NEUROLOGICAL ROLE OF CARTOGRAPHIC VISUAL CONTRAST IN GEOSPATIAL COGNITION

by

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A DISSERTATION

Presented to the Department of Geography
and the Division of Graduate Studies of the University of Oregon
in partial fulfillment of the requirements
for the degree of
Doctor of Philosophy

March 2023

DISSERTATION APPROVAL PAGE

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Title: Neurological Role of Cartographic Visual Contrast in Geospatial Cognition

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Degree awarded March 2023

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Doctor of Philosophy

Department of Geography

March 2023

Title: Neurological Role of Cartographic Visual Contrast in Geospatial Cognition

Cartographers assert that, as a core tenet of effective design, effective implementation of visual contrast is crucial for map reading. It is theorized that without sufficient contrast, readers are hindered from efficiently accessing the underlying spatial information. Yet this essential task of practically implementing effective visual contrast is left unsettled in modern cartographic literature beyond cursory discussions. Numerous cartographers over the past century have studied and failed to conclusively resolve this cartographic conundrum. Further, cartographic theories on visual contrast are themselves borrowed from dated Gestalt psychological theories dating back to the 1920s.

This research reexamined cartographic understanding of visual contrast through the modern lens of exploratory neuroscience. An interdisciplinary review of related cartographic, geospatial and neuropsychological literature highlighted the theoretical and epistemological dissonance across visual contrast research. Building from that review, a traditional cartographic behavioral experiment was conducted in parallel to a more novel-to-cartography fMRI neuroimaging experiment. The behavioral study evaluated the effect of visual contrast on the cognitive task of map rotation. The addition of fMRI neuroimaging methods enabled further insight into how visual contrast mediates the underlying geospatial cognitive brain processes associated with map rotation. Together, this novel dual-pronged approach attempted to resolve the cartographic contrast conundrum as well as pinpoint related perceptual and cognitive processes essential for map reading. The research found that changes to cartographic visual contrast result in corresponding changes to behavioral task performance (response time and accuracy) as well as associated brain activities. The behavioral statistical models showed that there were statistically significant relationships between combinatorial levels of hue and lightness contrast on map reader's accuracy and response time as indicators of general map cognitive performance. The neuroimaging models also showed that there were statistically significant brain activation differences for high versus low hue and high versus low lightness contrast. Further, this dissertation identified regions of the brain associated with map reading and design-centric information decoding that were previously poorly understood. Thus, this dissertation expands the importance and understanding of cartographic visual contrast within modern cognitive cartography literature.

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Lobben, A., & Limpisathian, P. W. (2021). Perception and Cognitive Processing of Geographic Phenomena. In *Geographic Information Science & Technology Body of Knowledge* (Vol. 2021, Issue Q4). https://doi.org/10.22224/GISTBOK/2021.4.1

Lobben, A. K., Lawrence, M., & Limpisathian, P. W. (2019). Representations of Place in the Human Brain. *Abstracts of the International Cartographic Conference*, *1*, 1–2. https://doi.org/10.5194/ica-abs-1-226-2019

Brooks, R. P., Limpisathian, P. W., Gould, T., Mazurczyk, T., Sava, E., & Mitsch, W. J. (2018). Does the Ohio River flow all the way to New Orleans? *JAWRA Journal of the American Water Resources Association*, 54(3), 752-756.

Limpisathian, P. W. (2017). Evaluating Visual Contrast and Hierarchy Relations of Cartographic Features Across Multi-Scale Map Displays. In *The Pennsylvania State University*. https://etda.libraries.psu.edu/catalog/14410pwl5119

ACKNOWLEDGMENTS

First, I want to thank my advisor, Amy Lobben. Through her steadfast support and encouragement, I dared to develop a scholarship that was not bounded by the theoretical or methodological status quo. From day one, Amy pushed me to expand the boundaries of cognitive cartography research, ever quietly demanding while allowing me the space to explore atypical facets and unmapped theoretical avenues. On the not-so-uncommon occasion where my wandering mind got the better of me, Amy was there to navigate through my intellectual detours and route me back onto the task at hand and onto more stable theoretical footing. Through Amy, I broaden the way I thought about the ideas and methods I was studying. More importantly, Amy taught me make space for myself and my goals theoretically, academically and professionally. I am thankful to have learned from Amy's unbounded brilliance. I look forward to continuing our neuro-geography scholarship at UW-Madison.

I additionally want to thank my committee member, and friend, Carolyn Fish. Perhaps more than anyone at UO, Carolyn not only witnessed but also guided me academically, professionally and personally over the course of our friendship. While an undergraduate research assistant at Penn State, I first met Carolyn when she was a graduate research assistant working on another project for the same PI. After that we became graduate school peer and friends – even sharing an office at one point. Eventually we both joined UO Geography, me as a PhD student and Carolyn a few years later as Assistant Professor. Through all that time, Carolyn has been a supportive friend, frank counsel and candid mentor. From Carolyn, I learned about the intricacies of academia, networking and maintaining professional relationships. Carolyn also taught me the importance of being pragmatic and learning have reasonable expectations for myself and others. I am a better scholar because of Carolyn.

I also would like to thank Henry for agreeing to be on my committee and for lending your statistical expertise to help guide the research in this dissertation.

I would like to thank Elliot for agreeing to be the institutional representative on my committee and for leading your psychology expertise to make this research more thoughtful and robust.

My cartographic scholarship would not have been possible without the enduring mentorship and guidance of my undergraduate and master's advisor, Cindy Brewer. I vividly remember how Cindy's introductory cartography class changed everything about how I thought of maps. Cindy taught me the importance of maps as an essential tool for science communication – the link between the arts and science within geography. Cindy taught me that groundbreaking geospatial analysis is worthless if we are unable to communicate it effectively and accessibly. Cindy opened my eyes to the world of cartography and was kind enough to take me under her capable wings to guide and shape my cartographic journey. Cindy pushed me out of my comfort zone and coaxed me to pursuit opportunities I thought I was undeserving of or unprepared for. It is not an understatement to say that none of my cartographic accomplishments would be possible without Cindy's support, guidance, and mentorship over the years. I am a cartographer because of Cindy. Thank you, Cindy.

I also want to thank my friends in and outside of the Department of Geography community. Specifically, I want to thank Lou Ginart. This dissertation would not be possible without your support and love. I want to thank Alex Wahl for his support and

help brainstorming analysis, scripting and statistical models. And of course, I want to thank everyone who pitched in to read, bounce ideas, help me pilot the experiment or volunteered to be my subject for this research projects. I also want to thank other friends who were there when I needed to think about anything other than my research. You know who you are, and I am grateful for all your support and help.

The investigation was supported in part by the author’s National Science Foundation Doctoral Dissertation Research Improvement Grant Award (Number 2132412), the University of Oregon Department of Geography Rippey Dissertation Writing Grant, and by a National Science Foundation grant (Number 1359800), to Dr. Amy Lobben at the University of Oregon. This work benefited from access to the University of Oregon high performance computing cluster, Talapas. This research was possible due in part to access to and support from the University of Oregon Lewis Center for Neuroimaging (LCNI) and LCNI’s dedicated and highly talented staff: Ali Burggren, Vince Quesada, Jolinda Smith and Dianna Alderette.

Dedicated to those fostering diverse and queer spaces in academia and beyond.

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CHAPTER I

INTRODUCTION

The task of establishing and maintaining visual contrast and hierarchy between map elements has always been crucial for map makers. Visual contrast is vital for establishing perceptual differences that allow readers to distinguish different encoded spatial phenomenon (Dent et al., 2008; Krygier & Wood, 2011; Slocum et al., 2008). More than that, contrast of visual features has been shown to be important for attention guiding and overall map communication (Garlandini & Fabrikant, 2009a). Cartographic visual contrast is generally established through the manipulation of five basic visual characteristics: line, texture, lightness, detail, and hue (Dent et al., 2008). Individual characteristics can be combined further to enhance contrast. Of these contrast components, the most impactful are lightness and hue (Limpisathian, 2017). Conversely, the overuse of combinatory visual contrast can lead to reduced visual salience through the introduction of burdensome visual complexity that weakens or distorts the underlying spatial information (Brewer, 2016). In the midst of all this complexity, the central task of determining the most optimal configuration of visual contrast remains unsettled in literature and imprecise in practice (Limpisathian, 2017; MacEachren & Mistrick, 1992; Wood, 1994).

Much of the theoretical knowledge that underpins cartographic understanding of visual contrast stems from antiquated Gestalt psychological principles dating to the 1920s (Limpisathian, 2017). Despite being an essential tenet of cartographic theory that is taught as part of every introductory cartography course, determinant rules or guidelines for the optimal implementation of visual contrast have long evaded research cartographers (Limpisathian, 2017; MacEachren & Mistrick, 1992). Cartographers and psychologists over the decades have arrived at interesting, yet unsettled, and often conflicting conclusions regarding an optimal implementation of visual contrast (Arnheim, 1941; Dent, 1970; Oyama, 1960; Wood, 1976). Other researchers subsequently pointed towards the need for dynamic consideration of the contextual spatial information underneath (MacEachren & Mistrick, 1992; Wood, 1994). Prior research by the author identified a link between visual saliency with the map reader's perceived subjective aesthetical attachment to the map rather than the strict implementation of visual contrast itself (Limpisathian, 2017). It is possible that this ambiguity is due to the incomplete understanding of the complex theoretical foundation that underpins visual contrast theory, as well as the intricate physio-psychological interplay of perception and cognition of visual information.

As such, with the advancement of neuropsychology, classical psychological theories are increasingly being reexamined under modern neurological methods (Ganis et al., 2004). This advancement has subsequently enabled a new neuro-geographic body of research through the bridging of the previously disconnected fields of geography and neuropsychology (Lobben, 2014). Accordingly, this dissertation addresses the inconsistency and gap in literature by using neuro-geographic methods and perspectives, specifically Functional Magnetic Resonance Imaging (fMRI), to examine the role of lightness and hue visual contrast in the map reading process and to identify associated brain activities. fMRI enables direct insight into the neuro-mechanisms that underpin mental processes (Amaro & Barker, 2006). Further, fMRI has proven to be highly productive for investigating both general mental processes as well as specialized visual perception and spatial cognition processes cited in cognitive cartography (Bohrn et al., 2013; Ganis et al., 2004; Lobben et al., 2009; Wraga et al., 2005). Neuroimaging enables a level of direct insight into processes that are theorized to directly underpin visual contrast cognition (Goodyear et al., 2000; Leguire et al., 2011b; Turkozer et al., 2016). Reflective of this, the goal of this research was not to examine these processes in isolation using traditional behavioral versus transdisciplinary neuroimaging methods. Rather, the aim of this research was to jointly investigate both the behavioral and neurological correlates of visual contrast together to better understand this crucial aspect of cartographic design. To achieve this aim, this dissertation incorporated parallel behavioral and neuroimaging studies that address the following research questions:

RQ1: How does varying visual contrast of lightness and hue in cartographic symbolization affect geospatial mental rotation task performance?

RQ2: How does varying visual contrast of lightness and hue in cartographic symbolization affect brain activation patterns of geospatial mental rotation tasks?

Intellectual Merit

This research advances knowledge in neuro-geography, cognitive cartography and geovisualization by validating and re-quantifying an essential tenet of cartographic design using novel neuro-geographic methods and perspectives. Cartographers contend that visual contrast is crucial in establishing the perceptual differences required for the map reading process. Yet research from neuroscience has classed visual contrast and its related proxies as largely preattentional and seemingly unimportant for higher function cognition tasks (Driver, 2001; Driver et al., 1992; Lamme, 1995). Accordingly, the results of this research attempted to either confirm cartographers' contention of visual contrast, as the basis of graphic communication design or demote the importance of visual contrast theory within cartographic design literature. Furthermore, the determination of an optimal configuration of contrast design in cartography has been under debate since at least the 1950s. Thus, empirical results from this neurological experiment will help to settle the debate. Regardless, this research brings this stagnant aspect of cartographic knowledge into the twenty-first century. Further, unlike the recent trends in neuropsychology, where classical theories undergo systematic reexamination, similar theoretical revitalization efforts are rare in cartography. As such, this research not only fills this gap but also expands the literature for cartographic design and map cognition. Similarly, interest in contrast within neuroscience has been largely limited to basic luminance and brightness properties, generally uninterested in holistic and integrative visual contrast arrays that accounts for detailed graphical characteristics (hue, line, detail, etc.). Thus, this research broadens such the literature both in scope and scale through the examination of individual contrast characteristics as well as different configurations of integrative visual contrast characteristics.

Broader Impacts

The disciplines of geography and cartography have contended with how humans make, use and interact with maps, as a medium for representing space, for more than two millennia. Furthermore, research on geospatial perception and cognition has been conducted for more than a half-century (Caquard, 2015). A primary goal of these research domains has always been to investigate how to produce better maps that are more suited for the human reader. Accordingly, with few exceptions, these explorations have relied on dated theoretical proxies for human cognition rather than a more direct measure of cognitive activities

(Lobben et al., 2005). The fMRI methodologies utilized here offer a more direct correlate for cognitive functions that goes beyond just theoretical musing and conjecture. At minimum, this research demonstrates the viability of an unrealized avenue for empirical cartographic research that complements existing methodologies. This direct insight into the neurological underpinning of cartographic design from this research serves as an important step towards better map design that is more tailored for the mind's eye. Furthermore, this research serves as an introduction and demonstration for the geographic discipline of novel and interdisciplinary approaches to conduct rigorous geospatial cognition and cartographic design research that ventures beyond the exclusive use of prevailing geographic tools. Thus, this research paves the way for geospatial cognition and cartographic design research to reposition themselves among allied cognitive and design science disciplines. Still, while this research used interdisciplinary neuroscience methods, the intellectual as well as the investigatory scopes are wholly geographic. Moreover, this research is the product of a burgeoning neuro-geographic research group – synthesizing and working across the previously disparate fields of geography and neuropsychology.

CHAPTER II

BACKGROUND

Visual contrast is an often-discussed tenant of effective cartographic design. Its importance justified by the very way humankind sees the world around us. Psychological research tells us that humans are inherently limited in our ability to intake and process visual information. Evidence of this has been thoroughly demonstrated across a breath of related sensory and memory research ranging from basic mnemonic tests (Bellezza & Reddy, 1978; Roediger, 1980) to the unreliability of episodic memories and accounts (Brainerd et al., 2010, 2014; Lu & Nieznański, 2020). At its core, our visual processing systems both at the base-level perceptual realm as well as our higher-level cognitive deliberators rely on the prioritization of salient informational signals and simultaneous generalization of the supplementary and surrounding details. In that sense, visual contrast can be considered as the graphical manifestation of this sensory trait. This disposition is used by cartographers and graphic designers to explain the process for prioritizing important visual information while simultaneously deemphasizing background details – tapping into the inherent way our mammalian brains evolved to see the world.

As such, this background chapter discusses the motivation, theoretical basis, critique and reconceptualization of existing research and limited understanding of visual contrast within cartographic and related neuropsychological literature. First, a review of the evolution of cartographic visual contrast, from its Gestalt psychological roots to its expansion under the development and systemization of scientific cartography is presented. Tracing scientific cartography's disentanglement and subsequent theoretical independence from its psychological roots, this chapter further explores how cartographic visual contrast research used existing psychological frameworks to move beyond existing theoretical gaps and progress into the applied and multifaceted breath of modern cartographic research. Parallel to this discussion, an examination was completed on the consequences of this epistemological separation that hindered constructive introspection and renewal of core tenants within cartography. A comparison was then done to highlight how related foundational psychological theories were continuously reexamined and challenged as part of the philosophical discourse on Gestalt psychology. Reflective of that review, a reconceptualized theorical visual contrast saliency model for how cartographers can better think about, study and implement visual contrast based on modern evidence from neuroscience and allied applied sciences was posited and discussed.

Theoretical Roots of Visual Contrast

Gestalt psychological principles on perceptual grouping and object recognition underpin much of modern cartographic design and cognitive theories

(Dent et al., 2008; MacEachren, 1995). These psychological principles resulted from the prevailing attempts at explaining the basic perceptual processes relating to how elements and figures in the visual field interact with one another (Arnheim, 1941; Goldstein, 2017; Spelke, 1990). These principals were established in the 1920s as perceptual laws by psychologists to conceptualize the observable human visual perceptual phenomenon (Wagemans et al., 2012). These laws were subsequently incorporated into foundational cartographic research as the basis of visual hierarchy on maps (Belbin, 1996; MacEachren, 1995). As such, Gestalt psychology is inextricably linked with the legacy of how scientific and cognitive cartography research came to be and burgeoned over the past century. This legacy likely benefited the early development of the field but likewise hindered it over the years as scientific cartography evolved and grew into a distinct discipline (Carvalho et al., 2009).

"Gestalt" can roughly be translated as the *optimal holistically organized visual configuration,* with the subfield of Gestalt visual psychology focused on understanding the ocular perceptive processes tied to this integrative phenomenon (Jäkel et al., 2016; Wagemans et al., 2012). At the heart of Gestalt psychology are a set of perceptual "laws" that enables *Prägnanz,* or an optimal, concise, salient and orderly state required for perceptual organization (Carvalho et al., 2009; Jäkel et al., 2016). These laws cover object formative and organizational processes based on the elemental properties of *proximity*, *similarity*, *closure*, *symmetry*, *commonality,* *continuity*, and *experience* (Bruce et al., 2003; Haber & Hershenson, 1973; Wagemans et al., 2012). Although these laws were proposed as applying to all visual stimuli, cartographers subsequently focused on its utility and applicability to planar graphic variables and map representations (Dent et al., 2008).

Most consequential to cartographic theory, the Gestalt concept of *figure-ground* relation, itself a derivative of the perceptual laws, summarizes the salient interaction of visual levels into *figure* (foreground) versus *ground* (background) elements (Dent, 1972; Lloyd, 2005; MacEachren & Mistrick, 1992). *Figure* elements are theoretically perceived at higher saliency while *ground* elements are perceived as secondary and complementary to the *figure*, thereby establishing a thematical hierarchy of saliency (Haber & Hershenson, 1973). In cartography as well as in other visualization sciences, figure-ground has been studied through the manipulation of visual contrast of map symbolization elements (points, lines, areas), with lightness (value) contrast being the most utilized visual contrast attribute (Brewer, 2016; Limpisathian, 2017; MacEachren & Mistrick, 1992; O'Connor, 2015). It is understood that greater visual contrast of the figure against the ground enables the figure to distinguish itself more effectively from the ground and perceptually elevate it onto a higher visual level (T. Griffin, 1990; Shapiro & Hamburger, 2007). This visual leveling, in turn, guides the attention of the reader towards the salient piece of information on the visual plane (Dent, 1972; Fabrikant et al., 2010).

An examination of cartographic literature and studies relating to cartographic visual contrast highlighted the sub-disciplinary expansion and simultaneous divergence from its psychological theoretical source (Montello, 2002). Cartographers took Gestalt laws as established by psychologists and broaden them both in terms of depth and scope to fit our communicative needs and curiosities (Dent et al., 2008; MacEachren, 1995). This divergence greatly benefited the subdiscipline in its early days, by providing the pioneers of scientific and cognitive cartography research with a theoretical framing that enabled them to conduct and structure their cartographic examinations beyond the often difficult to operationalize artistic and aesthetical sensibilities that formerly defined the guild of map making (Montello, 2002; Robinson & Petchenik, 1975). These early examinations became the core of cartographic thought that were themselves subsequently built-upon and expanded into modern cognitive cartography research. Consequently, Gestalt-derived theories were expanded and formalized over the past century into modern cartographic principals on visual contrast, visual hierarchy, map balance, map layout and organization, to name a few. Over time these theories bore decreasing resemblance to the psycho-physical perceptual examination that continued and progressed in psychology (Belbin, 1996; Blades & Spencer, 1986). This expansion helped scientific and cognitive cartography mature into a field that today deals with the fundamental questions surrounding maps as complex communicative and representative systems (Brewer, 2007; Çöltekin, Francelet, et al., 2018; Fabrikant et al., 2010; Fabrikant & Lobben, 2009; Garlandini & Fabrikant, 2009b; MacEachren, 1992; Opach et al., 2013).

However, while this divergence benefited the cartographic discipline, especially in its early days, a comparative examination of modern Gestalt psychological research sheds light on how that divergence may have concurrently hindered the progression and limited the theoretical scope of modern cartographic research.

Over the past decades, psychologists and especially neuropsychologists, perhaps reflective of the interdisciplinary shift towards postmodernism, took an increasingly more critical approach to many of the philosophic psychological theories that previously guided the discipline (Bruce et al., 2003; Jäkel et al., 2016). It is useful in this context to note that the discipline of psychology, like many others, diverged from and is ultimately rooted in philosophy. Thus, there exists a disciplinary tolerance, if not outright encouragement, for the development of competing theories and for the active reexamination of posited and established thoughts, at least to an extent not observed in geography and cartography (W. Epstein & Tfieldt, 1994; Jäkel et al., 2016).

Unlike dated psychological musings and contemplations, modern cognitive psychological theories tend to be characterized by the inclusion of neuropsychological mechanical models that support the descriptive and theoretical elucidation of the examined human experience (Poldrack & Wagner, 2004;

Seymour et al., 2008). Hence, many established and accepted laws were ultimately reexamined under renewed empirical lights. Gestalt psychological laws were subsequently challenged and criticized as “descriptive principles, but without a model of perceptual processing” with limited empirical quantitative grounding (Bruce et al., 2003, p. 105). A major issue taken by modern psychologists was the lack of theoretical and psycho-mechanical models that could ground and underpin the descriptive phenomenon that could, in turn, allow for rigorous testing and systematic examination (Jäkel et al., 2016). As such, theoretical and empirical research aimed at modernizing the prevailing theoretical foundation through the identification and examination of empirically grounded psychological and neuromechanical models subsequently flourished in Gestalt psychology (Bloechle et al., 2018; W. Epstein & Tfieldt, 1994; Herrmann & Bosch, 2001; Hoffman & Dodwell, 1985; Kuai et al., 2017; Seymour et al., 2008; Shapiro & Hamburger, 2007; Zaretskaya et al., 2013).

Thus, a major consequence of the divergence and isolated development of cognitive cartography from its foundational psychological roots is the obliviousness towards the need for actively reexamination and modernization of foundational theories. While Gestalt psychology has continuously been questioned, criticized, bolstered and reexamined through basic and novel psychological explorations, cognitive cartography accepted the Gestalt principles as settled laws and went about applying it to the myriad of cartographic variables (Jäkel et al., 2016; Montello, 2002).

