Four Ways of Reasoning about Space and their Relation to Visual Search

by

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Abstract

A framework of spatial thought and language proposed by Chatterjee (2008) was extended to organize measures of spatial tasks (Uttal, Meadow, Tipton, Hand, Alden, Warren, & Newcombe, 2013). Uttal et al. posited that people reason about space based on recognizing and manipulating objects; dimensions of object features (intrinsic vs. extrinsic) and object movement (static vs. dynamic). Thus, Uttal et al. proposed four types spatial of spatial processes: Spatial visualization (intrinsic-static); spatial perception (extrinsic-static); mental rotation (intrinsic-dynamic); and spatial orientation (extrinsic-dynamic). Each type of spatial process involves a particular focus of spatial thought, language, and task on the object proper (spatial visualization), its locative relations (spatial perception), manner of motion (mental rotation), or path of motion (spatial orientation). Undergraduates ($N = 304$) completed 14 spatial tasks identified by Uttal et al. (2013) as measures of the four spatial types. Participants also completed a visual search task that was hypothesized to involve spatial processes.

Measurement models of the four-factor theory of spatial reasoning were tested. The four-factor model provided a good fit to the spatial ability measures and thus supported the proposed model. Although men performed better than women on most of the spatial measures, the model of spatial reasoning implied by the typology fit the data for both men and women. For visual search, a two-factor model of easy and difficult visual search fit the observed data. However, structural models relating all four spatial types to visual search did not converge, presumably because there were multiple unmeasured relations between visual search performance and the 14 spatial tasks.

Multiple regression showed that mental rotation predicted easy visual search and spatial visualization, spatial orientation, and gender predicted difficult visual search. Men performed better on the visual search task than women.

These findings support the validity of the four factor model, specifically, the relations between easy and difficult visual search and the three indices of spatial reasoning (mental rotation, spatial visualization, and spatial orientation). Mental rotation as an ability to recognize the manner of motion of objects predicted performance on easy visual search trials. Spatial visualization, operationalized as the recognition of objects by their static, intrinsic features, appears to be a fundamental factor in resolving difficult visual search. In future research with other complex visual tasks, spatial orientation might be a more important predictor if participants need to distinguish moving targets from distractors on the basis of their unique features. In summary, the current results extend our understanding of individual differences in spatial abilities and provide support for the Uttal et al. framework.

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Table of Contents

Abstract	ii
Table of Contents	vi
List of Tables	x
List of Figures	xi
List of Appendices	xiii
Chapter 1: Introduction	1
Objects as the Focus of Spatial Thought	4
Focus on Object Features	4
Types of Motion	5
Chatterjee's Framework for Describing how People Process Spatial Properties	6
Four Spatial Semantic Types	7
A Typology of Spatial Tasks	9
Spatial Thought, Language and Task Performance	13
Visual Search	14
Overview of the Dissertation	18
Chapter 2: Literature Review	21
Overview	21
Theoretical Basis for a Framework of Spatial Reasoning	22
A Neurological Basis of Object Recognition and Manipulation	38
Spatial Ability and Gender	42
Recognition and Manipulation of Gestalts	44

Biological Basis for Gender Differences.....	45
Section Summary.....	48
Visual Search	48
Hypotheses.....	54
Chapter 3: Method	60
Participants and General Procedure	60
Participants	61
Measures.....	62
Part I: Spatial Abilities.....	62
Card rotation.	63
Hidden figures.	64
Figure completion.	65
Measure of the Ability to Form Spatial Mental Images.	66
Mental rotation test.....	67
Rotated blocks.	68
Revised Purdue test of visualization of rotations.	69
Water level.	70
Plumb line.	71
Crossbar horizontal.....	72
Crossbar vertical.	73
Visualization of viewpoints.	74
Revised perspective taking/spatial orientation test.....	75
Map perspective test.	76
Part II: Spatial Training	77

Part III: Visual Search.....	77
Procedure	80
Chapter 4: Statistical Analysis	92
Overview of the Analyses.....	92
Statistical Criteria	93
Structural Equation Modeling.	97
Chapter 5: Results	104
Descriptive Analyses of Spatial Ability Tests.....	105
Measure of the ability to form spatial imagery.	105
Card rotation.	105
Figure completion test.	108
Hidden figures test	108
Crossbar horizontal test.....	110
Crossbar vertical test.....	113
Water level test.....	113
Plumb line test.....	114
Mental rotation test.	116
Rotated blocks test.	118
Revised Purdue spatial visualization test.	118
Guay’s visualization of viewpoints.	119
Map perspective taking test.	120
Perspective taking spatial orientation test.....	120
Section summary.....	125
Confirmatory Factor Analysis of Spatial Types and Visual Search	127
Spatial visualization.....	127

