involving experimental animals:** State details of authority granting ethics approval (IRB or equivalent committee(s), provide reference number for approval. | | x |
| **Studies involving specimen and field samples:** State if relevant permits obtained, provide details of authority approving study; if none were required, explain why. | | x |

| **Dual Use Research of Concern (DURC)** | **indicate where provided: page no/section/legend** | **n/a** |
|---|---|---|
| If study is subject to dual use research of concern regulations, state the authority granting approval and reference number for the regulatory approval. | Methods and Materials | |

## Analysis:

| **Attrition** | **indicate where provided: page no/section/legend** | **n/a** |
|---|---|---|
| Describe whether exclusion criteria were preestablished. Report if sample or data points were omitted from analysis. If yes report if this was due to attrition or intentional exclusion and provide justification. | Methods and Materials | |
| **Statistics** | **indicate where provided: page no/section/legend** | **n/a** |
| Describe statistical tests used and justify choice of tests. | Methods and Materials | |

| Data availability | indicate where provided: page no/section/legend | n/a |
|---|---|---|
| For newly created and reused datasets, the manuscript includes a data availability statement that provides details for access or notes restrictions on access. | Methods and Materials | |
| If newly created datasets are publicly available, provide accession number in repository **OR** DOI **OR** URL and licensing details where available. | | x |
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| Code availability | indicate where provided: page no/section/legend | n/a |
|---|---|---|
| For all newly generated custom computer code/software/mathematical algorithm or re-used code essential for replicating the main findings of the study, the manuscript includes a data availability statement that provides details for access or notes restrictions. | Methods and Materials | |
| If newly generated code is publicly available, provide accession number in repository, **OR** DOI **OR** URL and licensing details where available. State any restrictions on code availability or accessibility. | | x |
| If reused code is publicly available provide accession number in repository **OR** DOI **OR** URL, **OR** citation. | | x |

**Reporting**

MDAR framework recommends adoption of discipline-specific guidelines, established and endorsed through community initiatives. Journals have their own policy about requiring specific guidelines and recommendations to complement MDAR.

| Adherence to community standards | indicate where provided: page no/section/legend | n/a |
|---|---|---|
| State if relevant guidelines (e.g., ICMJE, MIBBI, ARRIVE) have been followed, and whether a checklist (e.g., CONSORT, PRISMA, ARRIVE) is provided with the manuscript. | MDAR checklist provided in Appendix E | |

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