Thus, modern cognitive cartography research would benefit considerably from both a greater introspective research outlook and a more transdisciplinary approach to the theories and methods cartographers are interested in. Cartographers have been eager to embrace the modern techniques offered by computer and aligned information sciences (Wilbanks, 2004). However, the field subsequently failed at maintaining and ensuring the relevancy of our theoretical footing in the name of disciplinary progress and theoretical infallibility. Indeed, the theoretical interests of cartographers are not completely indifferent from more interdisciplinary scholarship across neuropsychology (Boccia et al., 2014), neuroeconomics (Houser & McCabe, 2013) and neuroaesthetics (Pak & Reichsman, 2017).

Nevertheless, it is important to note the recent positive research trends within cartographic scholarship. In recent years, there has been increased support and interest in a broad critical reflection of the discipline, both theoretically and philosophically (A. L. Griffin et al., 2017). On the qualitative side, cartographers are again interested in the basic philosophical contemplations of what it means to make and use maps through critical cartographic research (Bosse, 2020; Caquard, 2015; Fish, 2020; Kelly, 2021). On the quantitative and empirical side, scientific and cognitive cartographers are showing broader acceptance and greater inclusion of novel and nontraditional methods from fields such as neuropsychology and behavioral psychology (Çöltekin, Francelet, et al., 2018; Fabrikant & Lobben, 2009; Jiang, 2015; Keskin et al., 2016; Lobben et al., 2009, 2014, 2015a). For example, in addition to measuring subjective or self-reported attitudes or response towards cartographic stimuli, cartographic researchers are measuring neurophysiological markers or measures of emotional saliency to complement traditional behavioral measures to holistically study the map reading process (Anderson & Robinson, 2021; R. A. Epstein et al., 2017; Fabrikant et al., 2010; Lobben et al., 2005, 2014; Soh & Smith-Jackson, 2004). Furthermore, cognitive cartography can also benefit from learning and applying approaches from other transdisciplinary fields such as neuroaesthetics, an art and architecture subfield that is similarly interested in neuropsychological markers of human response to affective design (Brown & Dissanayake, 2006; Skov et al., 2018; Vidal, 2012; Zaidel, 2015). Still, despite this positive disciplinary growth, there is considerable work to be done to modernize foundational cartographic theories. Such work requires broad renewed interest and support for basic and foundational research aimed at reexamining and modernizing cartographic foundational theories.

Moving Beyond the Perception-Cognition Hierarchy

To accomplish such a feat, cartographic visual contrast must be situated within related literature. Accordingly, this section tracks the thematic evolution and subsequent divergence of cartographic visual contrast and connect it with related neuropsychological proxies of visual contrast.

As previously eluded, the cartographic discipline has long been interested in understanding how humans uniquely use maps as a tool to communicate and represent the spaces around them and beyond (Montello, 2002). Through cognitive cartography research that began in the twentieth century, the cartographic field developed a foundational understanding that the design of maps plays a crucial role in determining the effectiveness of spatial communication and navigation (Fabrikant & Lobben, 2009; A. L. Griffin et al., 2017; Montello, 2002). Much of this literature is underpinned by dated psychological *Gestalt principles* (Dent, 1970, 1972). These theories established in psychology in the early 1900s and expanded throughout the last century posits and explains visual perception that permits the processing of visual information (Arnheim, 1941; Treisman, 1982). Cognitive cartographers took these principles and expanded them to suit our more specific interest in the cartographic design process (Arnheim, 1976; Dent, 1972; Petchenik, 1977). From this body of research, improved conceptualizations of effective map design beyond the basic artistic considerations were established.

The specific concept of *visual contrast* resulted from discussed Gestalt psychology principles on perceptual grouping. Cartographers subsequently applied this concept to help explain the visual interactions of the spatial representations and design of map elements (Dent, 1970). From that body of research, a more expansive and distinct view of *cartographic visual contrast* began to take hold. This expanded understanding went beyond the traditional psychological notions surrounding perception in the traditional sense. An expanded view that saw perception as not the precursor that enables attention and cognition of the visual information but instead as an integral part of those *higher* mental processes (Brewer, 2016; Limpisathian, 2017).

Cartographic visual contrast research moved away from isolated psycho-behavioral experimental paradigms that measured specific responses to basic non-contextual graphical stimuli. In turn, research moved towards observing general responses to arrays of graphical yet cartographically applied and contextual stimuli (MacEachren, 1995). For example, instead of just testing Gestalt figure-ground of two overlapping geometries, research cartographers tested how that figure-ground interaction affected recognition of land versus water along coastal maps (Head, 1972; Lloyd, 2005; MacEachren & Mistrick, 1992). It could be inferred that this cartographic nature, where the modality of design and graphical arrays cannot truly be separated from the spatial context represented by them, meant that the contextual detachment central to pure psychological perception research became incompatible with more applied cartographic research. As theorized and studied by many cartographic researchers since the very beginning, at the heart of these explorations is the interaction between the spatial and graphical properties, with an accepted but not-fully qualified supremacy of the spatial properties (Bertin, 1983; MacEachren, 1995). Thus, owing to this interactive tradition, any isolated examination of supposed cartographic visual variables without the spatial context likely proved to be an unfruitful cartographic exercise (Dent, 1970; Lobben et al., 2014).

Unlike in cartography, visual contrast within neuroscience remained fairly rooted in its psychological roots. Visual contrast has been studied as an important component to perceptual vision and the construction of the cognitive prototypes. However, it is theorized to be irrelevant for cognitive processing and manipulation of the cognized prototypes (Driver, 2001; Driver et al., 1992; Lamme, 1995). As such, most neuroscientific research that directly examines visual contrast focuses primarily on ocular sensory response to luminance (lightness) contrast within the visual cortex. (Ben-Bashat et al., 2017; Goodyear & Menon, 1998; Yan et al., 2010). The visual cortex is the functional region of the brain posteriorly located in the occipital lobe (*Figure 1*). Most are specifically aimed at investigating contrast sensitivity in human – that is the rudimental neuro-ocular ability to discern luminary differences of the elements or objects in the visual field (Avidan et al., 2002; Goodyear & Menon, 1998; Mohamed et al., 2002). Other neuro-gestalt research focused on examining the neurological perceptual correlates of rudimental figure-ground segmentation and perceptual grouping (Driver et al., 1992; Jäkel et al., 2016; Leguire et al., 2011a; Mohamed et al., 2002; Spelke, 1990). This limited research scope seemingly reenforces the notion that visual contrast is only relevant for lower-level perceptual processes. This prevailing notion is in line with a bottom-up view of a lower-level generalized all-purpose perceptual system that prepares basic information for higher attentional and cognitive processes (Williams, 2019).

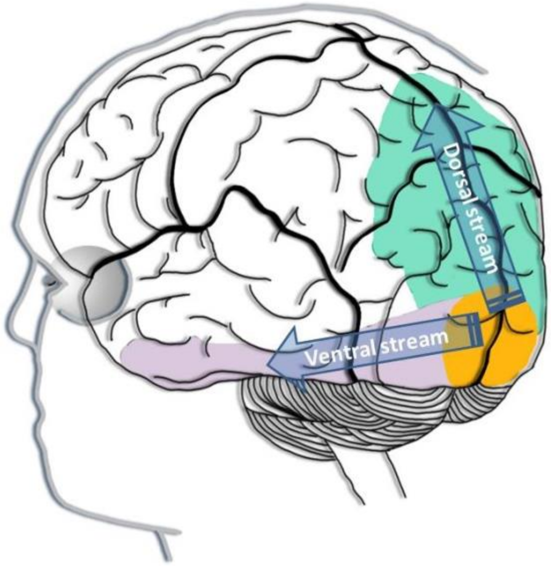


Figure 1: Approximate location of the visual cortex comprising of the primary visual cortex (orange), ventral visual cortex (lilac) and dorsal visual cortex (teal). Figure reproduced from Vyshedskiy et al., 2017.

Nonetheless, while these examinations explicitly frame visual contrast as relevant for perception, most do not explicit dissociate and discount it from higher-level cognitive processes. Only one study, with considerable validity concerns, explicitly declare that figure-ground segmentation – as an analog of visual contrast – occurs exclusively as part of lower-level visual perception and therefore isolated from higher-level visual attention processes (Driver et al., 1992).

To reconcile and move beyond the contrasting theoretical perspectives of visual contrast within cartography and psychology, the neuropsychological basis for the conceptualization of perceptual visual contrast must be examined, which at its core is structured around the bottom-up versus top-down mental processing hypothesis. This dichotomous explanation of how the human brain processes information is rooted in the hierarchical neuroanatomy of the brain. Related brain structures are understood to be more likely localized and anatomically co-located thereby allowing for efficient processing and relaying of increasingly complex characteristics of perceptual forms from one part to the next (Konen & Kastner, 2008; Williams, 2019).

The bottom-up hypothesis posits that these perceptual systems are part of an all-purpose hierarchical center where information is received as basic input, is then processed, and ultimately passed to higher-level cognitive functions but is generally independent from more complex thoughts (Buschman & Miller, 2007; Teng & Kravitz, 2019). Conversely, the top-down hypothesis posits that higher-level cognitive processes such as attention modulates and exert partial control over the processing of lower-level perceptual information (Gilbert & Li, 2013; Kravitz & Behrmann, 2011; Wischnewski et al., 2010; Wolfe & Horowitz, 2017). Both perspectives coexist in psychological discourse where specific systems are identified and debated as belonging to one or the other (Beck & Kastner, 2009).

However, cartographic visual contrast presents an interesting dilemma that fits neither perspective neatly. On the one hand, cognitive cartography literature suggests that the design and visual contrast implementation of the map likely affect the efficiency of spatial information processing, thus providing credence to the notion that cartographic visual contrast is a bottom-up component of map cognition (Dent, 1972). However, because of the spatial context of the map, it is logical that a top-down attentional control mechanism may modulate and exert control over the lower-level perceptual processes of visual spatial information (Nanay, 2018; Shapiro & Hamburger, 2007). In simpler terms, is map reading akin to the processing of any other visual information or does the inherent spatial attributes of maps dictate how that information is processed? Neurogeographic research has indicated that the spatial attributes within maps result in distinct specialized mental processing (Çöltekin, Francelet, et al., 2018; Lobben et al., 2014).

In comparison, neuropsychological visual contrast and other gestalt research are studied extensively as part of an entirely bottom-up all-purpose perceptual system (Herrmann & Bosch, 2001). This distinction, while seemingly incompatible at first read, makes some sense because even if gestalt psychology and visual contrast are part of an all-purpose perceptual system, *cartographic visual contrast*, being innately tied to its spatial context, is by definition explicitly not all-purpose. Cartographic visual contrast likely recruits larger and complex cognitive processes that subsequently exert attentional control over an otherwise lower-level process. Further, this view would be reflective of recent literature on conscious visual perception and *visual saliency* (Liu et al., 2019). Therefore, the spatiality of maps likely plays an outsized role in modulating its perceptual processing.

Compatibility With the What-Where Pathway Paradigm

This supremacy of spatiality can be better understood by framing against another foundational psychological paradigm. The paradigm of the what-where pathway, also known as the two-streams hypothesis, is the prevailing neuropsychological theory that explains context-specific visual (and auditory) information processing in the human brain (Betts et al., 2013; Gazzaniga et al., 2019; Konen & Kastner, 2008). At its core, the paradigm forms the basis for understanding how inbound visual information is processed. The theory, which spans the perception-cognition hierarchical divide, posits that at a fundamental level the human brain evolved to process visual information as either for the purpose of object identification (what) or localization (where) (Goodale & Milner, 1992; Ungerleider & Haxby, 1994). In the neurogeographic and cartographic context, this paradigm is interesting in that, at the surface, it confirms geographer’s connotation that, indeed, *spatial is special* and that the exploration undertaken in the geographic discipline is supported by the very foundation of how human perceive and cognize the world around us.

This two-streams hypothesis was posited by psychologists in the late 1960s and early 1970s (Gazzaniga et al., 2019; Ungerleider & Haxby, 1994). Studies done on primates that were later correlated with lesion human patients suggested that the primate brain distinctly processes visual (and auditory) information in supposedly distinct parallel pathways for spatial information and representational object recognition (see *Figure 3*) (Goodale & Milner, 1992; Ungerleider & Haxby, 1994). The what-stream, also referred to as the anatomical ventral stream, is associated with the recognition of visual forms and object formation and is comprised of the V1, V2, ventral V3, and V4 of the visual cortex as well as the inferior temporal cortex (Deubel et al., 1998). The inferior temporal cortex is believed to be related to multiple specialized functional areas of the brain including the parahippocampal place area (PPA), the fusiform face area (FFA) and the lateral occipital complex (LOC) (Gazzaniga et al., 2019; Grill-Spector et al., 2001; Tong et al., 1998). The PPA is a functional region of the brain that has been shown to possess a neurological specialization for the identification of place-scene and spatial environments (R. Epstein et al., 1999; Tong et al., 1998). Moreover, the LOC has been studied for its importance for object formation and recognition (Grill-Spector et al., 2001; Keskin et al., 2016; Konen & Kastner, 2008; Lobben et al., 2014). Conversely, the where-stream, or the anatomical dorsal stream, is the pathway associated with processing of spatially defined information and locational representations and is comprised of the V1, V2, dorsal V3, V5, V6 of the visual cortex as well as the posterior parietal cortex (Foley et al., 2015; Gazzaniga et al., 2019; Ungerleider & Haxby, 1994). The posterior parietal cortex, a region in the parietal lobe located immediately posterior to the primary somatosensory cortex, has been examined for its role in resolving and maintaining spatial reasoning, locomotion, attention and egocentric planning (Buschman & Miller, 2007; Goodale

& Milner, 1992; Grassi et al., 2018; Konen & Kastner, 2008; Kuai et al., 2017; Malhotra et al., 2009).

While the lower-level perceptual processors of each stream are generally well-defined, possible exclusive association or dissociation of either stream to higher cognitive functions or their neurological correlates are less understood (Takahashi et al., 2013). Indeed, one of the pending issues of the two-stream hypothesis is the identification of the specific arbitrator(s) where information from both streams would re-converge for more complex conscious and cognitive thinking and specifically how that re-convergence occurs (Boly et al., 2017; Grieves & Jeffery, 2017; Levy & Goldman-Rakic, 2000; Odegaard et al., 2017; Takahashi et al., 2013). The entorhinal cortex (EC) is located inferoanterior to the hippocampus while the retrosplenial cortex (RSC) is posterior to the hippocampus. The EC and RSC has been proposed as highly important for spatial cognition, spatial memory, navigation and proprioception. Further, the regions have been advanced as possible cognitive processors of spatial cognitive information stemming from both streams (Bellgowan et al., 2009; R. A. Epstein et al., 2017; Kravitz et al., 2011; Mitchell et al., 2018; Schultz et al., 2015; Vann et al., 2009). Additionally, the hippocampus itself, as the central encoder and decoder of working and long-term memory, likely plays a significant role together with the RSC and EC in resolving and aggregating information from the two streams, in addition to other possible functional processors in the prefrontal cortex (Antonova et al., 2009;

Bellmund et al., 2018; Eichenbaum, 2017; Ekstrom et al., 2014; R. A. Epstein et al., 2017; Fink et al., 2001; Morganti et al., 2013). Accordingly, the association of spatial cognitive functions with hippocampal processes additionally highlights the likely multidirectional (simultaneously top-down and bottom-up) nature of spatial cognition and its explicit link to memory and visual attention (Bellgowan et al., 2009; Deubel et al., 1998; Mitchell et al., 2018).

With the democratization of technology and the ubiquity of mapping applications, people are more than ever inclined to take for granted the specialty of maps and spatial media (Milner, 2016). Theoretically, maps as a tool represents a unique avenue to understand the human experience both behaviorally and psycho-physiologically. In that vein, maps can be conceptualized in a manner similar to many of the tools created by humankind to interact with and manipulate the natural environments around us (Arnheim, 1976). However, maps as a spatial tool are uniquely human in that it transfers and communicates information about our environment in a modality not observed elsewhere in the natural world (Arnheim, 1976; Lobben, 2004; MacEachren, 1992; Robinson & Petchenik, 1975). In that sense, humankind evolved in a specific manner to enable us to *allocentrically* convey this spatial information through representative abstractions of the actual environment, similar to how written language is used to convey meaning and knowledge through representative configuration of characters (Lobben, 2004; Montello & Raubal, 2012; Rauschecker, 2012). Even in the egocentric context of

You Are Here (YAH) locator maps, where the spatial perceptive of the cartographic media aligns with the reader's egocentric navigational outlook, the map as a media is still a detached abstraction and arguably allocentric representation that requires the reader to mentally resituate and collocate themselves to achieve proprioception and perspective alignment (Montello, 2010; Proulx et al., 2016). Furthermore, when considering the properties of maps, as a representational media of space, it is logical to theorize about the possible cross-modal nature of cartographic representations (Lobben & Lawrence, 2015). Reflective of this theorization, many geographers and psychologist alike have had a special interest in maps as representative abstractions (Arnheim, 1976; Caquard, 2015; Freksa, 2015; Lobben & Lawrence, 2015; MacEachren, 1992; Olson, 2007; Seubert et al., 2008; Veale et al., 2017; Wischnewski et al., 2010). Indeed, maps and cartographic representations are special in that they are inherently spatial where it is unfeasible to strip away the spatial context while still maintaining meaningful graphical icons, lines and points (MacEachren, 1995). Additionally, maps as a human tool serves specific purposes – navigation and knowledge communication (Lobben, 2004).

Accordingly, this cross-modal nature of maps as a what representation of the where makes it difficult to position it within the existing psychological paradigm. Humans are able to utilize maps to egoistically place ourselves in space, situate ourselves among our surroundings and plan our movements and interactions with our environment (Lobben, 2007). Thus, it is logical that the visuospatial information from a map would be processed in the dorsal-where stream. However, maps and cartographic representations are additionally and undeniably conceptual depictions that are comprised of forms and objects that require mental identification, recognition and abstraction (Çöltekin, Francelet, et al., 2018; MacEachren, 1995). Additionally, reference and thematic maps are not for the purpose of self-location or movement but rather to communicate knowledge and information about a distant geographic place (Lobben & Lawrence, 2015; MacEachren, 1995). Thus, it is additionally logical that the visual information from a map would additionally be processed as part of the ventral-what stream (Grill-Spector et al., 2001; Konen & Kastner, 2008; Lehky & Sereno, 2006). In fact, resolving this spatial specialty is a significant theoretical exercise that cognitive cartographers and neuro-geographers alike have always and continued to grapple with in, both in the philosophical and psychological contexts (Arnheim, 1976; Fabrikant & Lobben, 2009; Lobben & Lawrence, 2015; MacEachren, 1995).

Indeed, much of what is known about the neurological process of map reading supports this multi-stream outlook. Research has shown that map reading, like other visual activity, elicits broad activation throughout the visual cortex spanning both the what and where pathways (Lobben et al., 2014, 2019). More specifically, neurogeographic research have highlighted the varying activities in the LOC and the PPA possibly associated with different levels of representations and abstraction of the map (satellite, schematic, navigational, etc.) (Lobben et al., 2014, 2019). Additionally, navigational maps have been shown to further elicit activities in the motor cortex that has been linked to the visuospatial sketchpad, locomotion and imagined movement (Grieves & Jeffery, 2017; Lobben et al., 2014; Seubert et al., 2008; Yamamoto & DeGirolamo, 2012). Thus, this body of research affirms that at the neurological level, maps are indeed the "what" representation of the "where."

Framing this conceptualization against MacEachren's (1994) widely cited cartographic information cube (*Figure 2*), the what-where paradigm does not neatly fit along its three posited axes. While neurological evidence affirms the supremacy of spatial information for the purpose of cognition in the navigational sense, the cartographic information cube highlights the broad theoretical foundation that is more reflective of the representative and communicative aspects associated with the what-ventral stream (Iglói et al., 2009; Kravitz et al., 2011; MacEachren, 1995; Plank et al., 2010). That is not to say that these conceptualizations are incompatible, rather, much like other framing research examined here, they reflect the distinct and perhaps incomparable theoretical perspectives that underpin modern cartographic and psychological research. Indeed, Lobben and Lawrence's (2015) synthesized model of spatial thinking, itself a theoretical reflection and enhancement of MacEachern's cartographic information cube, eschews the restriction of the what-where divide by reframing spatial thinking towards intent and attentional controls. This conceptual reframing towards the cognitive intent associated with the attentive task itself is further bolstered by ongoing and expanding neuropsychological exploration of more holistic perception-cognition models (Himmelbach et al., 2012; Kravitz et al., 2011; Trés & Dozzi Brucki, 2014; Wischnewski et al., 2010). Furthermore, recent neuropsychological research has highlighted the less-distinct nature of the what-where stream which suggests that while information may be simultaneously process in the two separate streams, they are not entirely insular and may actually be shared and communicated between the streams (Kravitz et al., 2013; Zachariou et al., 2017).

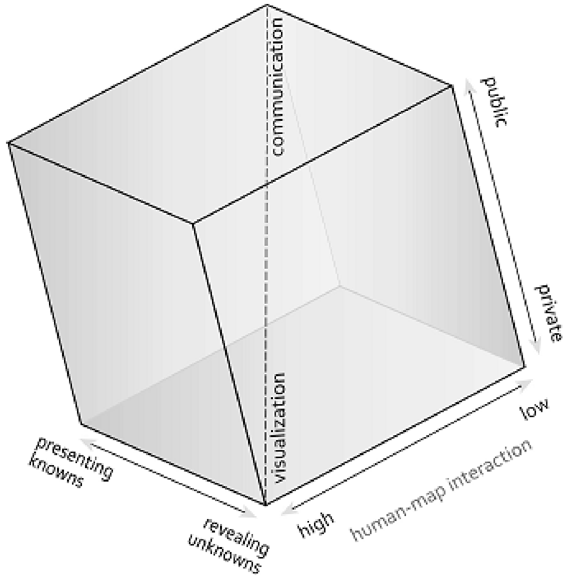


Figure 2: MacEachren's (1994) Cartography3 cartographic information cube of geovisualization on tasks, users, and interaction types as dimensions. Figure reproduced from Çöltekin, Janetzko, et al., 2018.

Therefore, it can be concluded that while the what-where streams may be distinct, these streams are nonetheless entangled. Thus, it is likely unproductive to attempt to force the what-where segmentation onto cartographic representations. Additionally, despite the possibility of functional dissociation at lower-level perception, evidence suggests that this distinction may have limited effect on complex higher-level process such as map cognition (Deubel et al., 1998; Takahashi et al., 2013). Thus, reflective of theoretical progress toward a more collaborative understanding of the what-where stream, it is likely more constructive to acknowledge the inextricably multi-modal nature of maps and proceed by reframing it under more holistic conceptualizations based on visual saliency, attention and intent (Suh & Abrams, 2018).