Spatial perception.	128
Four-factor model fit.....	130
Overall model fit and gender.	134
Figure 5.8: Factor Structure of Easy and Difficult Search	138
Visual search.	138
Structural Regression Modeling.....	141
Chapter 6: Discussion	144
Future work.....	150
Visual Search	156
Limitations.....	161
Conclusion	164
Appendices	165
Appendix A - Fit Statistics.....	165
References.....	171

List of Tables

Table 1.1: A General Framework for Categorizing Spatial Characteristics of Objects	7
Table 1.2: A Typology of Spatial Processes by Object Features and Motion	10
Table 5.1: Descriptive Statistics Mean Spatial Visualization Response by Gender	106
Table 5.2: Correlations between Spatial Visualization Measures	109
Table 5.3: Descriptive Statistics Mean Spatial Perception Response by Gender	111
Table 5.4: Pearson Correlations between Spatial Perception Measures	112
Table 5.5: Descriptive Statistics Mental Rotation Mean Response by Gender	115
Table 5.6: Correlations between Mental Rotation Measures	117
Table 5.7: Descriptive Statistics Spatial Orientation Mean Response by Gender	122
Table 5.8: Correlations between Spatial Orientation Measures	124
Table 5.9: Fit Statistics by Model of Spatial Reasoning	132
Table 5.10: Descriptive Statistics on Visual Search by Gender	140
Table 5.11: Correlations between Visual Search Spatial Types and Gender	141
Table 5.12: Summary Statistics for a Regression Model of Easy Visual Search	142
Table 5.13: Summary Statistics for a Regression Model of Difficult Visual Search	143

List of Figures

Figure 3.1	Card Rotation Test Sample Item	64
Figure 3.2	Hidden Figures Test Sample Item	65
Figure 3.3	Figure Completion Test Sample Item.....	66
Figure 3.4	MASMI Test Sample Item	67
Figure 3.5	Mental Rotation Test Sample Item.....	68
Figure 3.6	Rotated Blocks Sample Item.....	69
Figure 3.7	Revised Purdue Spatial Visualization Sample Item	70
Figure 3.8	Water Level Test Sample Item	71
Figure 3.9	Plumb Line Test Sample Item	72
Figure 3.10	Crossbar Horizontal Test Sample Item.....	73
Figure 3.11	Crossbar Vertical Sample Item	74
Figure 3.12	Visualization of Viewpoints Sample Item.....	75
Figure 3.13	Revised Perspective Taking Spatial OrientationSample Item.....	76
Figure 3.14	Map Perspective Taking Sample Item.....	77
Figure 3.15	Visual Search Task Sample Item	78
Figure 3.16	Initial Website Screen on Download.....	80
Figure 3.17	The Study's Home Page	81
Figure 3.18	The Study's Registration Webpage.....	82
Figure 3.19	The Study's Main Menu	83
Figure 3.20	The Personnel Selection Instructional Menu	84
Figure 3.21	The Participant Demographic Information Webpage.....	85

Figure 3.22	Personnel Selection / Spatial Test Instructional Menu	86
Figure 3.23	Sample Test Instruction (Visualization of Viewpoints).....	87
Figure 3.24	A Display Panel from the Basic Spatial Training Module	88
Figure 3.25	The Mission Performance Instructions Webpage.....	89
Figure 3.26	A Visual Search Task under Infrared Condition.....	90
Figure 3.27	An Example of a Mission Debrief Display	91
Figure 5.1	Factor Structure of Spatial Visualization	127
Figure 5.2	Factor Structure of Spatial Perception	128
Figure 5.3	Factor Structure of Mental Rotation	129
Figure 5.4	Factor Structure of Spatial Orientation	130
Figure 5.5	Factor Structure of the Four-Factor Model of Spatial Reasoning	133
Figure 5.6	Factor Structure of Women's Spatial Reasoning	135
Figure 5.7	Factor Structure of Men's Spatial Reasoning	137
Figure 5.8	Factor Structure of Easy and Difficult Visual Search	138
Figure 5.9	Proportion Correct by Visual Search Type by Gender	139

List of Appendices

Appendix A.....165

Chapter 1: Introduction

People use spatial processes in many aspects of their daily lives, from complex tasks such as giving directions or driving a vehicle to simpler activities like finding a ladle in a drawer full of kitchen utensils (Athreya & Mouza, 2017; Berthoz, 2017). Spatial reasoning is also involved in academic learning (Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006; Höffler, 2010; Shipley, Tikoff, Ormand, & Manduca, 2013), particularly in the domains of science, mathematics, engineering, and technology (STEM; Else-Quest, Hyde, & Linn, 2010; Harle, & Towns, 2010; Lubinski, 2010; Wai, Lubinski, & Benbow, 2009; Park, Lubinski, & Benbow, 2008; Robert & Harel, 1996). Accordingly, spatial reasoning is needed in a variety of STEM-related work settings (Schmidt, Oh, & Shaffer, 2016; Schmidt & Hunter, 2004) such as air traffic control (D'Oliveira, 2004), aircraft navigation (Barton, Valtchanov, & Ellard, 2014; Hund & Nazarczuk, 2009), and piloting aircraft (Bertua, Anderson, & Salgado, 2005; D'Oliveira, 2004; Johnson, Barron, Rose, & Carretta, 2017).