Visual saliency, in its most generalized terms, can be operationalized as the cognitive parallel of perceptual visual contrast or as the non-planar cognitive analog of visual contrast itself (Itti, 2007; Veale et al., 2017). While visual contrast and visual hierarchy attempt to examine the fundamental psychology of visual information processing through object formation and the interaction of elements, visual saliency allows for a more holistic and integrative examination of how elements of visual information mentally stand out from its surroundings (Cong et al., 2018; Paschke et al., 2012; Veale et al., 2017; Wischnewski et al., 2010). Therefore, visual saliency can serve as the holistic reframing of visual contrast and cognitive figure-ground – expanding it beyond just the visual characteristics and with an added emphasis on the role of visual attention filtering and mediation (Kravitz & Behrmann, 2011; Teng & Kravitz, 2019; Wagemans et al., 2012; Wolfe

& Horowitz, 2017). This visual mediation process of salient information is thought to be simultaneously driven both by bottom-up as well as top-down mechanisms, such as visually prominent designs and goal-depended attentional controls, respectively (Gilbert & Li, 2013; Masrour et al., 2015; Veale et al., 2017; Wischnewski et al., 2010).

Further, while much has been theorized about the specificity of visual perceptual and cognitive processes by cartographers such as Dent and MacEachren, it is more productive to eschew that theoretical debate and instead focus on the larger neuropsychological systems that supersede those theoretical musings. Therefore, this research reconceptualizes *cartographic visual contrast* not as simply a function of basic psychological visual perception but rather as the operationalized perceptual attributes of visual saliency as a mechanism of holistic visual attention modulation. In this reconceptualization, the visual and design characteristics are not scrubbed from the cognitive process once a mental prototype is constructed. Rather, the attributes and the cognitive association and prototypical preferences to these attributes are essential in determining how the visual information is processed at the cognitive level (Shapiro & Hamburger, 2007). In this sense, visual saliency serves as the interface that resolves bottom-up perceptual visual contrast with top-down visual attention (see *Figure 3*) (Itti, 2007; Schneider, 1995; Veale et al., 2017; Wischnewski et al., 2010).

Although this reconceptualization may be novel for cartographic thought, a review of psychological literature shows that over time classical gestalt principles have likewise moved further away from basic perceptual research and towards applied visual attention research that is characterized by the top-down cognitive controls that modulates the processing of perceptual inputs (Deroy, 2013; Masrour et al., 2015; Shapiro & Hamburger, 2007; Siegel, 2012; Stokes, 2013, 2018; Wischnewski et al., 2010). And indeed, much of recent spatial and map cognition literature, while not all explicitly evaluating visual design characteristics of cartography, has increasingly been more interested in cognitive processes related to visual attention (Fabrikant et al., 2010; Garlandini & Fabrikant, 2009b; Liao et al., 2017; Lloyd, 2005; Lobben et al., 2009; Ory et al., 2015).

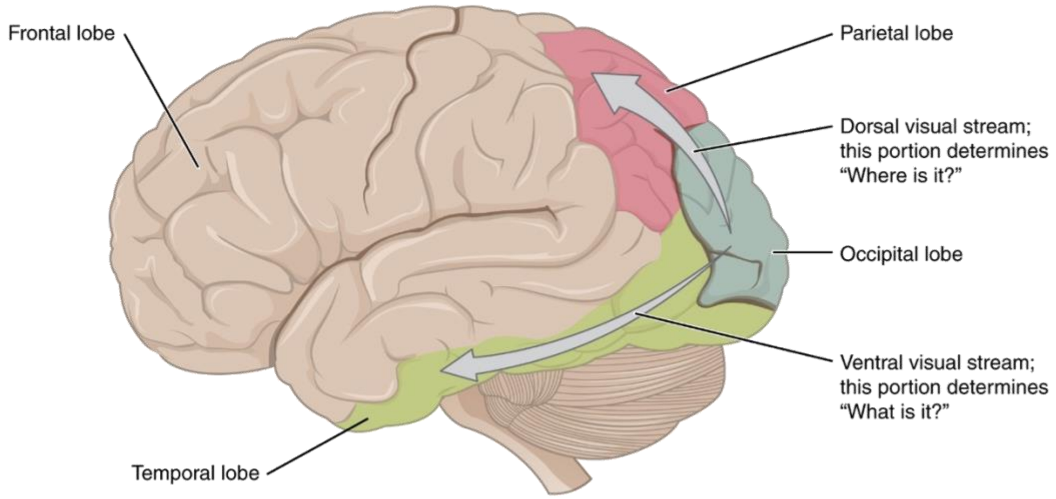


Figure 3: Left sagittal view of the visual streams in the human brain. The streams instigate from the posteriorly located occipital lobe and diverges dorsally (where) and ventrally (what) towards the parietal and temporal lobes, respectively. Figure republished under CC BY 3.0 license from Betts et al., 2013.

In this reconceptualization, visual saliency and cartographic visual contrast are intrinsically linked as part of the expansive process. Accordingly, this holistic cartographic visual contrast model would span across both lower-level map perception and higher-level map cognition (*see Figure 4*). In this regard, this progressive conceptualization avoids the arguably unproductive neuro-psychological endeavor of identifying where exactly lower-level perception ends, and higher-level cognition begins. Further, this reconceptualization helps resolve conflicting findings from previous cognitive cartographic research into visual contrast (Limpisathian, 2017). More importantly, this reconceptualization would be reflective of cartographers' contention regarding the importance of visual contrast and its paramount role for map cognition.

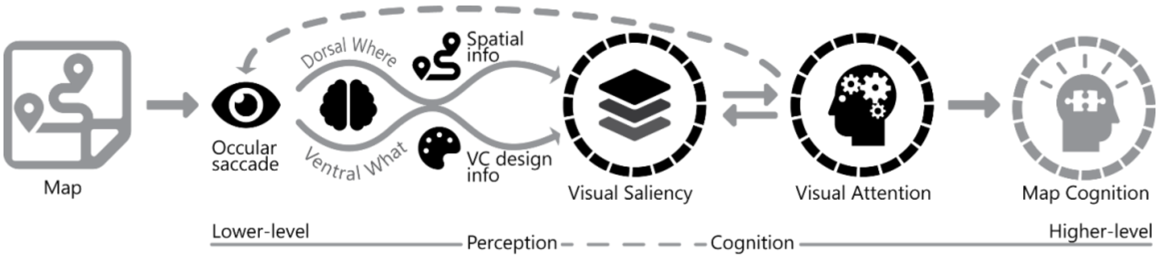


Figure 4: Reconceptualized holistic cartographic visual contrast model for map cognition. Visual contrast abbreviated as VC. (Original work, some icons from Font Awesome used under CC BY 4.0 License)

Simply stated, modern cartographic visual contrast bears little resemblance to the psychological visual contrast theories it was originally derived from. Visual contrast in modern cartographic context aligns more with theories on visual attention mediation. Therefore, a reconceptualized model is needed to guide our understanding of cartographic visual contrast. This novel model considers basic processing of visual contrast prototypes but also incorporates modern understanding about visual attention and spatial cognition. More importantly, the model provides a framework for cartographic visual contrast that is compatible with both cartographic and neuropsychological thought – thus eschewing and helping to resolve decades of inconclusive cartographic investigations into the role of visual contrast.

CHAPTER III

METHODOLOGY

The methodology describe in this chapter was developed to investigate and support the proposed reconceptualized model for cartographic visual contrast. Specifically, the role of cartographic visual contrast on the geospatial cognition process was investigated. Furthermore, this research attempted to quantify to what extent do different levels of visual contrast affect the ability of a map reader in accomplishing the geospatial cognition task of map mental rotation. Further, an analysis to identify recruited brain regions that could be associated with this map cognition process was completed. Reflective of the holistic nature of the reconceptualized model, this investigation went beyond examining these processes in isolation using traditional behavioral versus transdisciplinary neuroimaging methods. Instead, the behavioral and neurological correlates of visual contrast were jointly investigated to understand this crucial phenomenon.

The task of mental map rotation was selected as the surrogate for geospatial cognition due to its well-established and well-understood body of work on the associated and underlining cognitive processes spanning cartographic and psychological research (Aretz & Wickens, 1992; Frankenstein et al., 2012; Hintzman et al., 1981; Levine et al., 1984; MacEachren, 1992; Pazzaglia & Moè, 2013; Peter et al., 2010). A traditionally structured cartographic behavioral experiment was paired with a more-novel counterpart that utilizes an interdisciplinary fMRI neuroimaging methodology. Map rotation tests on specially designed contrast maps were conducted to evaluate and address the previously introduced research questions.

The overarching methodology of these evaluations can be primarily characterized as a correlational experiment design where map mental rotation performance was evaluated against different configurations of cartographic visual contrast. The behavioral component followed an established method used in cartographic research to identify between-subject preferences. In contrast, the fMRI methodologies utilized here offers a more direct correlate for cognitive functions that goes beyond theoretical musing and conjecture. Previous neuro-geographic research has demonstrated the viability of fMRI neuroimaging methods for this avenue of geospatial research (Lobben, 2004; Lobben et al., 2009, 2014, 2015b, 2019). The fMRI methods utilized here has previously been shown to be rigorous and effective for investigating mental processes from both a behavioral as well as a neuro-mechanical approach (Voyvodic et al., 2011). The methodology demonstrated here provides an additional avenue for empirical evidence that ultimately complements more-traditional behavioral approaches. Accordingly, these methods acted as complementary measurements of geospatial cognition and were of equal importance to the overarching goals of this project.

This research was partly built upon results from the author's prior behavioral cartographic research aimed at identifying optimal and preferential implementation of visual contrast (Limpisathian, 2017). The result of that prior research identified statistically significant patterns that pointed to a context-dependent optimal configuration of visual contrast (Limpisathian, 2017). This research expanded on those partially quantified patterns using exploratory neuroimaging methods in combination with a traditional behavioral component. In other words, the methods used in this research move beyond the limits of traditional cartographic behavioral studies and the exclusive reliance of subject-reported measures and inferential preferences. Thus, by integrating an accompanying neuroimaging component, this research pushed beyond more-fallible traditional measures to directly explore the underlying neuro-mechanical model often cited in modern neuropsychological literature. Reflective of the novel dual-pronged approach of, the methods discussed in this chapter is broken up thematically by the previously introduced research questions.

How Does Varying Visual Contrast of Lightness and Hue in Cartographic Symbolization Affect Geospatial Mental Rotation Task Performance?

To address this research question, a behavioral contrast rotation test was conducted. A test instrument where participants’ performance on mental rotation tasks under different contrast conditions was created. 18 participants were recruited for the test. Recruitment occurred on the University of Oregon campus and around the City of Eugene community. Participants were compensated for their time and participation at the rate of $30/hour. Cognitive and perceptual impaired individuals, non-English speaking individuals, individuals under 18 years of age, individuals unable to consent, unsighted individuals and individuals with color or other uncorrected vision deficits were excluded from the study. Prior to the commencement of data collection, non-exempt review and approval was obtained from the Institutional Review Board of the University of Oregon.

Instruments

A psychophysical test of mental rotation was the primary test instrument for this research question. The test was structured as a block design experiment mimicking the structure used for the subsequent neuroimaging experiments. Participants completed a series of map rotation tasks varied with randomized combinations of hue and lightness contrast conditions (high versus low of hue and lightness). The map rotation task comprised of two variants where the map was rotated 90 degrees or were rotated 90 degrees and then also flipped vertically.

The primary experimental contrast conditions being tested were lightness and hue. Accordingly, other unexamined visual contrast conditions (line, detail, texture) were kept at a uniform and minimal level across test instruments. Contrast variables were derived from the most distinctive contrast schemes identified in previous research (Limpisathian, 2017). Lightness and hue levels were referenced using the Munsell perceptual color system to maintain the uniformity of perceptual lightness and hue spacing (Munsell, 1946). The Munsell Value (lightness) space contains nine levels (excluding absolute black and absolute white) while the Munsell Hue space contains a total of 100 steps (10 intermediate steps between 10 primary hues) (Munsell, 1946). Unlike other color systems such as RGB or CMYK, the color space between each hue steps and each lightness levels are perceptually equal (Munsell, 1946).

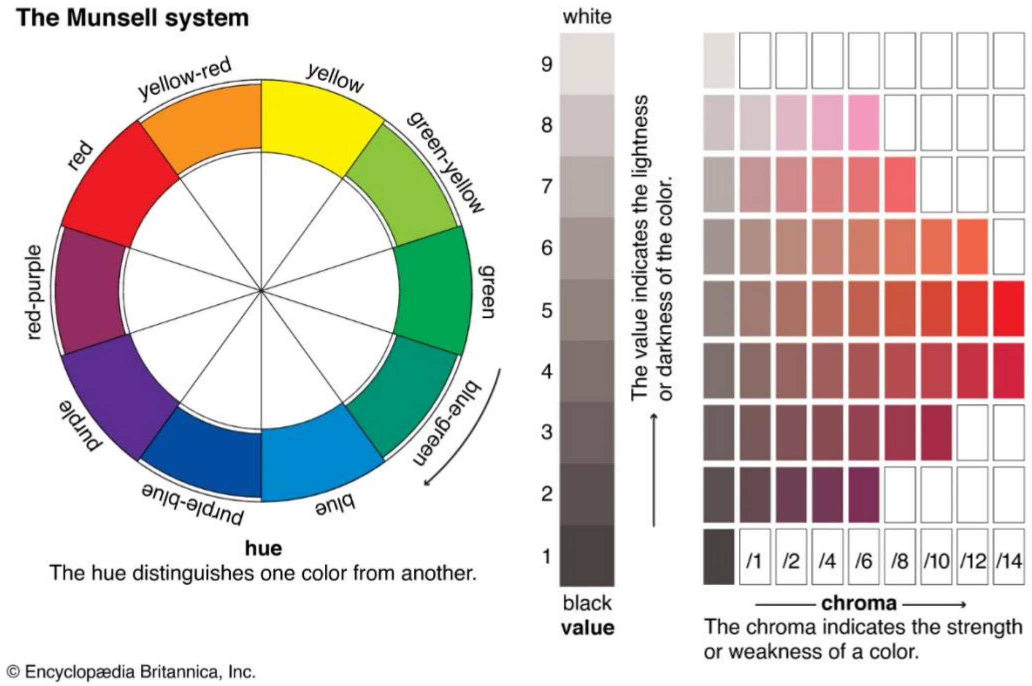


Figure 5: Diagram of the Munsell Color system showing 10 primary hues, nine intervening value (lightness) levels and the chroma space. Not shown in the hue portion of the figure are 10 intervening hue slices between

each primary hue. The vertical bar and slice on the right respectively show the value (lightness) and chroma dimensions of a single unspecified hue. Each hue slice has 11 possible value levels from zero (absolute lack of light a.k.a. pure black) to 10 (maximum light a.k.a. pure white), with nine intervening levels of lightness. Figure was reproduced from Encyclopaedia Britannica & Pallardy (2018).

High lightness contrast is defined as schemes where feature lightness is spread across the entire Munsell Values space with a minimum Munsell Value range of seven to a maximum of nine levels. Low lightness contrast is defined as schemes where feature lightness is limited to only three adjacent Munsell Value levels. To maintain a realistic representation of schemes, original hue pairs were chosen with the condition that hues from the green through blue to magenta range would act as anchors to represent waterbodies on the basemaps. Hue pairs were used instead of more complex multi-hue schemes to control for perceptual color shift caused by a simultaneous contrast effect. High hue contrast schemes were defined as complementary hue pairs that are at least 35 Munsell Hue steps apart. Low hue contrast schemes were defined as adjacent or analogous hue pairs.

As shown in *Figure 6*, one high hue contrast and one low hue contrast hue-pairs derived from the author’s prior research on visual contrast perception was selected (Limpisathian, 2017). These hue-pairs were identified as the most contextually representative schemes used in that prior research project. Contrast conditions were tested as configurations of combinatory permutations of high versus low contrast levels of hue and lightness (value). Thus, four contrast configurations, as visual contrast permutations, were incorporated into the behavioral psychophysical test. Each contrast configuration was applied to stimuli maps. These stimuli maps were generated using a modified open-source JavaScript fractal globe generator and have no referenceable real-world location (Olsson & Wizards of the Coast Inc., 2011). Fractal globe parameters were modified to generate maps that had four uniform visual levels divided between roughly equal water to land ratio. Furthermore, labels were excluded from these maps to prevent possible confounds due reading of text.

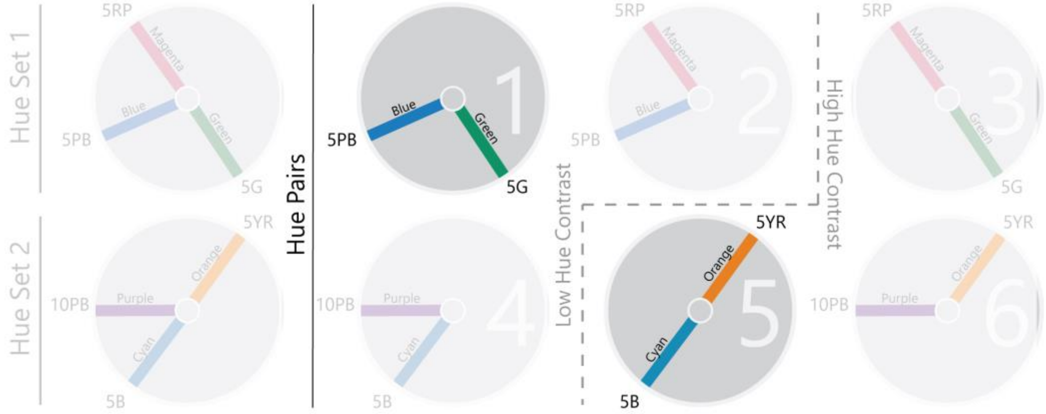


Figure 6: Color wheel hue pairs extracted from prior research by Limpisathian (2017). Hue pairs number one (low hue contrast) and five (high hue contrast) were selected for implementation in this research as the respectively most salient low and high hue contrast pairs.

Maps were enclosed in a circular frame on a 60% gray background instead of a square or rectangular frame with no thematical marginalia or directional and scalar reference elements (see Figure 7 for example stimuli maps). Four fractal globes were generated with two being selected for test instruments.

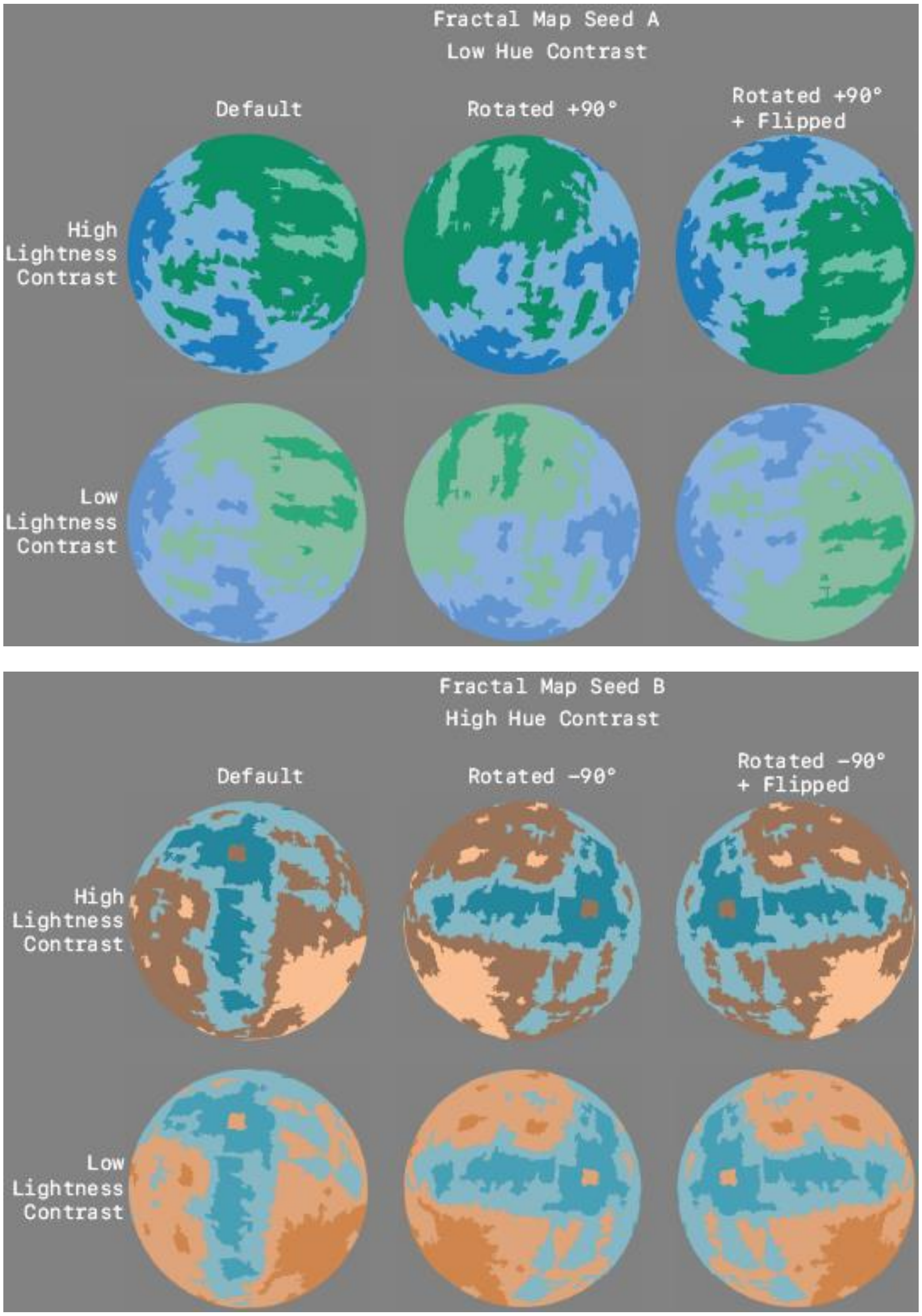


Figure 7: Example sets of visual contrast map stimuli for high and low hue contrast in combination with high and low lightness contrast applied to the two fractal map seeds. Columns show possible rotation task type.

To create additional variations, the two selected fractal globes were each rotated -45 degrees to create an additional variant map stimuli deck (see example deck in Appendix C). The four contrast permutations were then applied to each deck. Accordingly, 48 unique variant of map stimuli were constructed for the study. Variant maps were paired up to create 128 orientation judgement pairings for the experiments. Additionally, a brief pilot evaluation was conducted prior to the commencement of the participant testing confirmed the uniformity and reliability of the test instruments.

Data Collection and Processing

Participants were tested individually in-person at the Spatial Cognition, Computation and Complexity Lab (S3C) of the Department of Geography on the University of Oregon campus in Eugene, Oregon. Each test session lasted approximately 30 minutes. Participants complete the test on a provided research laptop computer with identical software configurations and display setup (Apple MacBook Air [M1 2020], 13.3-inch [diagonal] LED-backlit display with IPS technology; 2560x1600 native resolution at 227 pixels per inch with a 60 hertz refresh rate with P3 wide-gamut RGB color range and 400 nits [candela per square meter] peak brightness).

The structure of the data collection process was informed by a prior map rotation study by Lobben, et al. (2014). The data collection instruments were constructed and deployed using SR Research ExperimentBuilder version 2.3.38. ExperimentBuilder supports computer-based behavioral data collection but more importantly is compatible with the MRI scanner. Accordingly, two near identical versions of the experiment were built for data collection under both experiment modalities. At the start of the test, participants were given an overview of the map rotation task. Additionally, a summary explanation of visual contrast was also provided. During the orientation, participants were given ample opportunities to ask additional questions before confirming that they understood the task. Participants then completed a colorblindness check consisting of 10 randomly selected Ishihara test plates (*Figure 3*). Only participants with 90 percent or above accuracy were allowed to proceed. The colorblindness check ensured general uniformity of color perception among participants. The orientation was administered using Qualtrics with demographics and educational attainment information additionally collected.

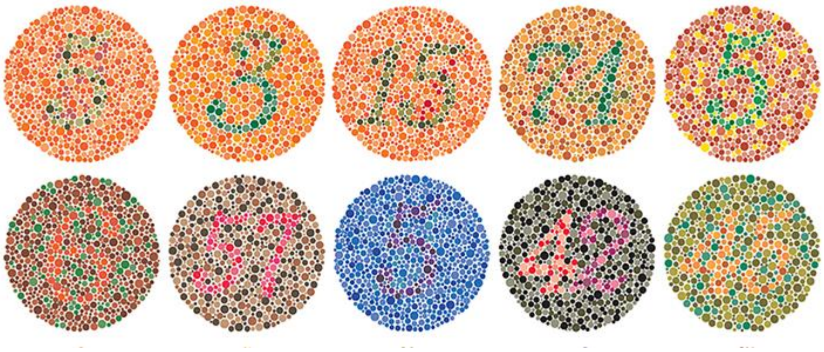


Figure 8: Example Ishihara colorblindness test plates used to test for colorblindness. Only participants that scored 90% or higher were allowed to continue to the experiment.

Once the orientation was completed, participants moved on to a practice run of the map rotation trials. The practice run ensured that they were familiar with the mechanics of the experiment. The experiment consisted of a series of map rotation trials. For each trial, a randomly selected pair of maps was presented where the map on the left served as the reference orientation and where the map on the right was either rotated or rotated and additionally flipped (*Figure 9*).

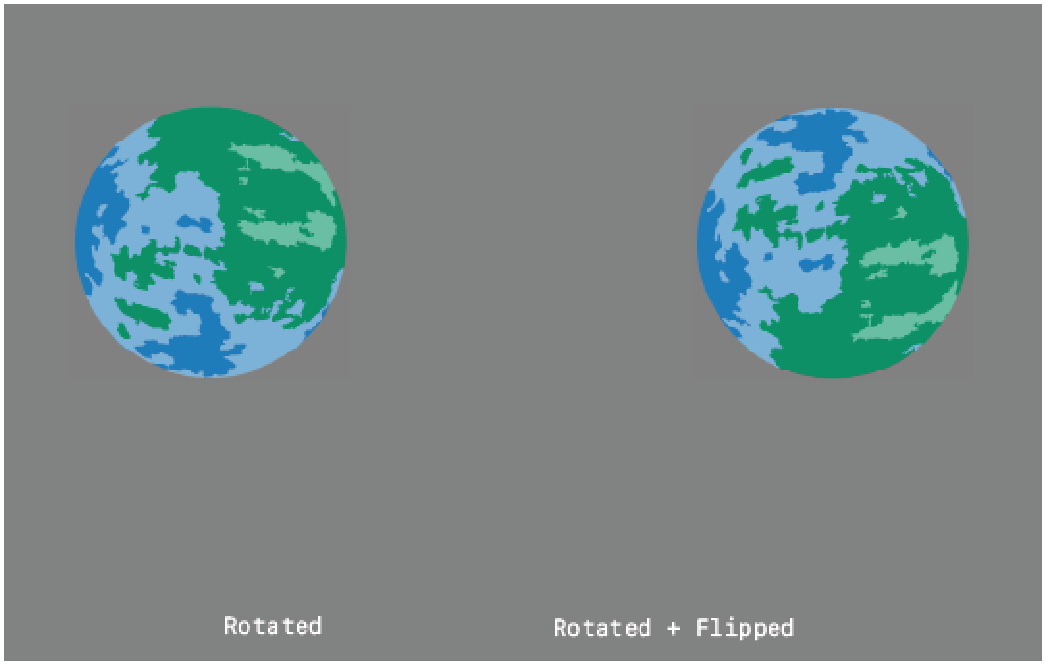


Figure 9: Example trial of the rotation judgement task showing the reference map stimuli on the left and the judgement map stimuli on the right. Users are tasked with judging how the map on the right was modified based on the two choices. The correct answer for this example is rotated and flipped.

Participants were given a maximum of eight seconds to judge the change via keyboard input – “Z” key if the map on the right was only rotated and the “/”

key if the map on the right was rotated and then flipped. These two keys were chosen for the ease of finger placement as the bottom-left and bottom-right character keys on the standard QWERTY keyboard layout. If participants exceeded 8 seconds, a warning message to proceed faster was shown before the test automatically proceeded to the next task in the series. Participants were advised to try to be as accurate as possible but to follow their snap judgement.

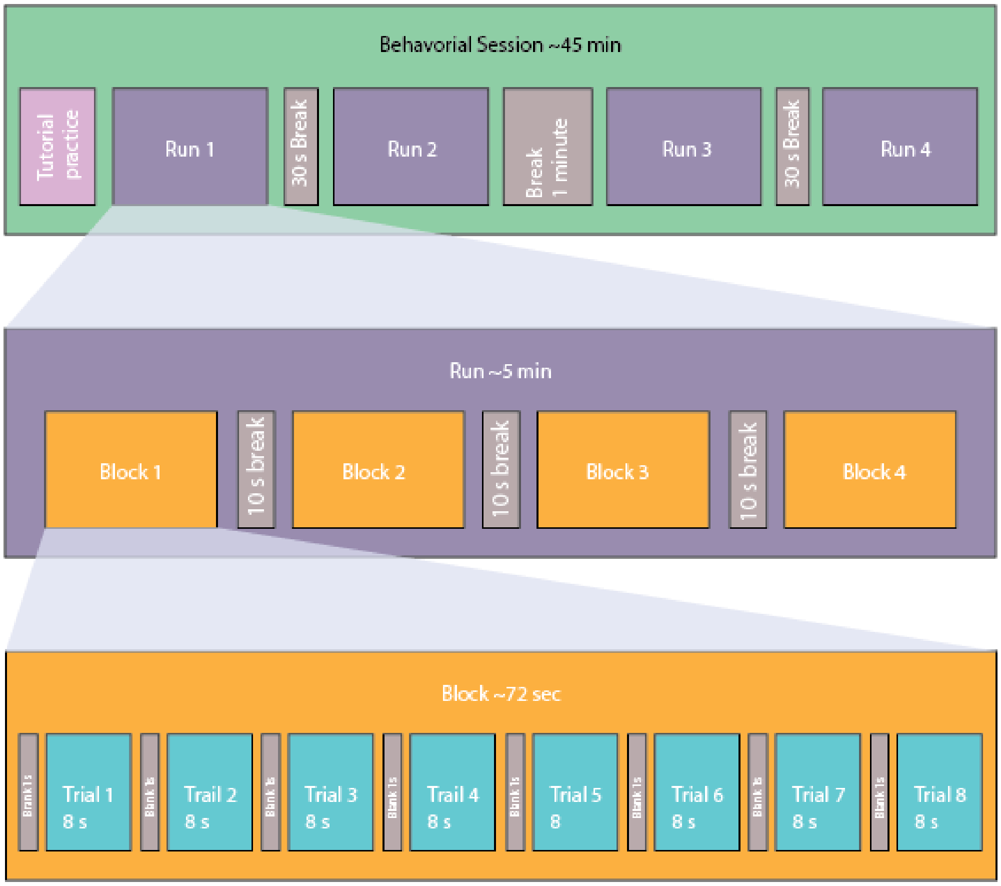


Figure 10: Full structure and duration of the behavioral experiment block design. Each session includes 4 runs. Each run includes 4 blocks. Each block includes 8 trials.

The practice run consisted of 4 sample stimuli maps that were similar in design to the experiment maps. After the practice run, participants proceeded to the actual experiment where they completed 128 trials of the map rotation judgement task spread across four runs of four block with each block containing eight trials (4x4x8) (see full design in *Figure 10*). To mitigate participant fatigue, a 10-second break occurred at the end of each block and a longer half-time 30-second break occurred between runs two and three. The resulting data collected from the experiment consisted of the binary correctness of participants' answers and the associated response time in seconds as the measure of accuracy and performance.

Behavioral Data Analysis

The response time and accuracy as the measures of performance served as the primary dependent variables for the analysis. The permutations of the tested contrast conditions served as the primary independent variable. An analysis of instrument reliability and validity was conducted. Because of the nature of the test instrument, as a proxy measure of cognitive abilities, scrutiny was warranted to ensure that they perform the required functions appropriately. A generalized linear mixed model (GLMM) analysis was conducted using IBM SPSS 28.0. The GLMM accounts for repeated measures where the same contrast permutation – for example high hue with high lightness contrast – were repeatedly tested across multiple map variations and across subjects (Seltman, 2018). The mixed model factors the variance of response variables across repeated measures and subjects (Seltman, 2018). In other words, the GLMM extends the traditional general linear model (GLM) to quantify both fixed effect from the experiment variable and random effect due to subject-level variations. Experiment modality and subject ID were set as the random variables for the model. Hue contrast level, lightness contrast level, map rotation task type, and fractal map seed were inputted into the model as the primary factors to investigate the effect and significance. Summary statistics were additionally calculated to identify and pinpoint the interaction effect.

The generalized linear mixed model (GLMM) produces three primary tests of significance: a type III tests of fixed effects, mean estimates of fixed effects, and a random effect estimate of covariance parameters. The fixed effect tests check for significance of independent variables across individuals. The type III test of fixed effects is a F-test that evaluates the equality of variances within the model. The mean estimates of fixed effects test is a t-test that evaluates the equality of means within the model. The random effect estimates of covariance parameters (Wald Z-test) checks if observations are significantly uncorrelated with the independent variables due to unobserved heterogeneous variation across subjects. The results from the behavioral generalized linear mixed model analysis are further described in results chapter.

How Does Varying Visual Contrast of Lightness and Hue in Cartographic Symbolization Affect Brain Activation Patterns of Geospatial Mental Rotation Tasks?

To address this research question, an offshoot contrast rotation test was adapted and repeated as an fMRI neuroimaging study. Findings and results from the behavioral study served to pre-validate the structure of the fMRI neuroimaging. All participants from the preceding behavioral study were given the opportunity to participate in the sequel fMRI study. No participants elected to discontinue participation. Further, all participants elected to allow for the release of their deidentified functional and structural MRI data for submission to OpenNeuro at the end of this dissertation research. The neuroimaging study was covered by the same IRB review and approval process as that of the behavioral testing.

No initial brain region of interest was set as existing research on the cortical and subcortical structures associated with map reading and map cognition is incomplete. However, general and subcortical activations across the visual cortex, hippocampus, motor cortex and prefrontal cortex were expected. Accordingly, a whole brain analysis approach guided the initial analysis neuroimaging data.

Instruments

A psychophysical test of mental rotation was again the primary test instrument but adjusted for a neuroimaging environment. The behavioral test instrument where participants' performance on mental rotation trials under different contrast permutations was modified and adapted specially for the fMRI neuroimaging environment. Crucially, the experiment instrument was modified so that the pulse trigger (the start time of the neuroimaging sequence) was recorded from the MRI scanner and synced over to the research computer running the data collection software. This timing information was necessary to temporally connect response input with corresponding brain activation for neuroimaging analysis. Furthermore, displaying visual stimuli inside the scanner necessitated a specialized setup. Instead of being directly displayed on a laptop display, stimuli maps were presented to participants inside the scanner via a mirror and projector setup. An angled mirror apparatus attached to the MR head-coil allowed participants to see stimuli maps displayed on a projector screen situated behind the scanner bore (LG 1280 x 720 native resolution 60 hertz projector) (*Figure 11*). Instead of inputting response via keyboard press, participants were outfitted with a five-finger button box for inputting their response (labeled as "Reponses Box" in *Figure 11*). Further, the requisite 6-minute structural neuroimaging scan sequence replaced the 30-second break between run two and three in the behavioral experiment.

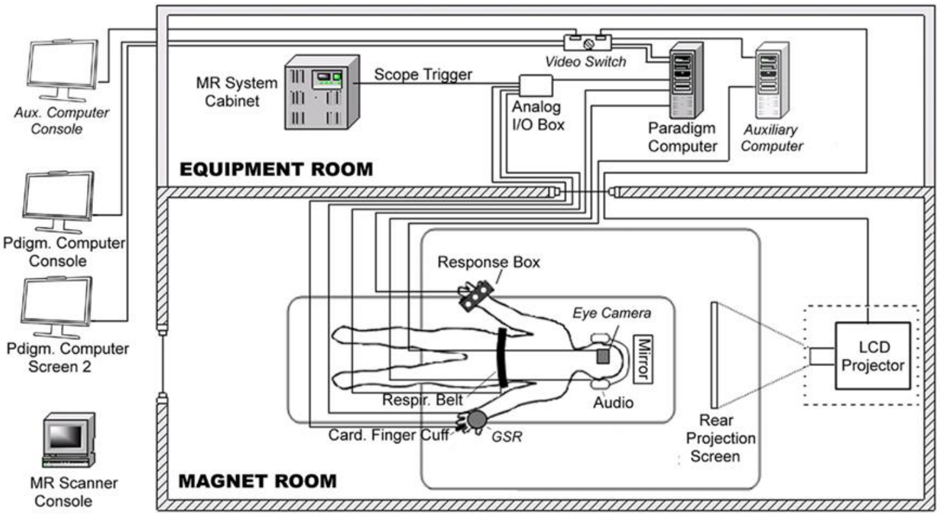


Figure 11: Example diagram of fMRI experimental setup for simultaneous behavioral and physiological data acquisition and stimuli presentation. While in the scanner, map stimuli were presented via a mirrored projector setup. Participants recorded their response via the button response box placed in their right hand. Figure was reproduced from Voyvodic et al. (2011, fig. 1).

Similar to the preceding behavioral experiment, the neuroimaging component was structured as a block design experiment (*Figure 12*). Participants completed a series of map rotation trials under permutations of hue and lightness contrast conditions. Each participant completed four runs of four blocks of eight experiment trials interweaved with requisite structural neuroimaging scans and breaks between runs (4x4x8). The map rotation trials comprised of the same two variants where the map features were only rotated or were flipped and then rotated. The map stimuli were the same ones used in the behavioral experiment. All contrast characteristics and specifications were kept identical to the set used in the behavioral experiment. An identical permutation of four contrast configurations was likewise carried over for the neuroimaging experiment. Each contrast permutation was again applied to the fractal-generated rotation maps. Other map-instrument parameters regarding reference locational property, labeling, visual levels of hierarchy, water to land ratio, scaling, marginalia and framing remained identical to maps used for the behavioral component of this study. A pilot of the neuroimaging-specific test instrument was conducted prior to participant scanning to ensure the reliability of the test instrument.

block sequence	blank	trial	blank	trial	blank	trial	blank	trial	blank	trial	blank	trial	blank	trial	blank	trial
duration in seconds	1	8	1	8	1	8	1	8	1	8	1	8	1	8	1	8

Figure 12: Simplified structure of an experiment block showing the duration of each trial and intervening blank screen. Participants have 8 seconds to complete each rotation judgement trial before moving on to the next. An experiment block contains 8 trials. In full, each block lasts 72 seconds maximum. In practice, participants rarely needed the full 8 seconds to input their response.

Data Collection and Processing

Neuroimaging sessions occurred on the University of Oregon campus at the Robert and Beverly Lewis Center for Neuroimaging (LCNI). Neuroimaging fMRI scans were completed on the center’s Siemens Skyra 3 tesla MRI scanner. All testing and imaging were conducted individually and in-person. A LCNI staff MR technologist or MR physicist operated the MRI scanner while the researcher managed the data collection instrument and oversaw communications with the participant. As discussed, map stimuli were presented via the center’s in-bore mirror and projector setup.

Upon arrival, the participant was instructed to store their belonging in a locker and to remove any jewelry or metal objects on their person. Afterwards, the participant was screened using the center's wall-mounted metal detector. Once cleared, the participant enters the MRI control room where they reviewed the MRI safety form with the scan operator to ensure safety and review any risks. The scan operator was empowered to disqualify any potential participants if the operator determines that there may be a safety risk. Once cleared by the scan operator, the participant was guided into the scanner bay and situated on the MRI scanner bed. While in the scanner, the participant was given an emergency squeeze ball for their left hand and a button box used to input responses for their right hand. The participant was also provided with hearing protection to guard against potential hearing damage due to load noises produced by the MRI scanner during operation.

Once situated in the scanner, the participant completed a practice run of four sample trials to ensure they were familiar with the experiment mechanics. After the practice run but before the start of the experiment trials, ancillary scout MRI scans were briefly collected. After the scout run, the participant proceeded to the contrast rotation experiment trials while undergoing fMRI scanning. Each neuroimaging session lasted 45 minutes to one hour comprising of a pre-scan tutorial, four runs of the neuroimaging experiment as well as additional requisite MRI reference and ancillary scans (see *Figure 13* for the modified structure of the neuroimaging block design experiment). Three pilot sessions were conducted to determine the appropriate experimental timing and test the data collection instrument. The block timing was based on the average reaction time accounting for the stimuli trial presentation length coupled with the behavioral response delay and the anticipated neurological reaction time for the experiment task. Identical to the behavioral trials, for each trial a blank screen was displayed for one second followed by a randomly presented map stimuli pair. The participant had a maximum of eight seconds to judge the rotation type – again only rotated or rotated and flipped. An experiment block consisted of eight trials followed by a 10-seconds break. An experiment run consisted of four blocks – with a 30-seconds break between runs one and two and runs three and four. In lieu of a 30-seconds break, a six-minute anatomical reference scan sequence occurred between runs two and three. The participant was instructed to remain still and stay awake but otherwise rest during the reference scan. A complete experiment session consisted of four runs in addition to the requisite reference and ancillary neuroimaging scans. *Figure 13* shows the full setup of the block design neuroimaging experiment.

To conduct neuroimaging analysis, several types of scans were gathered. While completing the contrast rotation test, temporally sequenced functional scans of participants' brain activities were collected with a two second repetition time (TR). The repetition time (TR) is the time between successive pulse sequences applied to the same scan slice. These functional scans served as the spatio-temporal snapshot of brain activity and were later analyzed to identify significant clusters of blood oxygenated level dependent (BOLD) signals.

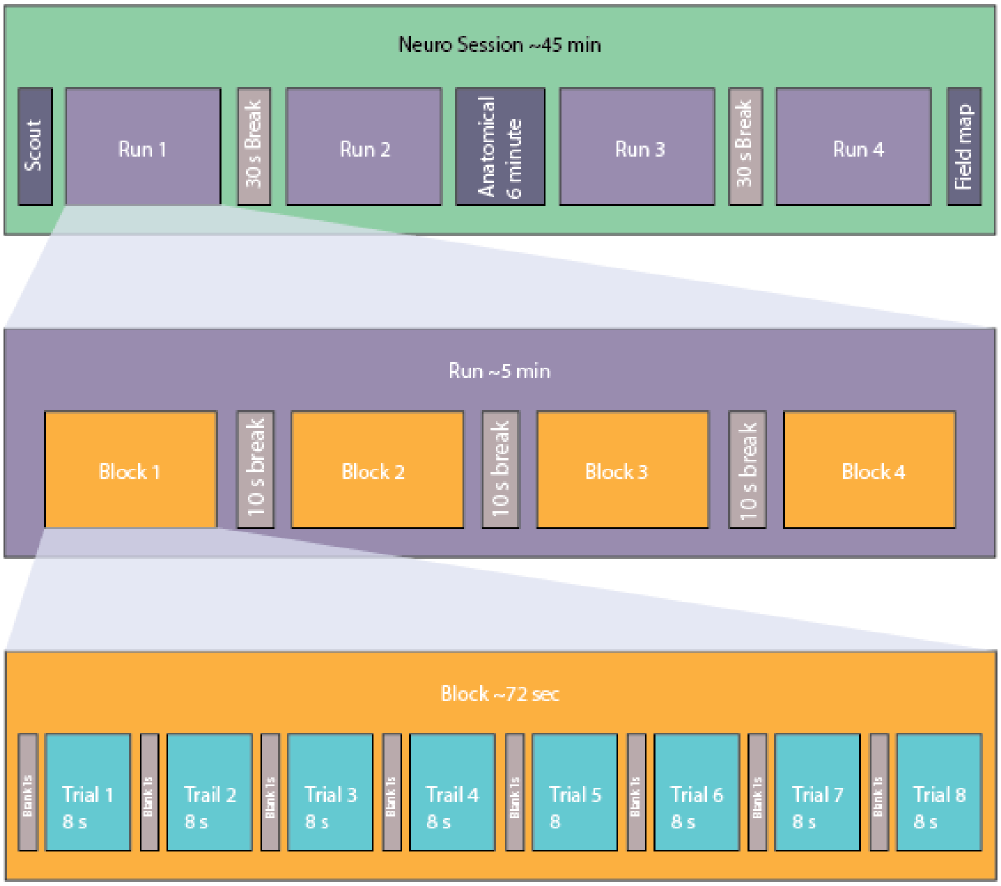


Figure 13: Full structure and duration of the behavioral experiment block design. Each session includes 4 runs. Each run includes 4 blocks. Each block includes 8 trials.

The fMRI BOLD signal denotes metabolic hemodynamic response and is widely used as the measure for task-correlated brain activities (Bruce et al., 2003).

Additionally, high resolution reference anatomical scans were collected while the participant was at rest during the half-time break between runs two and three. These slower but higher resolution scans captures the structure (bones, tissues and fluids) of the participant's head and neck. This data is essential for mapping the activation signals collected during functional scans to the structural brain features. Field maps were also collected for use during early data analysis to account for and correct potential distortion caused by the magnetic field interaction in the scanner. The neuroimaging component of this study follows established protocols honed under previous neuro-geographic studies and based on guidelines provided by and with input from LCNI.