My interest in spatial reasoning stems from the question of what kinds of spatial processes are required for certain specialized military activities like aerial surveillance. Accordingly, in this thesis, I tested a proposed model of spatial processes (Chatterjee, 2008; Uttal, Meadow, Tipton, Hand, Alden, Warren, & Newcombe, 2013) and then examined whether individual differences in spatial processes as defined within the model were predictive of adults' performance on a surveillance activity similar to that required of military personnel. The goal of the present research was to obtain a better understanding of (a) the specific processes that characterize spatial reasoning, and (b)

how individual differences in those spatial processes are related to search performance within a complex task context.

This study contributes to the theoretical and practical understanding of spatial reasoning. Testing the proposed model of spatial reasoning clarifies the dimensionality of spatial reasoning. It is commonly accepted that spatial reasoning is a specific cognitive ability. There is less consensus on whether specific spatial factors are distinct from one another and how they may be organized. Many tests and tasks have been developed that are commonly used to indicate specific spatial factors. Structural equation models can be developed to compare single and multiple factor models of spatial reasoning. The fit between such implied models and observed data will contribute to the theory and application of spatial reasoning by revealing the parsimony between models based on underlying dimensions used to group measures as indicators of spatial factors. Subsequent replications and continued model testing will further confirm the structure of spatial reasoning.

Specifying and confirm the measurement model implied by the framework will also further its application to predict performance criteria. For instance, if a single-factor measurement model is confirmed, then perhaps a discreet set of three tests or tasks that indicate that single factor could be administered to predict training or job performance. Other single factor models based other combinations of spatial measures may also confirm multi-factor models are less parsimonious and therefore not worth the effort and administration to predict a performance criterion. Alternatively, if a multiple factor model is confirmed, then specific combination of spatial factors can be tested again using a

variety of spatial tests as indicators to determine the most parsimonious model to predict a performance criterion. Such research would improve efforts to develop the theory and application of spatial reasoning.

Chatterjee (2008) proposed a typology that was based on an analysis of the semantics used to articulate spatial thought and language. Uttal et al. (2013) operationalized this typology and specified measures of the four spatial processing types. People use their spatial reasoning to think about the spatial relationships among objects. Spatial reasoning involves various processes of thinking about space in a logical way in order to form a conclusion or judgment (Byrne & Johnson-Laird, 1989; Frank, 1996; Gentner, 2001; Hegarty, 2010). Space in itself is defined by dimensions of height, depth, and width within which all objects exist and move (Einstein, 1934; 2013; Smolin, 2004). A space can be confined to any lesser dimensions and the things that exist and move therein. An object for example, occupies a space as defined by its height, depth, and length (Mariani & Ogborn, 1991). In essence, objects are collections of material things consisting of matter and energy (Blake & Shiffrar, 2007).

The theory of special relativity showed that matter and energy are interchangeable, that they are one and the same (Einstein, 1939; 2013). Matter in the form of energy can either be stored as potential energy or released as kinetic energy (Abrams & Christ, 2003; Hegarty, 1992; Tipper, Brehaut, & Driver, 1990). Conversely, energy in the form of matter and in its purest form has a mass and takes up space. In either form, energy and matter make up the nature of things that can be described, explained, and predicted by the properties of matter and energy. A typology of semantics

used to convey spatial thought and language may also generalize to the reasoning used to resolve tasks measured by spatial tests if the types of processes specified by the model are focussed on the properties of objects as collections of matter and energy (Meneghetti, Pazzaglia, & De Beni, 2015).

Objects as the Focus of Spatial Thought

Theoretically, any material *thing* can be seen as an object (Norman, 2013; Turkle, 2007). For instance, a sub-atomic particle, a molecule, a chair, a building, a planet, a galaxy, and a cosmos are all types of objects comprised fundamentally of matter and energy. The composition of any object consists of an internal structure of matter and energy organized hierarchically as parts of parts of the whole object (Goldstein, 1999; Simons, 2000) starting from its smallest sub-atomic particle to its full completeness. The internal structure and composition of an object's matter can be represented by intrinsic and extrinsic features (Casati & Varzi, 1999; Ecker, Maybery, & Zimmer, 2013), with the state of its energy on a spectrum from stored, stationary or static to kinetic, or dynamic, or released (Desimone & Duncan, 1995). Intrinsic features are defined as those that are innate in the object (Chatterjee, 2008). Extrinsic features are not inherent in an object but affect its intrinsic features or motion in some way (Carlson-Radvansky & Irwin, 1993; Feldman, 1985).