Neuroimaging Data Analysis

The analysis of the fMRI scan data follows the established processes of the University of Oxford Centre for Functional MRI of the Brain (FMRIB) Software Laboratory (FSL) (Woolrich et al., 2001, 2004). *Figure 14* shows the general pipeline for processing and analysis of fMRI neuroimaging data using FSL. Due to the potential sensitivity of the collected personally identifiable data, a double randomized participant ID procedure was implemented for neuroimaging data. Participants were assigned a random six-digit alphanumeric ID when they signed up for the study. As the first step of the neuroimaging data preprocessing, participant IDs were rerandomized, with records of the rerandomization stored in a separate ledger file. Further, identifiable structural brain scans were deidentified by applying a defacing script. The defacing script erases all facial features from the structural brain scans. Additional preprocessing was conducted to omit the skull from the scan images, apply unwarping to mitigate the impact of the magnetic field inhomogeneity and detect motion artifacts. The preprocessing additionally remapped and reprojected each participant's unique brain anatomy onto a standardized brain structure to enable functional cross-subject analysis. The standardized brain structure is based on the MNI152 standard-space T1-weighted average structural template image used by FSL (FMRIB, 2022; Fonov et al., 2009, 2011). Separately, scan sequence and response input timing information were extracted from the neuroimaging and behavioral data to construct event related timing files (EVs). EV files were used to correlate the functional snapshot of brain activities to specific experiment conditions encoded in the stimuli presentation and behavioral data.

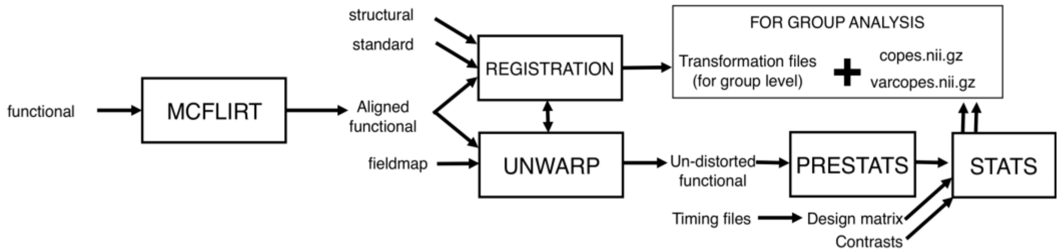


Figure 14: FSL standard preprocessing and analysis pipeline. Figure reproduced from the FSL FEAT User Guide (FMRIB, 2022).

The FMRIB Software Library (FSL) was utilized to conduct a general linear model (GLM) whole-brain analysis to measure the significance of the levels of activation in each voxel across the brain. Additionally, a cluster analysis was conducted in FSL to identify and isolate areas of activity. The statistical model includes explanatory variables for each condition and control. Due to the high risk of statistical rank deficiency in the general linear model for the neuroimaging data, analysis for hue contrast and lightness contrast were completed in separate pipelines – one model for hue contrast levels and one for lightness contrast level. An overview of the pipelines is shown in *Figure 14*.

First-level within-subject testing was conducted to isolate the distinct pattern of activation under each of the high versus low contrast conditions for each run. Second-level between-subject analysis averaged the first-level activation groups across participants. Third-level between-group analysis was subsequently conducted to examine the group-level difference between the conditions overall. In other words, the analysis was conducted to identify statistically significant clusters of brain activation at a whole-brain level that correlates with the map rotation task as the medium for geospatial cognition. This analysis made it possible to isolate relevant brain regions associated with geospatial cognition for further examination. Identified regions from this analysis were then cross-referenced to regions shown to be associated with geospatial cognition using the Harvard-Oxford cortical and subcortical structural atlases (Lobben et al., 2014). Identified regions of activation and activation difference between experiment conditions are discussed in Chapter IV.

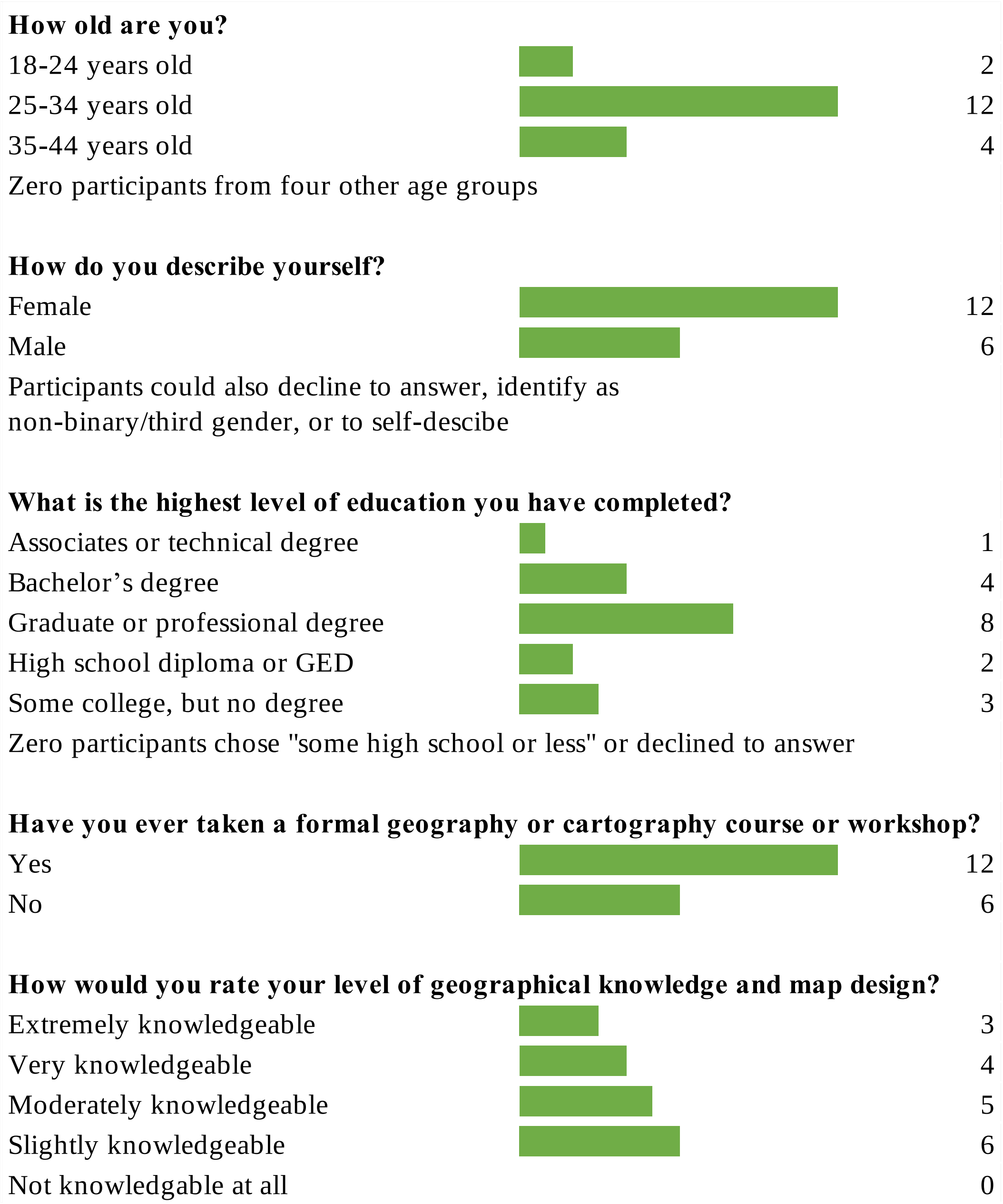
CHAPTER IV

RESULTS

This chapter reports the results of the completed data analysis discussed in Chapter III. Accordingly, this chapter is sequentially broken up by the specific analysis conducted for each research question.

Data from 18 participants were included in the analysis. Behavioral session data for one participant was determined to be corrupt and was subsequently excluded from the analysis. Pilot data spanning both experiments were excluded from the analysis. In total, 35 behavioral sessions were processed for analysis by aggregating collected data from 17 behavioral experiment sessions with the behavioral data collected during 18 neuroimaging experiment sessions. Neuroimaging data from all 18 neuroimaging experiment participants passed FIRMM and FSL visual and statistical quality checks for excessive motion and distortion and were subsequently included for the neuroimaging fMRI analysis (Dosenbach et al., 2017; Jahn, 2022).

A breakdown of the demographic information of participants is reported in *Table 1*. A majority (12) of research participants belonged to the 25-34 age group. Additionally, twice as many participants self-identified as female (12) than male (6). All participants reported being right-handed thus negating the need to conduct separate hemispherical neuroimaging analysis.



How old are you?	
18-24 years old	2
25-34 years old	12
35-44 years old	4
Zero participants from four other age groups	
How do you describe yourself?	
Female	12
Male	6
Participants could also decline to answer, identify as non-binary/third gender, or to self-descibe	
What is the highest level of education you have completed?	
Associates or technical degree	1
Bachelor's degree	4
Graduate or professional degree	8
High school diploma or GED	2
Some college, but no degree	3
Zero participants chose "some high school or less" or declined to answer	
Have you ever taken a formal geography or cartography course or workshop?	
Yes	12
No	6
How would you rate your level of geographical knowledge and map design?	
Extremely knowledgeable	3
Very knowledgeable	4
Moderately knowledgeable	5
Slightly knowledgeable	6
Not knowledgable at all	0

Table 1. Breakdown of research participants' demographic information. N=18 for all questions.

Further, two-thirds of participants reported having previously taken some type of geographic or cartography course or workshop. All participants reported having some level of geographic and map design knowledge. All 18 participants passed the colorblindness test.

Behavioral Analysis Results

The primary indicators of performance during the behavioral data collection were response time and nominal accuracy. Behavioral response data was collected during both the behavioral as well as the neuroimaging experiments. Accordingly, all cases were aggregated and processed for behavioral data analysis – with experimental modality being encoded as a variable for subsequent modeling. In total, 4480 individual cases were analyzed (2177 case from 17 behavioral sessions combined with 2304 cases from 18 neuroimaging sessions). Behavioral data for one participant was corrupted and subsequently excluded from the analysis. Each contrast permutation was tested 16 times by each participant (8 x 2 fractal map seeds). *Table* 2 shows a breakdown of case information.

Summary Statistics of Response Time and Accuracy

When hue contrast was examined on its own, participants responded faster for stimuli maps with low hue contrasts. Conversely, participants were more accurate on trials with high hue contrasts stimuli maps. This suggests a possible heterogeneous effect between hue contrast on response time and accuracy. When lightness contrast was examined on its own, participants responded faster and were additionally more accurate when completing trials with high lightness contrasts stimuli maps. This indicates a possible homogenous effect of lightness contrast on response time in seconds and accuracy. *Table* 3 shows the breakdown of the mean response time and accuracy for hue and lightness contrast level on its own.

Experiment modality by contrast permutation	**Case count**
Behavioral session	2176
High Hue + High Lightness	544
High Hue + Low Lightness	544
Low Hue + High Lightness	544
Low Hue + Low Lightness	544
Neuroimaging session	2304
High Hue + High Lightness	576
High Hue + Low Lightness	576
Low Hue + High Lightness	576
Low Hue + Low Lightness	576
Total cases (n sum)	4480

Table 2: Table of the case count for each experiment modality and contrast variable permutations.

However, the primary objective of this research was not to examine these variables in isolation but to highlight their possible interaction effects. Accordingly, when hue and lightness contrast were evaluated together as matrices for response time and accuracy, participants responded the fastest for trials with low hue with high lightness contrast. However, this quickness did not translate to accuracy as this contrast permutation had the second lowest accuracy rate. Participants scored the highest accuracy for trials with high hue with high lightness contrast. These observations were reflective of the observe patterns when each contrast variable was observed on its own and further highlight the likely interactive effects of hue contrast on response time versus accuracy. *Table* 4 shows the breakdown of the mean response time and accuracy for combinations of hue and lightness contrast level.

Hue contrast level	Mean response time (seconds)	Mean accuracy
High	2.66	**94.1%**
Low	**2.63**	93.5%

Light contrast level	Mean response time (seconds)	Mean accuracy
High	**2.64**	**94.2%**
Low	2.65	93.3%

Table 3:Table of mean response time in seconds and mean accuracy for independent levels of hue contrast and lightness contrast. Bolded numbers indicate faster response time and higher accuracy.

Response Time	**Lightness contrast**	
Hue contrast	High	Low
High	2.65	2.67
Low	**2.62**	2.63

Accuracy	**Lightness contrast**	
Hue contrast	High	Low
High	**95.1%**	93.0%
Low	93.3%	93.7%

Table 4: Matrix tables of mean response time in seconds and mean accuracy for combinations of hue and lightness contrast levels. Bolded numbers indicate faster response time and higher accuracy.

A summary statistics evaluation for task-related and stimuli design variables was additionally conducted. Summary statistics of mean response time and accuracy were produced for experiment modality, trial task type and fractal map seed (*Table 5*).

Experiment modality	**Mean response time**	**Mean accuracy**
Behavioral session	2.90	93.5%
Neuroimaging session	**2.40**	**94.0%**

Trial judgement task	**Mean response time**	**Mean accuracy**
Rotated only	**2.57**	91.5%
Rotated and flipped	2.72	**95.9%**

Fractal map seed	**Mean response time**	**Mean accuracy**
Fractal map a	2.80	91.5%
Fractal map b	**2.49**	**96.1%**

Table 5: Table of mean response time and mean accuracy for potential confounding task-related and map stimuli design variables. Bolded numbers indicate faster response time and higher accuracy.

Potentially confounding effects of task-related and stimuli design variables were observed. Participants were found to be both quicker and more accuracy during the neuroimaging session. This may have been due to the sequential setup of the experiments where participants completing the neuroimaging session had priorly completed the behavioral session. Interestingly, participants responded quicker for trials where the correct judgement task was *rotated only* but were markedly more accuracy for trials where the correct judgement task was *rotated and flipped*. Further, participants responded quicker and were more accurate for trials where *fractal map b* was used as the basis of the map stimuli (see *Figure 7* for fractal map seeds). *Chapter V* further discusses these contextual confounds and the implication for this research.

Generalized Linear Mixed Models Results

Generalized Linear Mixed Models (GLMMs) were constructed to check for significant fixed and random effects of contrast variables as well as trial-related and map stimuli design variables on response time and accuracy. Models were constructed separately to quantify the effect on response time versus accuracy. The input parameters and variable were identical aside from the dependent variables. Participants were nested with modality as the input random effect subject parameter for the models. Primary independent variables for the models were hue and lightness contrast levels. Trial rotation type and fractal stimuli map seed were additional co-variables for the models.

The generalized linear mixed model (GLMM) produces three primary tests of significance: a type III tests of fixed effects, mean estimates of fixed effects, and a random effect estimate of covariance parameters. The fixed effect tests check for significance of independent variables across individuals. The type III test of fixed effects is a F-test that evaluates the equality of variances within the model. The mean estimates of fixed effects is a t-test that evaluates the equality of means within the model. The random effect estimates of covariance parameters (Wald Z-test) checks if observations are significantly uncorrelated with the independent variables and are thus due to unobserved heterogeneous variation across subjects. The 0.05 p-value was used as the basis for determining statistical significance in all analysis.

Response Time GLMM

The results of GLMM type III test for response time showed that hue (F=0.038, p=0.846; Table 6) and lightness (F=0.667, p=0.414; Table 6) contrast on their own were not statistically significant for response time. However, hue and lightness contrast together had a significant interaction effect on response time (F=8.856, p=0.003; Table 6). Additionally, rotation task type had a significant effect on response time (F=10.724, p=0.001; Table 6). Interestingly, the interactive effects of hue and lightness contrast on response time remained significant when factoring in rotation task type and fractal map seed (see individual statistics in shaded rows of *Table* 6*)*.

The GLMM estimates of fixed effects test on response time further augments the results of the type III test. This t-test can evaluate the significance of levels of independent variables by comparing the mean estimates across the model. Differing to the F-test, statistical significance was identified for both levels of hue contrast on its own (t=2.241, p=0,025; Table 7).

Type III Tests of Fixed Effects (Response Time)				
Source	**Numerator df**	**Denominator df**	**F**	**Sig.**
Intercept	1	181.267	162.055	<.001
Hue Contrast	1	4396	0.038	0.846
Lightness Contrast	1	4407.267	0.667	0.414
Rotation Task Type	1	4396	10.724	**0.001**
Fractal Map Seed	1	4396	2.441	0.118
Hue Contrast * Lightness Contrast	1	4396	8.856	**0.003**
Hue Contrast * Rotation Task Type	1	4396	0.028	0.868
Hue Contrast * Fractal Map Seed	1	4396	0.073	0.787
Lightness Contrast * Rotation Task Type	1	4396	0.275	0.6
Lightness Contrast * Fractal Map Seed	1	4396	0.621	0.431
Rotation Task Type * Fractal Map Seed	1	4396	3.351	0.067
Hue Contrast * Lightness Contrast * Rotation Task Type	1	4396	8.462	**0.004**
Hue Contrast * Lightness Contrast * Fractal Map Seed	1	4396	9.185	**0.002**
Hue Contrast * Rotation Task Type * Fractal Map Seed	1	4396	0.353	0.552
Lightness Contrast * Rotation Task Type * Fractal Map Seed	1	4396	0.255	0.613
Hue Contrast * Lightness Contrast * Rotation Task Type * Fractal Map Seed	1	4396	8.851	**0.003**

Table 6: Generalized linear mixed model type III test of fixed effect table for response time. Shaded rows indicate statistically significant variables. Statistically significant p values bolded.

More importantly, the test confirmed the significance of the interactive effect between hue and lightness contrast (t=2.976, p=0.003; Table 7). Additionally, the test also yielded statistical significance for the effect due to rotation task (t=2.746, p=0.006; Table 7). While omitted from *Table* 7, the significance of the interactive effect of hue and lightness contrast across rotation type and fractal stimuli seed observed in the F-test was mirrored in the full results of the t-test.

Estimates of Fixed Effects (Response Time)

Mean Parameter	**Estimate**	**Std. Error**	**df**	**t**	**Sig.**	**Lower Bound 95% CI**	**Upper Bound 95% CI**
Intercept	2312.768	349.036	1122	6.626	<.001	1627.931	2997.604
Hue high	1016.164	453.379	4396	2.241	**0.025**	127.312	1905.016
Hue low	b	.	.	.	.	.	.
Lightness high	691.646	453.832	4430	1.524	0.128	-198.092	1581.385
Lightness low	b	.	.	.	.	.	.
Rotation task	556.871	202.757	4396	2.746	**0.006**	159.365	954.378
Fractal map seed	41.625	202.757	4396	0.205	0.837	-355.882	439.132
[Hue high] * [Light high]	-1908.029	641.175	4396	-2.976	**0.003**	-3165.055	-651.002
[Hue high] * [Light low]	b	.	.	.	.	.	.
[Hue low] * [Light high]	b	.	.	.	.	.	.
[Hue low] * [Light low]	b	.	.	.	.	.	.

b This parameter is set to zero because it is redundant.

Table 7: Generalized linear mixed model mean estimates of fixed effect table for response time. Shaded rows indicate statistically significant variables. Statistically significant p values bolded.

The GLMM random effect estimates of covariance parameters test for response time found no statistically significant effects caused by the experimental modality (behavioral versus neuroimaging session) and individual subject level variations (Z=1.175, p=0.240; Table 8).

Estimates of Covariance Parameters (Response Time)

Variance Parameter	Estimate	Std. Error	Wald Z	Sig.	Lower Bound 95% CI	Upper Bound 95% CI
Residual	1151096.303	24552.618	46.883	0.000	1103966.073	1200238.606
Intercept [modality * subject]	659543.127	163044.486	4.045	<.001	406274.137	1070698.567
Hue contrast [modality * subject]	b	.	.	.	.	.
Light contrast [modality * subject]	7191.381	6118.422	1.175	0.240	1357.096	38107.807
Hue * Light contrast [modality * subject]	b	.	.	.	.	.

b This covariance parameter is redundant. The test statistic and confidence interval cannot be computed.

Table 8: Generalized linear mixed model covariance estimates of random effect table for response time.

Accuracy GLMM

The results of the GLMM type III test for accuracy showed that hue (F=0.266, p=0.606; Table 9) and lightness (F=0.619, p=0.432;Table 9) contrast on their own did not have statistically significant effects. However, a statistically significant interaction effect was observed for hue and lightness together (F=5.069, p=0.024; Table 9). Interestingly, while rotation task type and fractal map seed on their own were not statistically significant, their combination yielded statistically significant interaction effect (F=4.139, p=0.042; Table 9). Additionally, the observed significant interactive effect of hue and lightness contrast remained significant even when factoring in rotation task type and fractal map seed (see individual statistics in shaded rows of *Table* 9).

Type III Tests of Fixed Effects (Accuracy)				
Source	**Numerator df**	**Denominator df**	**F**	**Sig.**
Intercept	1	1583.724	705.362	<.001
Hue Contrast	1	4397.212	0.266	0.606
Lightness Contrast	1	4397.212	0.619	0.432
Rotation Task Type	1	4328	2.656	0.103
Fractal Map Seed	1	4328	0.017	0.898
Hue Contrast * Lightness Contrast	1	4397.212	5.069	**0.024**
Hue Contrast * Rotation Task Type	1	4328	0.596	0.44
Hue Contrast * Fractal Map Seed	1	4328	0.532	0.466
Lightness Contrast * Rotation Task Type	1	4328	0.007	0.932
Lightness Contrast * Fractal Map Seed	1	4328	0.973	0.324
Rotation Task Type * Fractal Map Seed	1	4328	4.139	**0.042**
Hue Contrast * Lightness Contrast * Rotation Task Type	1	4328	3.893	**0.049**
Hue Contrast * Lightness Contrast * Fractal Map Seed	1	4328	4.064	**0.044**
Hue Contrast * Rotation Task Type * Fractal Map Seed	1	4328	1.177	0.278
Lightness Contrast * Rotation Task Type * Fractal Map Seed	1	4328	0.166	0.684
Hue Contrast * Lightness Contrast * Rotation Task Type * Fractal Map Seed	1	4328	3.606	0.058

Table 9: Generalized linear mixed model type III test of fixed effect table for accuracy. Shaded rows indicate statistically significant variables. Statistically significant p values bolded.

The GLMM estimates of fixed effects test on accuracy augments the results of the type III test. However, unlike the t-test for response time, this t-test for accuracy yielded more conservative findings. Individual hue and lightness levels yielded no statistically significant results. However, the test affirms the significant interactive effect of hue together with lightness contrast on response time (t=2.251, p=0.024; Table 10).

Estimates of Fixed Effects (Accuracy) **Mean Parameter**	**Estimate**	**Std. Error**	**df**	**t**	**Sig.**	**Lower Bound 95% CI**	**Upper Bound 95% CI**
Intercept	0.961	0.067	4050.270	14.361	<.001	0.830	1.092
Hue high	-0.114	0.093	4397.212	-1.228	0.220	-0.297	0.068
Hue low	b	.	.	.	.	.	.
Lightness high	-0.096	0.093	4397.212	-1.036	0.300	-0.279	0.086
Lightness low	b	0.000	.	.	.	.	.
Rotation task	-0.057	0.042	4328.000	-1.372	0.170	-0.139	0.024
Fractal map seed	-0.004	0.042	4328.000	-0.086	0.932	-0.085	0.078
[Hue high] * [Light high]	0.296	0.132	4397.212	2.251	**0.024**	0.038	0.555
[Hue high] * [Light low]	b	.	.	.	.	.	.
[Hue low] * [Light high]	b	.	.	.	.	.	.
[Hue low] * [Light low]	b	.	.	.	.	.	.

b This parameter is set to zero because it is redundant.

Table 10: Generalized linear mixed model mean estimates of fixed effect table for response time. Shaded rows indicate statistically significant variables. Statistically significant p values bolded.

The GLMM random effect estimates of covariance parameters test for response time found no statistically significant effects caused by the experimental modality (behavioral versus neuroimaging session) and individual subject level variation (Z=0.052, p=0.958; Table 11).

Estimates of Covariance Parameters (Accuracy)

Variance Parameter	Estimate	Std. Error	Wald Z	Sig.	Lower Bound 95% CI	Upper Bound 95% CI
Residual	0.049	0.001	46.519	0.000	0.047	0.051
Intercept [modality * subject]	0.005	0.001	3.824	<.001	0.003	0.008
Hue contrast [modality * subject]	b	.	.	.	.	.
Light contrast [modality * subject]	b	.	.	.	.	.
Hue * Light contrast [modality * subject]	0.00011	0.000216	0.052	0.958	0.000	242901350457.365

b This covariance parameter is redundant. The test statistic and confidence interval cannot be computed.

Table 11: Generalized linear mixed model covariance estimates of random effect table for response time.

Neuroimaging Analysis Results

Neuroimaging analysis was conducted as separate models for hue and lightness. Cross contrast-variable comparison was not completed due to the high risk of rank deficiency in the model. Accordingly, analysis was conducted to contrast BOLD signal of activities for high versus low hue contrast in one model and high versus low lightness contrast in another model. The 0.05 p-value was used as the basis for determining statistical significance in all analysis. This analysis for the first time identifies specific subcortical regions and differing levels of activation associated with visual contrast modulated map reading.

Hue Contrast Activation Differences

The results of the neuroimaging analysis for the hue contrast revealed broad brain activation across brain regions associated with general visual processing and mental rotation. Statistically significant activities were detected across regions including the frontal orbital cortex, superior frontal gyrus, frontal pole, precentral gyrus (primary motor cortex), supplementary motor cortex, frontal operculum cortex, paracingulate gyrus, lateral occipital cortex and occipital cortex (visual cortex). Areas of significant activities for high and low hue contrast are shown in *Figure 15*. A visual overlap of the two is shown in *Figure 22*.

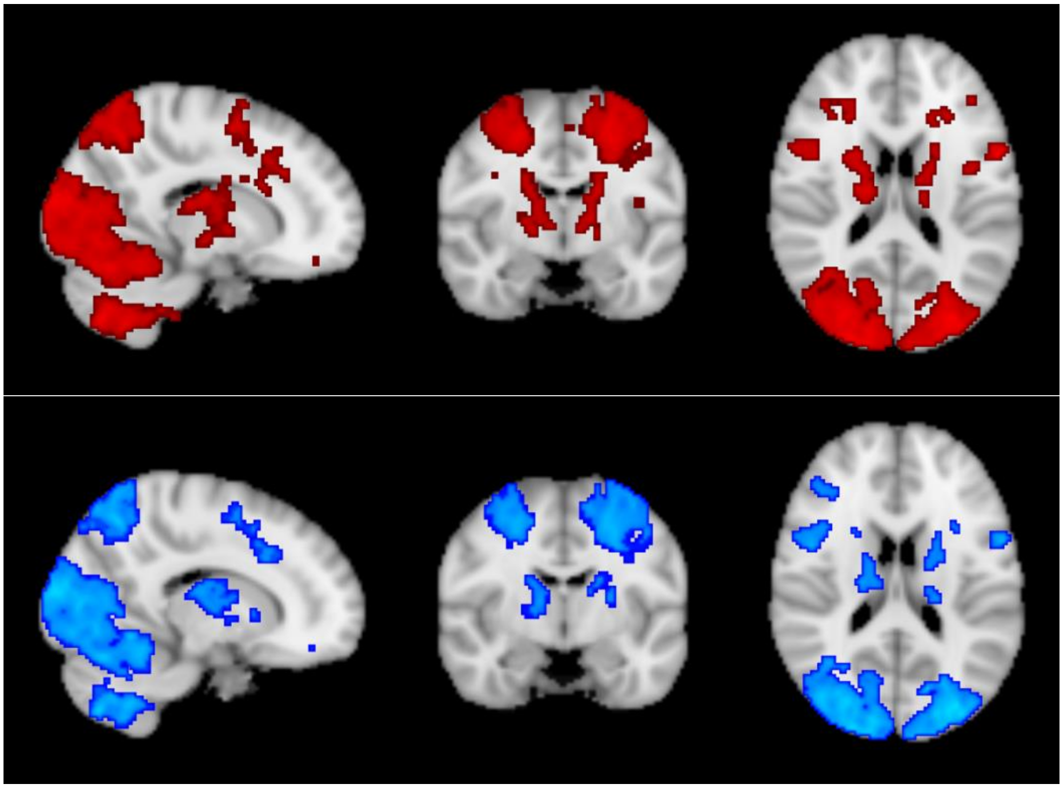


Figure 15: Clusters of statistically significant brain activities identified during trials with high (red) and low (blue) hue contrast stimuli (Z threshold=3.1).

The cluster-wise two-directional contrast test between high versus low hue contrast revealed two statistically significant clusters of activity difference corresponding to the bilateral occipital poles (primary visual cortex v1) and lateral occipital cortices (visual cortex) (*Table 12* and *Figure 16*).

Cluster Index	Voxels	P	-log10(P)	Z-MAX	Z-MAX X (mm)	Z-MAX Y (mm)	Z-MAX Z (mm)
1	367	0.006	2.22	3.9	-20	-102	-10
2	379	0.005	2.31	3.59	28	-96	-10

Table 12: Two directional contrast table identifying clusters of statistically significant activation and their location in MNI standard space for high versus low hue lightness contrast.

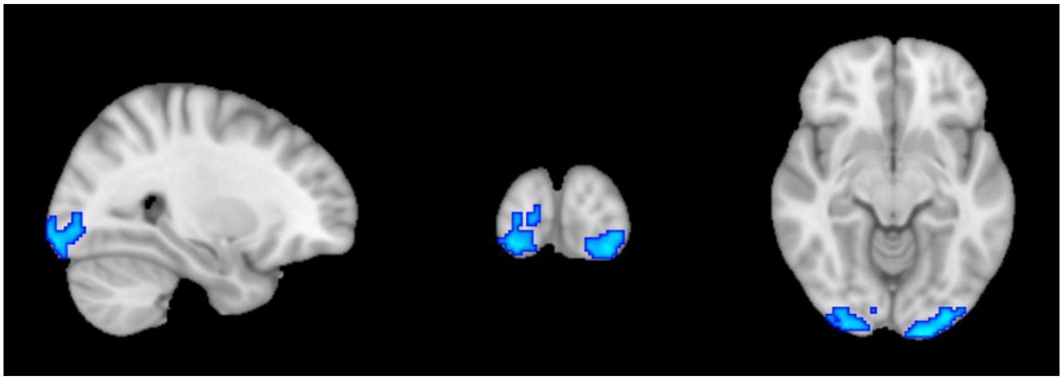


Figure 16: Clusters of statistically significant brain activation differences between high versus low hue contrast (Z threshold: 2.3).

Lightness Contrast Activation Differences

Similar to the brain activities detected for hue, the results of the neuroimaging analysis for the lightness contrast revealed broad activation across brain regions associated with the visual processing and mental rotation. Statistically significant activities were detected across regions including the frontal orbital cortex, superior frontal gyrus, frontal pole, precentral gyrus (primary motor cortex), supplementary motor cortex, frontal operculum cortex, paracingulate gyrus, lateral occipital cortex and occipital cortex (visual cortex). Areas of significant activities for high and low lightness contrast are shown in *Figure 17.* A visual overlap of the two is shown in *Figure 22*.

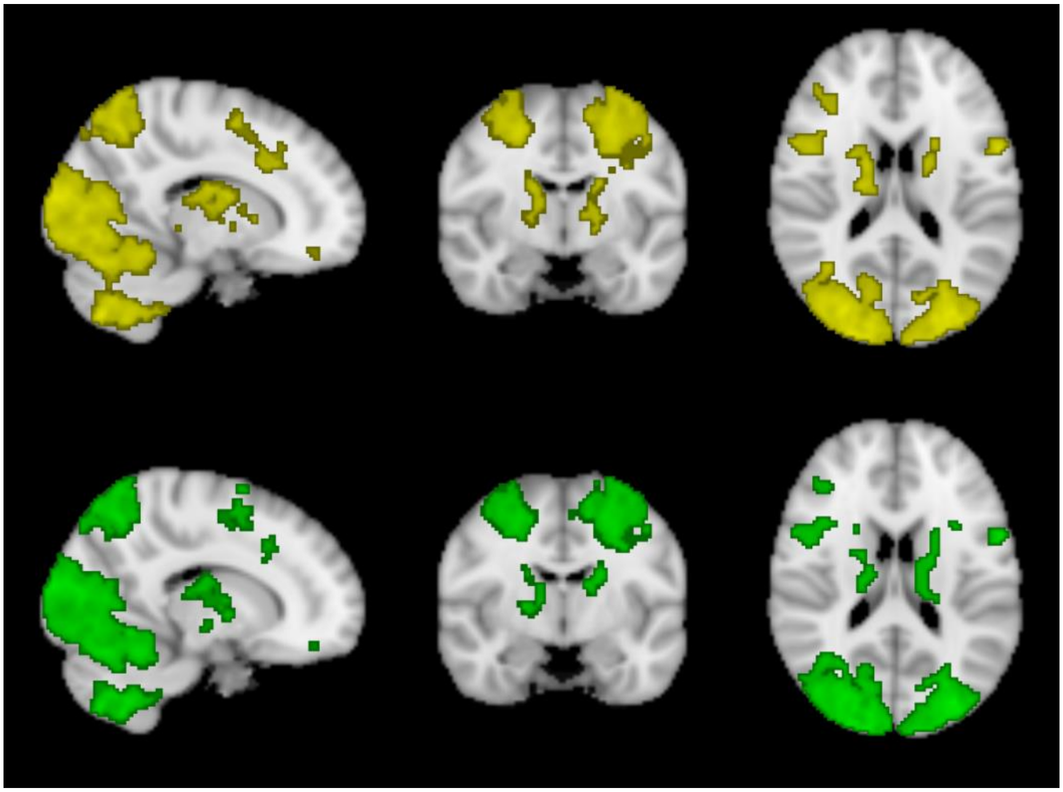


Figure 17: Clusters of statistically significant brain activities identified during trials with high (yellow) and low (green) lightness contrast stimuli (Z threshold=3.1).

The cluster-wise two-directional contrast test between high versus low lightness contrast revealed two statistically significant clusters of activity difference corresponding to the bilateral occipital poles (primary visual cortex v1) and lateral occipital cortices (visual cortex) (*Table 13* and *Figure 18*).

Cluster Index	Voxels	P	-log10(P)	Z-MAX	Z-MAX X (mm)	Z-MAX Y (mm)	Z-MAX Z (mm)
1	583	0.000	4.85	3.9	18	-98	-10
2	857	0.000	6.92	4.64	-12	-100	-14

Table 13: Two directional contrast table identifying clusters of statistically significant activation and their location in MNI standard space for high versus low lightness contrast.

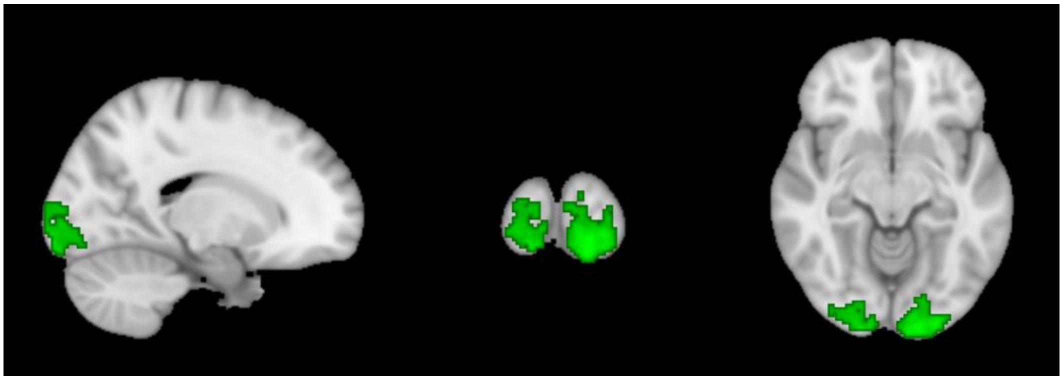


Figure 18: Clusters of statistically significant brain activation differences between high versus low hue contrast (Z threshold: 2.3).

CHAPTER V

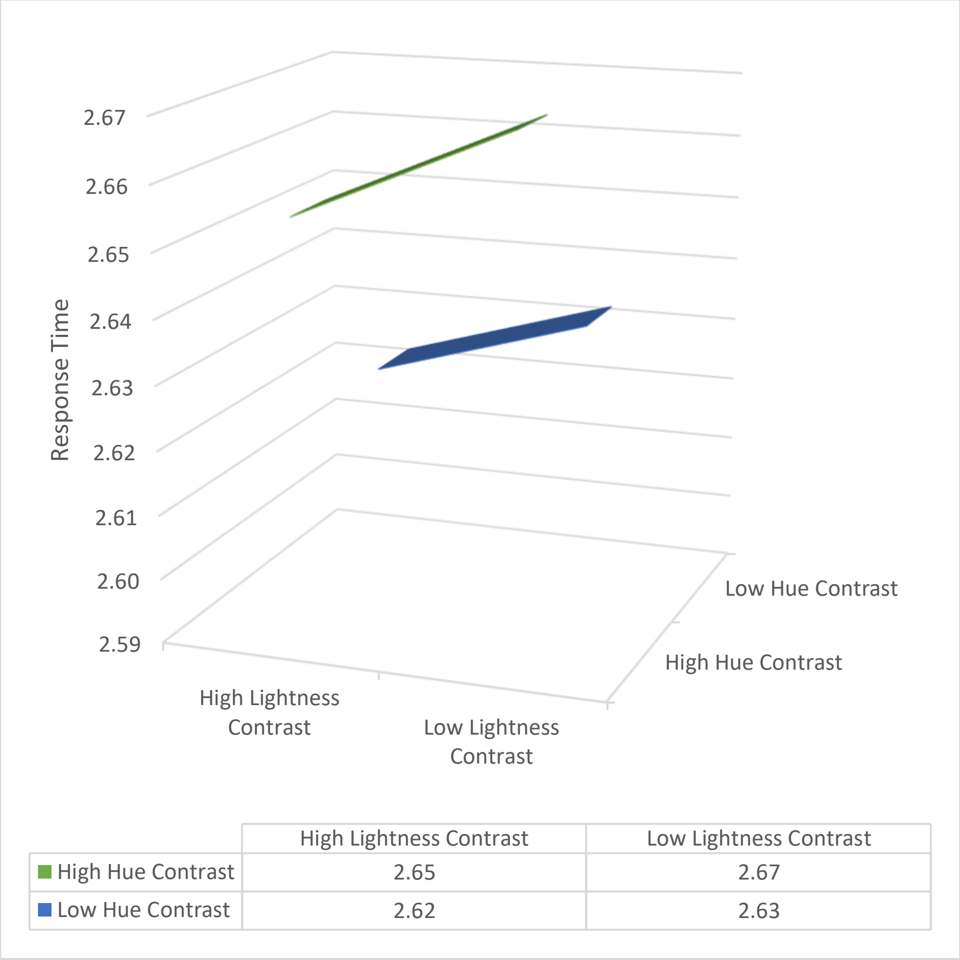
DISCUSSIONS

The aim of this research was to better understand the interactive effect of cartographic visual contrast as well as the neurological correlates of cartographic design on the map cognition process. The analysis and subsequent results provide empirical evidence helping to better understand the role of visual contrast when accomplishing map-based tasks such as mental map rotation. This chapter discusses the implications, reflections and findings of the behavioral and neuroimaging experiments. Those findings are then synthesized as part of a reflection on the proposed visual contrast saliency model. Lastly, ancillary findings are discussed.

Behavioral Performance Difference

The results of the behavioral study confirm the hypothesis and what cartographers have long insisted; that visual contrast of hue and lightness have significant effects on the map reader's ability to make spatial judgement. However, the statistical models for both response time and accuracy highlighted nuances that were not previously well-understood.

The analysis conducted on the collected behavioral data addresses the first research question – that is: how does varying visual contrast of lightness and hue in cartographic symbolization affect geospatial mental rotation task performance? The models showed that significant effects from hue and lightness contrast on map reading performance does not occur in isolation. Rather, it is the interaction of hue and lightness contrast together that directly modulates map task performance. This interactive and combinatory effect can be most clearly seen on the 3D interaction plots in *Figure 19* for response time and *Figure 20* for accuracy.



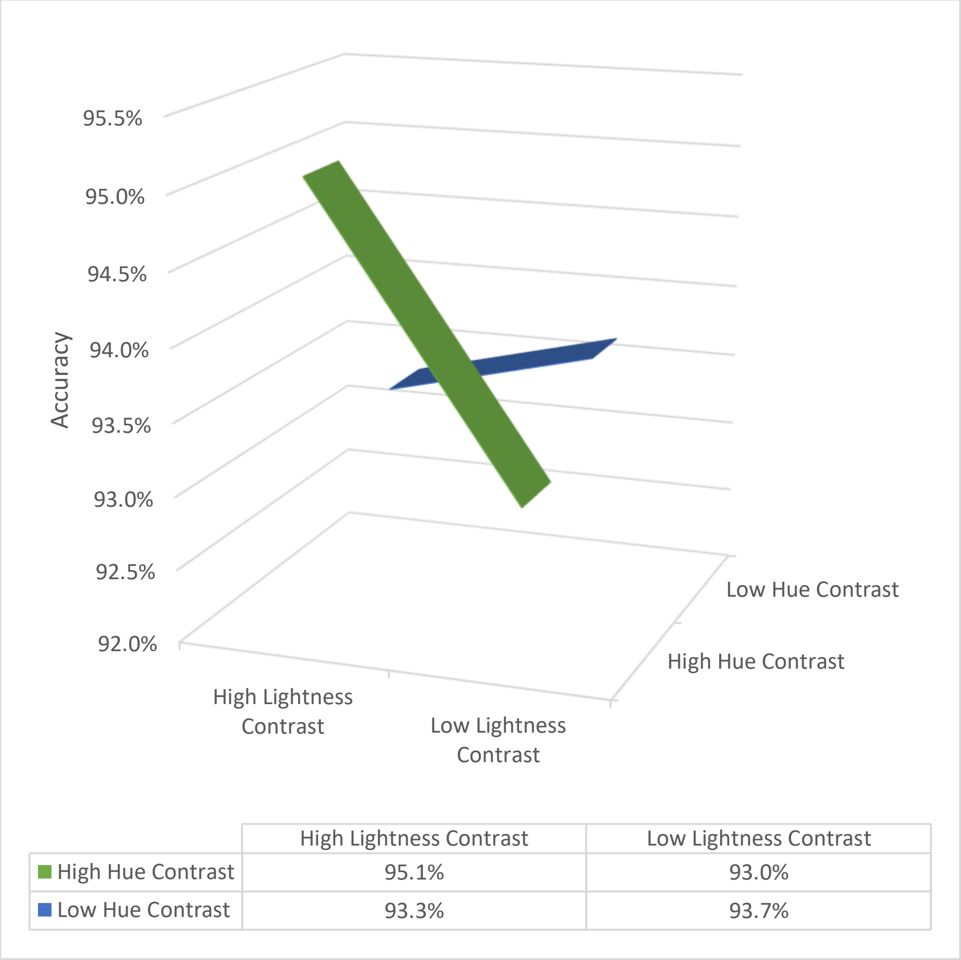
	High Lightness Contrast	Low Lightness Contrast
🟩 High Hue Contrast	2.65	2.67
🟦 Low Hue Contrast	2.62	2.63

Figure 19: 3D interaction plot showing mean response time for contrast variables.

Effect of Contrast on Response Time

The model showed that participants responded significantly faster when hue contrast was low in all cases. Interestingly, this consistency effect was not true for levels of lightness contrast on its own. However, the model identified an interactive effect of lightness contrast in modulating the strength of the significant hue effect. In other words, maps that had more similar hues were easier to read regardless of lightness contrast. Augmenting low hue contrast with high lightness contrast further improved the overall response time as a possible indicator of map legibility. Though, high lightness contrast on its own had no significant effect in improving the response time.

On the surface, the finding for response time runs counter to the notion that higher contrast generally results in improved performance. However, it is important to note that response time is an indicator of *faster* performance, it does not indicate better overall performance. When crosschecked for accuracy, the results showed that although maps with low hue contrast and high lightness contrast results in the fastest response time, those same maps scored the second lowest accuracy in the group. This indicates that a faster response does not translate to an accurate response. In fact, it could be theorized that this particular combination of hue and lightness contrast may have falsely misled participants and thus countered the map reading objective. Furthermore, the contrast combination with the slowest response time (high hue + low lightness) resulted in the lowest accuracy rate (see *Table 4*). From these observations, it can be inferred that participants who spent either too little or too much time on a trial likely performed worse in terms of accuracy. Accordingly, it may be more important to focus on contrast combinations that resulted in the highest accuracy rate rather than the fastest response time.



	High Lightness Contrast	Low Lightness Contrast
🟩 High Hue Contrast	95.1%	93.0%
🟦 Low Hue Contrast	93.3%	93.7%

Figure 20: 3D interaction plot showing mean accuracy for contrast variables.

Effect of Contrast on Accuracy

When accuracy was examined, the model found that on its own, hue contrast and lightness contrast had no significant effect on accuracy. However, the model identified strong significant interactive effect of hue and lightness contrast together. In other words, while specific levels of hue or lightness contrast on its own had little to no effect on accuracy, the combination of the high hue and high lightness contrast had a distinct interactive effect on accuracy.

More interestingly, as shown in the interaction plot in *Figure 20*, there is a homogeneous interactive effect between lightness and hue on accuracy where matching pairs of high-high or low-low hue-lightness contrast resulted in better accuracy than opposing high-low and low-high contrast pairs. Thus, there were clear preferences for consonant contrast pairing for accuracy. The combination of high hue and high lightness contrast resulted in the highest accuracy rate. This combination was also the second fastest for response time. The high hue and low lightness contrast combination scored the lowest accuracy rate and was also the slowest for reaction time. In other words, participants were more accurate and *generally* faster on high overall contrast maps. Conversely, participants were least accurate and slowest to response for maps with high hue and low lightness contrast. *Figure* 21 shows the best and worst contrast combination tested.

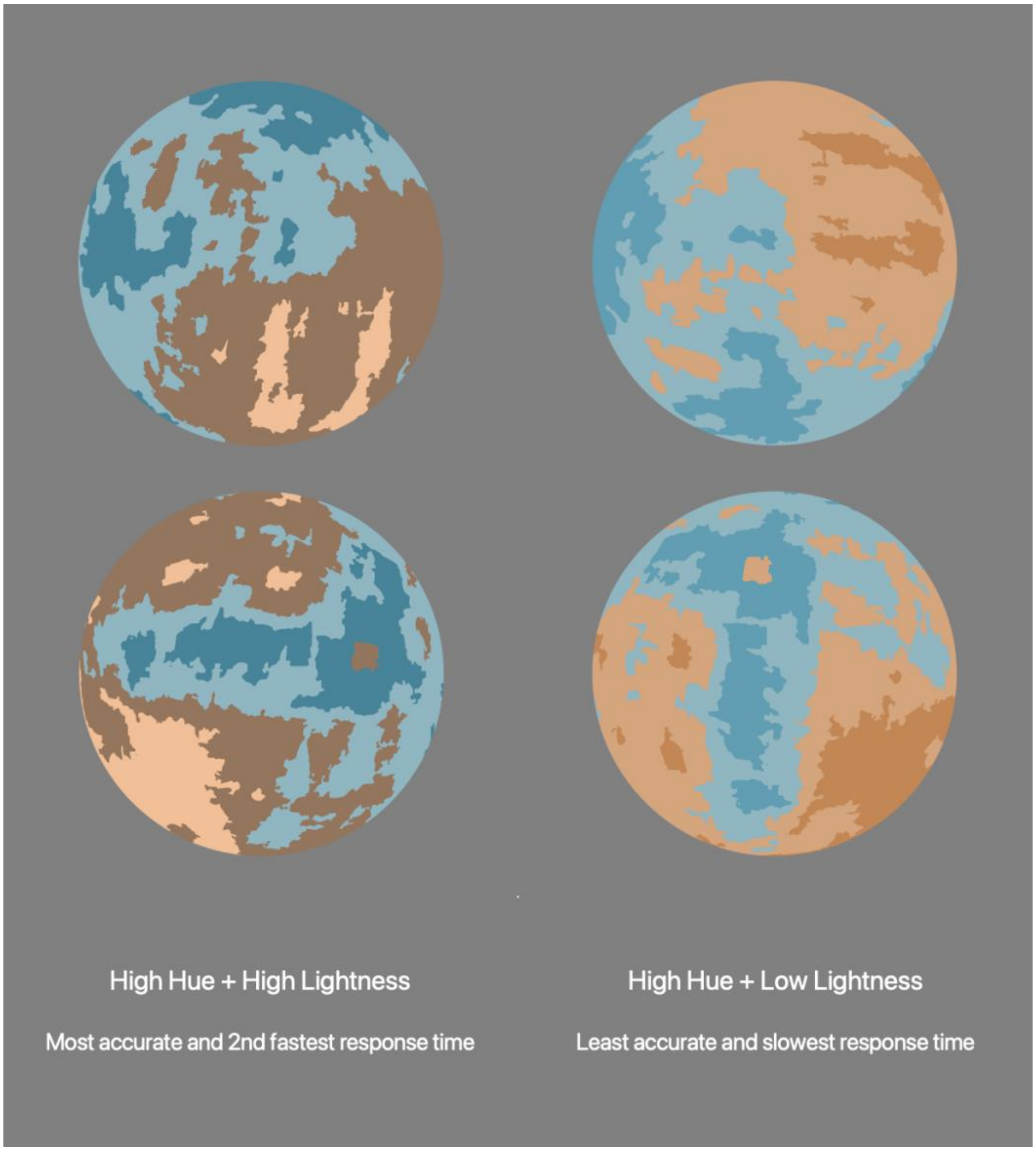


Figure 21: The overall best performing, and worst performance hue and lightness contrast combination applied to fractal maps used for the experiments.

The observed highest overall performance for the high hue and high lightness contrast maps was in line with the cartographic expectation that higher visual contrast maps are easier to discern and are thus more cognizable. Less clear is the reason why the high hue contrast with low lightness contrast performed the worst both for response time and accuracy. It could be inferred that this particular contrast combination resulted in maps that were hardest to read. Further research is needed to shed light on this finding.

These results suggest that the typical prioritization of lightness contrast over hue contrast may be misguided in improving user performance for map design. Accordingly, in terms of improving cartographic legibility and map reading performance, it may be more important to jointly and holistically consider both hue and lightness contrast together.

Neuro Activity Differences

The analysis conducted on the collected fMRI data addresses the second research question – that is: how does varying visual contrast of lightness and hue in cartographic symbolization affect brain activation patterns of geospatial mental rotation tasks? The results of the neuroimaging analysis highlighted the complexity of mental map rotation as a vehicle for map cognition. The analysis also highlighted the potentially limited resolution of fMRI on quantifying how specific cartographic design decisions modulate map cognition. Generally, the results of the neuroimaging models highlighted significant activation across major known brain correlates of the mental map rotation task. Cortical areas of the brain that were identified in the analysis include regions associated with higher cognition, working memory, imagined movement, spatial processing, thought and planning, decision-making and processing of visual information.

Areas of shared brain activation

As a whole, the analysis was productive in confirming and expanding what is known about regions of the brain involved in geospatial mental map rotation. Areas of shared brain activation across different levels of hue and lightness contrast are shown in *Figure 22*. Areas where activation was detected including the precentral gyrus (primary motor cortex), and the juxtapositional lobule/supplementary motor cortex, are associated with locomotion, spatial processing, imagined movement and mental rotation (Banker & Tadi, 2022; Tomasino et al., 2005). Other detected areas including the frontal pole, superior frontal gyrus, frontal operculum cortex and the frontal orbital cortex are areas associated with higher level thought, cognition and decision-making (Boisgueheneuc et al., 2006; Higo et al., 2011; Koechlin, 2011). The frontal orbital cortex has also been associated with the human behavioral reward system and may suggest a link with some participants feedback description of the experimental task as *feeling like a game* (Kringelbach, 2005). Further, areas including the paracingulate gyrus and the middle frontal gyrus are associated with working memory and retrieval (Japee et al., 2015; Wysiadecki et al., 2021). Areas of shared brain activities largely matched expected activation for completing the mental map rotation task.

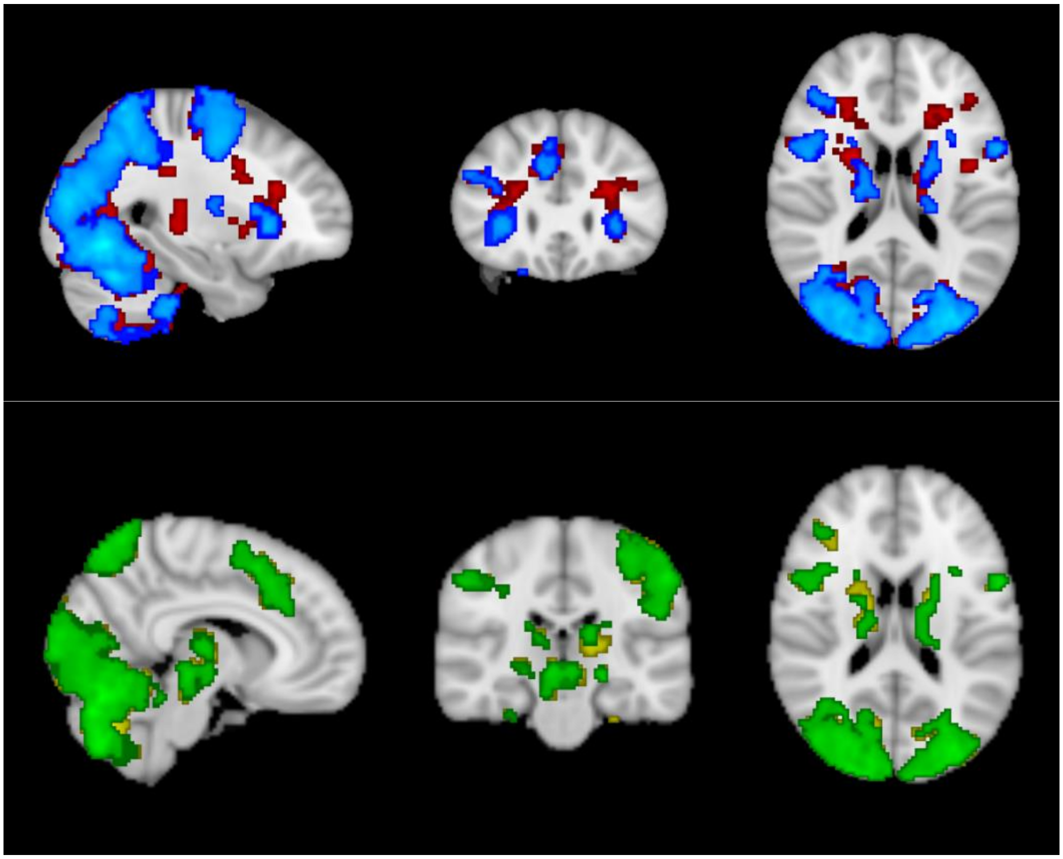


Figure 22: Overlay of clusters of statistically significant brain activities identified during trials. Brain activation associated with high hue contrast is shown in red. Brain activation associated with low hue contrast is shown in blue. Brain activation associated with high lightness contrast is shown in yellow. Brain activation associated with low lightness contrast is shown in green. Z value threshold is 3.1.

Area of brain activation differences

Conversely, contrast level-specific activation differences were largely limited bilaterally to the lateral occipital cortex and the occipital pole – two areas associated with object recognition and elementary perceptual processing within the primary visual cortex, respectively. High hue contrast elicited greater activation in the occipital cortex than low hue contrast. Similarly, high lightness contrast elicited greater activation in the occipital cortex than low lightness contrast. The utility of identifying these differences is up to debate. On the one hand, the identification of cartographic context-specific visual contrast-level dependent activation in the visual cortex is novel – as there is limited understanding on the pattern of activations beyond experiments using elementary luminance stimuli and even fewer conducted on humans (Bhattacharyya et al., 2013; Gardner et al., 2005; Glickfeld et al., 2013; Nassi et al., 2015). In comparison, this research identified specific differences in brain activation patterns associated with different levels of hue and lightness contrast in the visual cortex within the occipital lobe. In that vein, this research broadens existing understanding about contrast-related activities in the visual cortex to a more context-specific domain. On the other hand, the analysis conducted did not detect activation differences in higher cognitive areas of the brain that could be attributed back to the specific changes in the levels of hue and lightness contrast. Thus, the analysis provided limited utility in identifying how visual contrast modulates higher level map cognition beyond the brain's perceptual center. In other words, this research identified activation differences for *seeing* and *perceiving* visual contrast levels in maps but did not detect activation differences for how contrast affects *thinking about* and *using* the maps. Thus, further research is needed to study how the cognitive modulation identified in the behavioral analysis is expressed in the brain.

Reflection on Visual Contrast Saliency Model

Recall the visual contrast saliency model proposed at the end of Chapter II, the findings of this research partially confirm the contention of the importance of visual contrast for higher-level map cognitive functions. This is reflected in the findings of the behavioral data analysis. The analysis provided empirical evidence showing that map cognitive performance (through mental map rotation) was significantly modulated by the visual contrast designed into the map. This aligns with the proposed basis for the reconceptualized model – <u>that visual contrast can be operationalized as the perceptual attributes of visual saliency and as a mechanism of holistic visual attention modulation</u>. However, the results of the fMRI analysis to support this model was inconclusive. While the findings of the analysis identified areas of activation associated with modulation of visual attention, no changes to contrast-level linked brain activation were detected outside of the visual cortex. This finding suggests that the visual cortex may play a greater than expected role in visual attention modulation. Although the lack of activation outside of the visual cortex does not run counter to the proposed model per se, it fell short of providing the desired empirical evidence to validate the neuro-mechanism for the model.

Thus, further research is needed to expand and support the reconceptualized model.

Supplementary Observations

The results of the analysis confirmed the importance and role of visual contrast of hue and lightness in maps. However, the models also highlighted the role of contextual and possibly geospatial factors that may significantly affect this relationship. The results empirically showed that fractal map seed and rotation task type separately play statistically significant roles when combined with hue and lightness contrast. Specifically, the GLMMs spotlighted the strongest augmentation effect from fractal map seed on the effect of hue and lightness contrast combination. In other words, the geospatial characteristics of the map directly affect the usability and legibility of the map design specific to the experiment task. Thus, this finding underscores the need for holistic contrast design based on the cartographic context. This supplementary finding suggests that even the most optimal and best performing contrast combination identified in this or any such research may not always be the most optimal for *any and all* maps. This is reflective of what cartographers have long known and reflect the special attribute of spatial representation in the vein of the adage “*spatial is special*.”

CHAPTER VI

CONCLUSIONS

Recall the research questions of this dissertation:

1. How does varying visual contrast of lightness and hue in cartographic symbolization affect geospatial mental rotation task performance?
2. How does varying visual contrast of lightness and hue in cartographic symbolization affect brain activation patterns of geospatial mental rotation tasks?

This research successfully confirmed that there is both a change in the behavioral task performance as well as brain activities based on the cartographic visual contrast shifts. The behavioral statistical models showed that there were statistically significant relationships between combinatorial levels of hue and lightness contrast on map reader's accuracy and response time as indicators of general map cognitive performance. The neuroimaging models also showed that there were statistically significant brain activation differences for high versus low hue and high versus low lightness contrast. Accordingly, the findings of this research fulfill one of the stated primary objectives and reaffirms cartographers' contention of the importance of visual contrast, as the basis of map communication design.

Further, recall the discussion in *Chapter II* on the growth, expansion and divergence of early cartographic scholarship from their psychological foundation.

In that vein, the findings of this research additionally serve as an important neuro-psychological link to support expansive cartographic theories on visual contrast. In doing so, this research offers a major step towards reconnecting and realigning modern cartographic scholarship back with its contemporary psychological roots.

Nevertheless, it is important to note the potential limitations and pitfalls of this research. For one, the rigid constraints of conducting a neuroimaging experiment required tradeoffs to made when designing experimental instruments and procedures. Map stimuli complexity and quantity were constrained to fit the unique parameters of the fMRI testing paradigm. Despite the simplification, the setup of the EV event timing files used for the analysis of functional brain data posed elevated risk for by rank deficiency caused by the interactive and overlapping complexity of the visual contrast variables being studied. The potential for rank deficiency prevented the ability to conduct cross-variable analysis on the functional brain imaging data. Consequently, analysis of functional brain data was conducted separately for hue versus lightness contrast, thus limiting possible empirical inference that this research can posit.

Still, this research serves as proof of concept for future fMRI-based neuro-cartographic map cognition research. The findings of this research highlights multiple areas where further investigation is warranted. For one, further investigation is needed to explore the identified map reader preference against maps with high hue and low lightness (see *Figure* 21). Further, the identified brain activation patterns – with activation differences limited largely to the confines of the visual cortex – fell short of providing the comprehensive empirical evidence to fully support the neuro-mechanism for the reconceptualized virtual contrast saliency model proposed in *Figure 4*. Therefore, continued investigation of how visual characteristics such as visual contrast mediate visual attention is needed to further support the model. Additional examination and determination of possible neurological correlates of basic visual saliency may further provide the crucial neuro-mechanical endorsement for the proposed model. Accordingly, this research provides the structural foundation and launchpad for these and additional future studies to explore other neurological correlates that enables visual contrast saliency.

APPENDIX A

BEHAVIORAL EXPERIMENT PROCEDURE

A. Safety Questionnaire

Before starting, have you had a chance to read and complete the MRI Safety Questionnaire? *[LCNI_screening; if not, give time (up to 5 minutes) to do so.]*

You will also go through the questionnaire with the MRI technician.

B. Demographic Questions

We are collecting a few demographic details to help us understand our participant group.

What is your age group?

What is your sex/gender?

Which hand is your dominant hand?

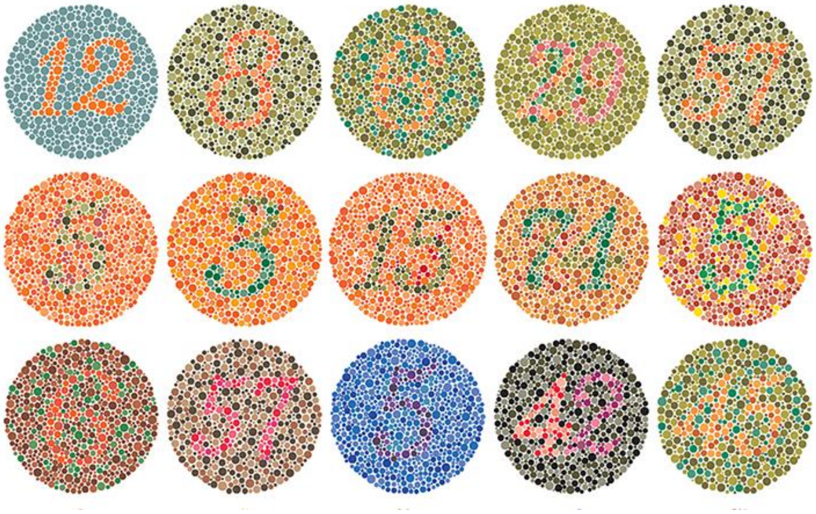
What is your career field or field of study?

How would you rate your level of geographical knowledge and map design? (7-point scale from “very low” through “average” to “very high”

C. Overview and terms

The purpose of the study is to learn about the cognitive processes that help people understand spatial information in the context of map reading. To study these cognitive processes, we will show you a series of graphics and ask you to make decisions about their contents. Before we continue to the task description, we want to make sure that the colors used in the maps are visibly distinct.

This color check will be conducted on the laptop. We will show you a series of randomly selected colorblindness test graphics. You will input the number embedded in each graphic. Example colorblindness test graphics:



Thank you for stepping through those pairs. Overall, your accuracy was __ ______%; *[If 90% or better, i.e., no more than two errors]* this tells suggests that you will be able to tell the colors apart when viewing them in the scanner.

[If less than 90%] this raises a concern that you may not be able to tell the colors apart when viewing them in the scanner; you will not be eligible to continue with the session, but you will be paid for your time up to this point. *[and proceed to test conclusion and receipt]*

D. Training Script

The purpose of the study is to learn about the role of map design in the map reading and cognition process. We will show you a series of graphics and ask you to make decisions about their contents. At a basic level, we are studying how the design of a map's visual contrast affect our ability to see and read the map:

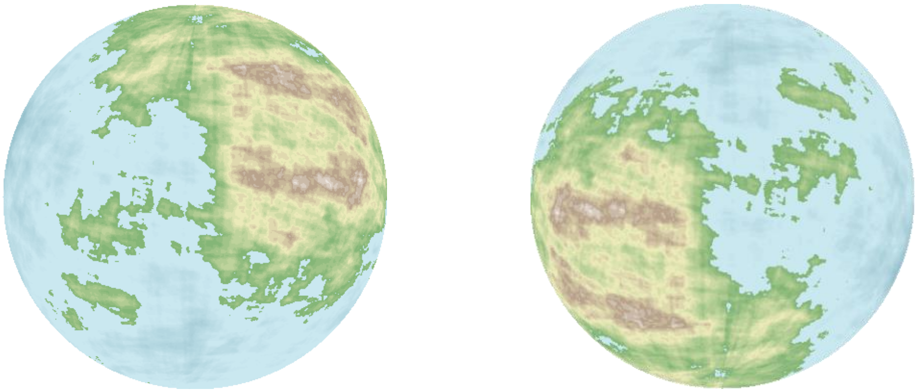
***Visual contrast** is the measure of visual distinctness of two or more graphical elements*

You will complete a series of questions on a lab computer. The same question will be asked repeatedly in relation to different graphics. We will go over an example of the question/task now so that you will be familiar with them; but you don't have to memorize them – we want your split-of-the-moment response for the experiment.

You will be shown map pairs. Each pair will consist of two graphically identical maps where the left map is the default orientation, and the right map is the same map either rotated or rotated and flipped. These maps are randomly generated and have no real-world reference.

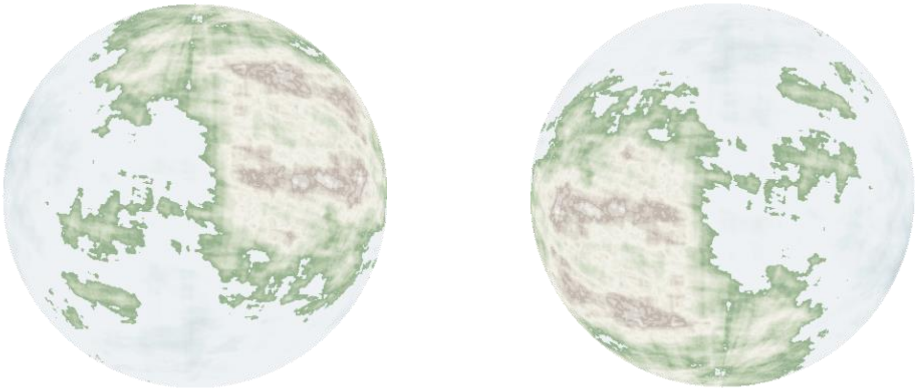
Here are two example map pairs – please note that the maps and designs you will see during the actual test may look different than these examples:

Example pair a1



A ***B***

Example pair a2



A ***B***

For each map pair, you will respond to the state of the right map by choosing one of two response options:

Map is rotated 90 degrees

Map is rotated 90 degrees AND then flipped horizontally

We would like to you respond to each graphic as quickly and accurately as you can. Decisions about some graphics may be more difficult than others.

Do you have any questions about the task?

E. Behavioral Study

[Before] You are now ready to start the test. I will launch the experiment on the lab computer you are stationed at.

[After] Thank you for your attention while completing the study. We will now wrap up with some quick paperwork for your payment.

F. Test Conclusion

And finally, to conclude today’s session I have a receipt for $__ to hand you. You can take the receipt to the Department of Geography front office and exchange it for cash; you will be asked to sign the receipt to confirm that you received the cash payment.

APPENDIX B

NEUROIMAGING EXPERIMENT PROCEDURE

A. Safety Questionnaire

As a refresher, have you had a chance to reread the MRI Safety Questionnaire and confirm that your initial answers are still accurate? *[LCNI_screening; if not, give time (up to 5 minutes) to do so.]* You will also go through the questionnaire with the MRI technician before entering the scanner room.

B. Training Script

As a refresher, I will go over the overview of the study from our last session then discuss the specific information relating to completing the study while undergoing neuroimaging.

The purpose of the study is to learn about the role of map design in the map reading and cognition process. We will show you a series of graphics and ask you to make decisions about their contents. At a basic level, we are studying how the design of a map's visual contrast affect our ability to see and read the map:

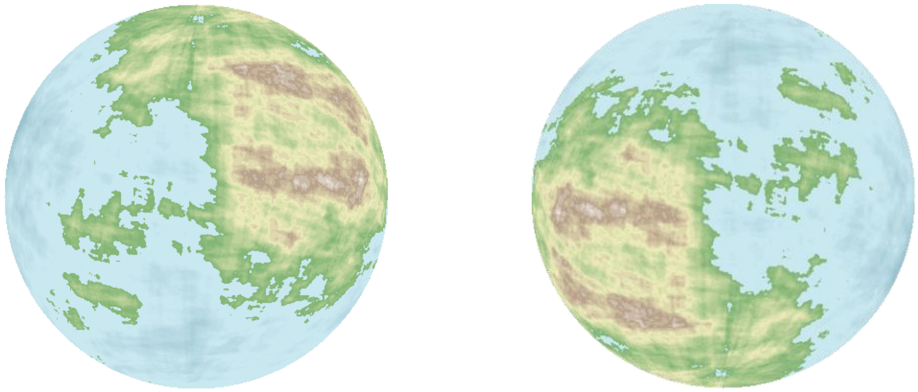
Visual contrast *is the measure of visual distinctness of two or more graphical elements*

You will complete a series of questions. The same question will be asked repeatedly in relation to different graphics. We will go over an example of the question/task now so that you will be familiar with them; but you don't have to memorize them – we want your split-of-the-moment response for the experiment.

You will be shown map pairs. Each pair will consist of two graphically identical maps where the left map is the default orientation, and the right map is the same map either rotated or rotated and flipped. These maps are randomly generated and have no real-world reference.

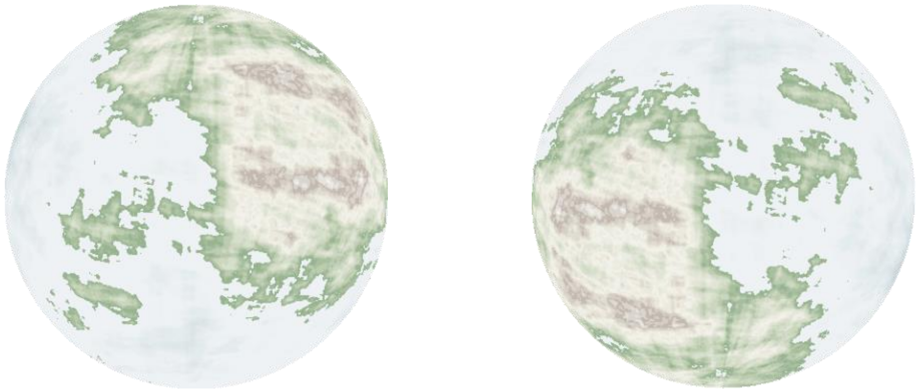
Here are two example map pairs – please note that the maps and designs you will see during the actual test may look different than these examples:

Example pair a1



A ***B***

Example pair a2



A ***B***

For each map pair, you will respond to the state of the right map by choosing one of two response options:

Map is rotated ***Map is rotated AND flipped***

We would like to you respond to each graphic as quickly and accurately as you can. Decisions about some graphics may be more difficult than others.

So far in this training, you have been responding to me verbally. When you are in the scanner you will use a button box. The button box is a small piece of hardware that is roughly the shape of your hand and has a button for each finger. You will press the button under your index finger for ***Map is rotated***, and the button under your middle finger for ***Map is rotated AND flipped***. You indicated that you are [right | left] handed, so you will respond with your [right | left] hand. For each set of graphics, there will be a reminder about the question and how to indicate your response.

Do you have any questions about how you will respond when in the scanner?

We will help you get in and out of the scanner. Once you are settled in the scanner, we will ask you to remain still. Please do breathe! But we ask that you otherwise remain still - this means avoiding flexing muscles or tapping your toes. If you are uncomfortable or need a break, please let us know so that we can stop the scan. A good tip for remaining still in the scanner is to get comfortable so that you are relaxed and do not tense up.

As a reminder, you will place your dominant hand on the button box. In your other hand you will have a squeeze ball; if you need to stop the test at any time, compress the squeeze ball.

Do you have any other questions before we move to the scanner room?

C. Scanning

[Before] You have already gone over the safety screening questionnaire with the technician; do you have any questions or concerns about scanning before we go to the scanner room?

Before we enter the scanning room, we want to make sure that none of us has any magnetic objects. Please leave any personal items, such as backpacks, purses, or keys here; this will remain locked while you are in the scanner.

[After] Thank you for your attention during the scan. We will now go back to the other room where you can pick up your belongings, and we will wrap up with two pieces of paperwork.

D. Debriefing Survey

The last task in today's session is a short, one-page, open-ended survey. While you fill it out, I will complete the receipt that you can take to the Geography front office.

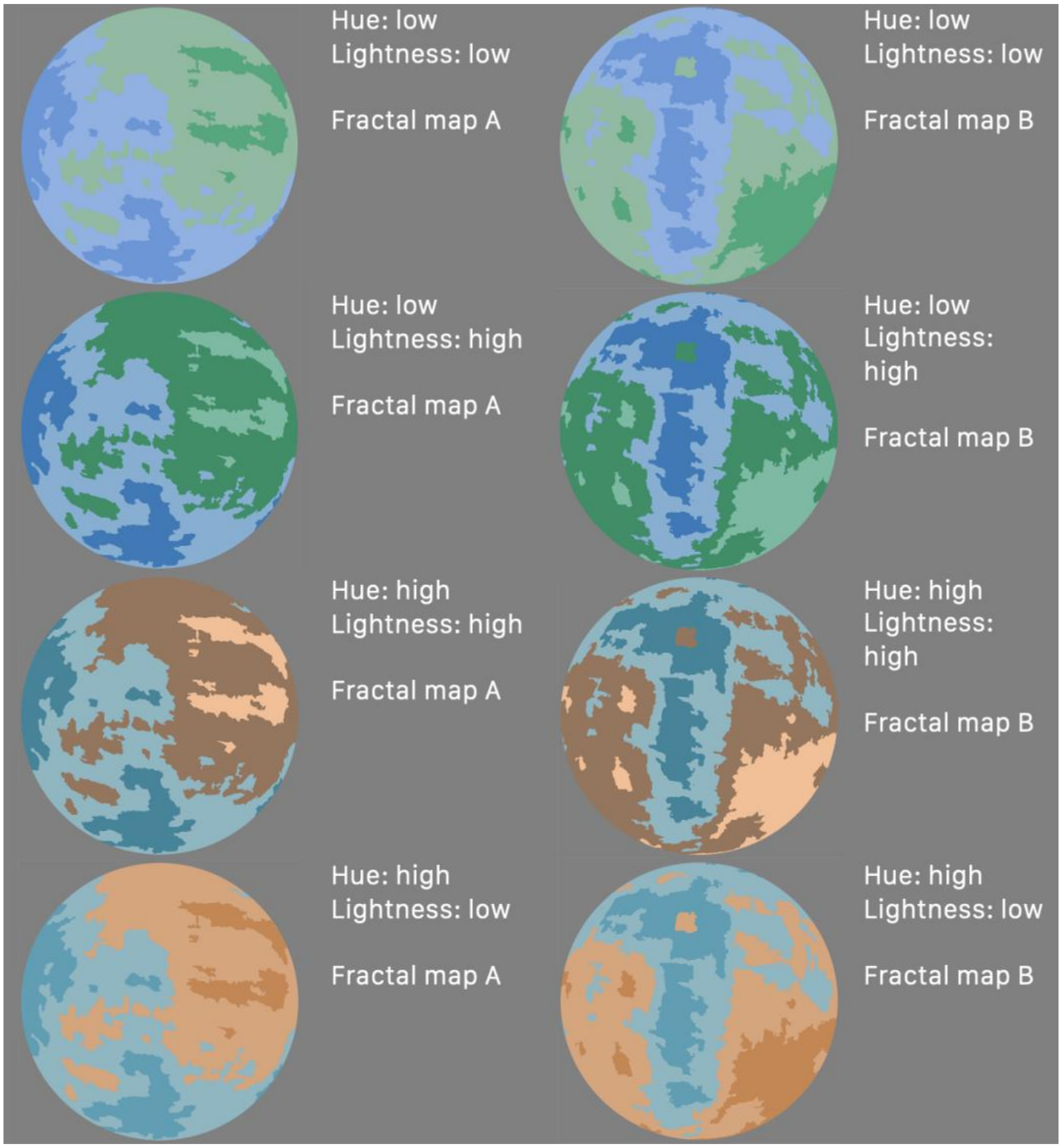
E. Test Conclusion

And finally, to conclude today’s session I have a receipt for $__ to hand you. You can take the receipt to the Department of Geography front office and exchange it for cash; you will be asked to sign the receipt to confirm that you received the cash payment.

APPENDIX C

EXAMPLE EXPERIMENT STIMULI DECK

Shown here are the default orientation map stimuli for deck 1. There are 24 stimuli per deck (8x3 orientations), 2 map decks are in the study producing 128 unique orientation pairings for the experiments.



APPENDIX D

EXAMPLE INFORMED CONSENT FORM

Consent for Research Participation

Title: Neurological Role of Cartographic Visual Contrast in Geospatial Cognition
Sponsor: NSF
Researcher(s): Bill Limpisathian, University of Oregon
Amy Lobben, University of Oregon
Researcher Contact Info: 541-346-0785, billl@uoregon.edu
541-346-4566, lobben@uoregon.edu

You are being asked to participate in a research study. The box below highlights key information about this research for you to consider when making a decision whether or not to participate. Carefully consider this information and the more detailed information provided below the box. Please ask questions about any of the information you do not understand before you decide whether to participate.

Key Information for You to Consider

- **Voluntary Consent**. You are being asked to volunteer for a research study. It is up to you whether you choose to participate or not. There will be no penalty or loss of benefits to which you are otherwise entitled if you choose not to participate or discontinue participation.
- **Purpose**. The purpose of this research is to study cognitive processes associated with cartographic map reading by coupling innovative fMRI neuroimaging with a traditional cartographic behavioral study.
- **Duration.** It is expected that your participation will last 2 hours over the course of 2 one-hour sessions. One hour completing computer-based testing. One hour completing neuroimaging-based testing. You can elect to participate in the computer-based testing, the neuroimaging-based testing, or both.
- **Procedures and Activities.** You will be asked to respond to a series of questions that are part of cartographic evaluation tasks. During both parts of this research, you will complete a series of quick reaction question about the orientation of the map shown. You will

complete this task once in a traditional computer-based testing setting. Then again while undergoing fMRI neuroimaging during the second session. For the neuroimaging session, you will be placed into the MRI scanner and provided with a button box to respond to the task questions. The inclusion of neuroimaging will measure your brain activities as it relates to you competing the research task. Functional scans of your brain activities will be collected. Additionally, scans of your head and brain’s anatomy and magnetic field maps will accompany the functional scans. The MRI scanner is operated by trained MRI scan operators in conjunction with the MRI-safety certified research team. Additional details on the procedures are described in a later section of this form.

- **Risks.** There are no known greater-than-minimal risks associated with participation. Participants may feel anxiety or uncertainty related to a completing the study in a testing center like setup. There are some mitigatable associated risks with fMRI neuroimaging. The magnetic forces generated by the machine presents a risk to some types of ferromagnetic objects that may be inadvertently brought into the room. The research team and the neuroimaging center staff will conduct a thorough screening for any potential problems, to make sure we have accounted for all MRI-related concerns. Additionally, the MRI machine produces loud noise during scanning which may be discomforting to you as a participant. We will provide hearing protecting to reduce noise exposure. Those that experience claustrophobic may find the scanner discomforting over the course of the scan session. Participants may elect to stop the practice or real MRI scans at any time.
- **Benefits**. There are no anticipated direct benefits to participation. The results of this research will contribute to generalizable knowledge of map cognition and behavioral geography.
- **Alternatives.** Participation is voluntary and the only alternative is to not participate.

Why is this research being done?

The purpose of the research is to study cognitive processes associated with cartographic map reading. You are being asked to participate because you are an adult aged 18 or older who have normal or corrected vision and have use of both hands. About 24 people will take part in this research.

What happens if I agree to participate in this research?

If you agree to be in this research, your participation will include taking part in a cartographic behavioral user study session as well as a subsequent neuroimaging

study session. By agreeing to participate, you agree to take part in both research sessions.
You will be asked to respond to a series of questions that are part of cartographic evaluation tasks. During both parts of this research, you will complete a series of quick reaction question about the orientation of the map shown. During the first research session, you will complete this task in a traditional computer-based testing setting in the S3C participant testing room in Condon Hall. We will then schedule you for follow-up neuroimaging session where you will complete the same experiment task while undergoing fMRI neuroimaging.

Prior to the start of the neuroimaging session, you will review the priorly filled MRI safety form with the license MRI scan operator. The operator will determine whether the scan session can safely proceed. After a positive safety determination has been made, you will store your personal belongings in a keyed locker at the center. Before entering the scanner room, we will check for any remaining metal objects on your person using the center's metal detectors. Once cleared, we will lead you into the scanner room and will lay you in the scanner bed and provide you with a button box for your dominant hand and a call button for your non-dominant hand. The button box is used instead of a keyboard to input your response to the experiment task. The call button is used to interrupt scanning and get the attention of the research team and scan operator. A helmet-like head coil will additionally be placed over your head. The coil is part of the MRI scanner and acts as an antenna to receive the magnetic signal coming out of your body and transmit that data to a computer which then generates images. MRI is magnet-based and non-ionizing so there is no radiation-related risk. The MRI machine produces loud noise during scanning which may be discomforting to you as a participant. We will provide hearing protecting to reduce noise exposure.

We will collect your response and reaction time while you complete the cartographic evaluation tasks. Just like in the prior session, you will complete a series of quick reaction question about the orientation of the map shown. Additionally, we will collect both functional as well as anatomical MRI scans of your head and brain. These scans include the tissue and bone structure of your head and brain as well as the proxy measure of your metabolic brain activity. We will also collect magnetic field maps to aid in the processing and analysis of your neuroimaging data. We will use collected data to study how the design of visual contrast in maps affect how you think about and react those maps. You will remain in the MRI scanner for approximately 45 minutes.
We will tell you about any new information that may affect your willingness to continue participation in this research.

This study uses the standard procedures for the Siemens Skyra or Prisma 3 Tesla MRI at the Lewis Center for Neuroimaging (LCNI). Magnetic resonance imaging (MRI) and magnetic resonance spectroscopy (MRS) are approved by the US Food and Drug Administration (FDA) to look at structure and function of your brain and body. MRI uses a very strong magnetic field and radio frequency pulses to create digital pictures. There is no ionizing radiation (like X-rays) or injections into your body with this MRI.

Scans are done for research purposes only and cannot rule-out or confirm a diagnosis. A medical doctor does not always review the scans. However, if a member of the LCNI staff observes something unexpected in a scan, the scan will be sent anonymously to a radiologist. If the radiologist suggests that you follow-up with your regular doctor, we will discuss what the radiologist said in detail with you. You will be able to take all your images from this study to your doctor and the LCNI director can point out the area of possible concern, if needed.

What happens to the information collected for this research?
Information and data collected for this research will be deidentified then subsequently analyzed and aggregated. Identifiers will be removed from identifiable private information and/or identifiable neuroimaging data collected in this research. After removal of identifiers, the information and/or biospecimens may be used for future research or distributed to another investigator for future research without obtaining additional consent. With your expressed consent, we may release your deidentified individual-level neuroimaging data according to current standards and publish it to the OpenfMRI database.

How will my privacy and data confidentiality be protected?
We will take measures to protect your privacy including your personal and demographic information, contact information, study response and neuroimaging data. Despite taking steps to protect your privacy, we can never fully guarantee your privacy will be protected. Only one participant is scheduled for study participation and data collection at a time. We will space out study sessions to ensure there is no possible overlap between participants.

We will take measures to protect the security of all your personal information including demographic information, contact information, scheduling information, study response and neuroimaging data. Despite these precautions to protect the confidentiality of your information, we can never fully guarantee confidentiality of all study information. The web-based scheduling data will be password protected and available to the PI and their research assistant. E-mail messages sent or received by the PI and/or research assistant will be password protected on

UO (uoregon.edu) email accounts (e-mail messages sent or received by respondents will be maintained or deleted at their own discretion).

To protect your privacy, you will be assigned a numeric code which will be used to label the data collected during your session; your names will not be directly associated with data. Your informed consent documents will be stored in a locked cabinet in the access-limited S3C research lab and destroyed three years after the conclusion of the study.

Data will be stored on the Oregon Neuroscience Grid and on the Spatial Computation, Cognition, and Complexity Lab research computer, both of which are access-limited and password protected. At the conclusion of the study, data will be de-identified according to current standards and published to the OpenfMRI database. Scanning data for participants who elect to restrict sharing will not be published, but will be archived locally.

Imaging data are additionally kept on a secure computer by the LCNI with an anonymous code. There is no identifying information kept with LCNI imaging data. Access and information related to these data are described further in this section.

Individuals and organization that conduct or monitor this research may be permitted access to and inspect the research records. This may include access to your private information and your study responses and neuroimaging data. These individuals and organizations include: The Institutional Review Board (IRB) that reviewed this research and the research's sponsor, the National Science Foundation.

What if I want to stop participating in this research?

Taking part in this research study is your decision. Your participation in this study is voluntary. You do not have to take part in this study, but if you do, you can stop at any time. You have the right to choose not to participate in any study activity or completely withdraw from continued participation at any point in this study without penalty or loss of benefits to which you are otherwise entitled. Your decision whether or not to participate will not affect your relationship with the researchers or the University of Oregon.

What are the risks of participating in this research?

LCNI has multiple safety features to reduce the potential for harm. The strong magnetic field of the scanner presents a risk if some types of metallic magnetic objects are brought into the room. There is a risk these objects may be attracted to the MRI machine, or they may lead to heating and burns to you. This can also occur if your body or our equipment are not positioned properly inside the scanner. We will minimize this risk by carefully positioning you with special insulating pads. LCNI staff will conduct a thorough screening for any potential problems, to make sure we have accounted for all MRI-related concerns. Depending on what you are wearing (e.g., metal buttons or clasps), you may be asked to remove some clothing and put on 'scrubs'.

The MRI scanner makes loud thumping, pounding and whining sounds during scans, which may be discomforting to some people. You will be provided with hearing protection to reduce the noise from the scanner. You may become anxious and/or tired from lying in the MRI machine. Some individuals who are claustrophobic (scared of small spaces) may find the scanner too confining. To get an idea of what the experience of being scanned will be like, you may ask to do a ‘practice’ session in our mock-scanner before your session. You may ask to stop the practice or real MRI scans at any time. You will be given an emergency squeeze ball during the real MRI and instructed in its use. You may squeeze this ball at any time to stop the scan and be removed from the scanner.

Although there are no known risks to having an MRI when you are pregnant, it is a time when the heart and brain are still developing. Therefore, if you think that you may be pregnant, we will encourage you to choose not to participate until you are finished with your pregnancy.

What if I am injured because of participating in this research?
While we expect less than minimal risk of injury, if you are injured or get sick because of being in this research, call the researchers immediately.

In the event you suffer a research -related injury your medical expenses will be your responsibility or that of your insurance company (or other third-party payer), although you are not precluded from seeking to collect compensation for injury related to malpractice, fault, or blame on the part of those involved in the research. If you are a UO student or employee and are covered by a UO medical plan, that plan might have terms that apply to your injury.

If you experience harm because of the project, you can ask the State of Oregon to pay you. If you have been harmed, there are two University representatives you need to contact. Here are their addresses and phone numbers:

General Counsel/ Office of the President	**Research Compliance Services**
1226 University of Oregon	5237 University of Oregon
Eugene, OR 97403-1226	Eugene, OR 97403-5237
(541) 346-3082	(541) 346-2510
	ResearchCompliance@uoregon.edu

A law called the Oregon Tort Claims Act may limit the amount of money you can receive from the State of Oregon if you are harmed.

Will I be paid for participating in this research?

For participation in this research, you will be compensated for your time at a rate of $30/hour for the behavioral session and $70/hour for the neuroimaging session. We expect each session to last about one hour. This study involves participation in 2 1-hour research sessions. You will also earn a $10 bonus for completing both sessions. In total, you will earn $110 for completing the study. You will receive a cash payment at the conclusion of each session, prorated for the time spent calculated to the nearest 15 minutes.

Please be aware, compensation for participation in research studies may be considered taxable income.

Who can answer my questions about this research?

If you have questions, concerns, or have experienced a research related injury, contact the research team at:

Bill Limpisathian
541-346-0785
billl@uoregon.edu or geobrain@uoregon.edu

An Institutional Review Board ("IRB") is overseeing this research. An IRB is a group of people who perform independent review of research studies to ensure the rights and welfare of participants are protected. UO Research Compliance Services is the office that supports the IRB. If you have questions about your rights or wish to speak with someone other than the research team, you may contact:

Research Compliance Services
5237 University of Oregon
Eugene, OR 97403-5237
(541) 346-2510
ResearchCompliance@uoregon.edu

STATEMENT OF CONSENT
I have had the opportunity to read and consider the information in this form. I have asked any questions necessary to make a decision about my participation. I understand that I can ask additional questions throughout my participation.
I understand that by signing below, I volunteer to participate in this research. I understand that I am not waiving any legal rights. I have been provided with a copy of this consent form. I understand that if my ability to consent or assent for myself changes, either I or my legal representative may be asked to re-consent prior to my continued participation in this study.
I consent to participate in this study.

____
Name of Adult Participant

____
Signature of Adult Participant

______
Date

Researcher Signature (to be completed at time of informed consent)
I have explained the research to the participant and answered all of his/her questions. I believe that he/she understands the information described in this consent form and freely consents to participate.

____
Name of Research Team Member

____
Signature of Research Team Member

______
Date

SUPPLEMENTARY CONSENT FOR OPTIONAL RELEASE OF DEIDENTIFIED INDIVIDUAL-LEVEL NEUROIMAGING DATA

All information and data collected for this research will be deidentified then subsequently analyzed and aggregated. All identifiers will be removed from identifiable private information and/or identifiable neuroimaging data collected in this research. After removal of identifiers, the aggregated information and/or biospecimens may be used for future research or distributed to another investigator for future research.
With your expressed consent, may we additionally release your deidentified individual-level neuroimaging data and publish it to the OpenfMRI database for the benefit of future research? (Check one)

☐ Yes, I consent to the release of my deidentified individual-level neuroimaging data

☐ No, I do not consent to the release of my deidentified individual-level neuroimaging data

___________ Initial of Adult Participant

___________ Initial of Research Team Member

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