Focus on Object Features

An object's intrinsic and extrinsic features are dependent on the state of the energy contained in its matter and the matter that surrounds the object in the form of other objects. The state of energy of an object's features vary on a spectrum. At one end

of the energy spectrum, features are static - the structure of each level of matter is stationary – a situation most often found in a solid state and density is concentrated. At other end of the energy spectrum, object features are dynamic -- energy found in either liquid or gaseous state is much less dense, fluid, and in motion (Coventry & Garrod, 2004; Kourtzi & Kanwisher, 2000). These material properties characterize the nature of objects as defined by the form of their matter in the form of intrinsic and extrinsic features and the range of static to dynamic motion of their energy (Malafouris, 2013). The words, phrases, and sentences used to describe, explain, and predict the nature of objects depend on spatial reasoning about matter and energy in the context of the intrinsic and extrinsic features and static and dynamic motion of objects (LaRock, 2007; Van der Velde, 2007).

Types of Motion

Chatterjee (2008) operationalized *intrinsic motion* as movement by an object without an external referent. It is localized to actions occurring among the object's constituent parts without consideration of any external referent. Such motion can be stored within an object such that there is potential but no movement by any of its constituent parts. The object's features are stationary by virtue of the static state of the energy stored therein. Alternatively, an object's stored energy can be released causing dynamic activity by one or more of its constituent parts in some form of motion such as rotating, for example. Along any point of this spectrum of movement thought, intrinsic motion is specific to the object.

Alternatively, *extrinsic motion* conveys translational movement due to an external referent. The contents of a stationary object for instance, are subject to gravitational forces which cause liquids and pendulums to rest horizontally and vertically respectively to the ground. An object's dynamic or transitory motion is determined by its pathway, position, and location relative to an external referent or among an array of external referents. Extrinsic motion is specific to the object in relation to an external referent. The subsequent actions occurring among the object's constituent parts are determined by references external to the object in the context of the overall or globalized defined space.

Chatterjee's Framework for Describing how People Process Spatial Properties

Chatterjee (2008) presented an object-oriented typology to capture the semantics that individuals use to generate spatial thought and language. The typology of spatial semantics posited that spatial thought and language convey meaning about the properties of objects, most readily by their features and motion (Damasio, Grabowski, Tranel, Ponto, Hichwa, & Damasio, 2001; Meneghetti, et al., 2015). A central premise of Chatterjee's framework is that thought and language are artifacts of spatial processing (Bateman, 2010; Bufferey & Gray, 1973; Tyler, Russell, Fadili, & Moss, 2001). According to the framework, thought is either localized to one specific object or globalized to express the spatial relations between objects, their features and motion (Epstein & Kanwisher, 1998; Wu, Waller, & Chatterjee, 2007). Individuals verbalize their thoughts on spatial relations through language and semantics most readily by the nouns and adjectives used to describe (a) an object; (b) its manners of motion; (c) the locative relations between objects; and (d) the relative paths of motion between objects (Bateman,

2013; Davis, 2013). These four semantic types were hypothesized to capture human thought and understanding concerning the spatial relations within an object and between objects (Chatterjee, 2008). Under the Chatterjee (2008) framework, the crossing of the two dimensions based on an object's intrinsic-extrinsic features and its static-dynamic motion indicates how people process visual information to recognize objects. This crossing of the intrinsic-extrinsic and static-dynamic dimensions of objects produced four different spatial types (see Table 1.1).

Table 1.1: *A General Framework for Categorizing Spatial Characteristics of Objects*

	Intrinsic	Extrinsic
Static	An object proper	Its locative relations
Dynamic	Its manner of motion	Its path of motion

From Chatterjee, A. (2008). The neural organization of spatial thought and language. *Seminars in Speech and Language*, 29(3), 226–238. doi: 10.1055/s-0028-1082886.

Four Spatial Semantic Types

By definition, according to the Chatterjee (2008) framework, the semantics of spatial thought and language describe an object (proper) when attention is paid solely to its static, intrinsic features such as colour, shape, and size. The position of an object relative to an external referent is expressed when spatial thought and language is focused on the extrinsic features of a static object (Davis, 2013). People use language describing,

explaining, or predicting an object's features in relation to its surroundings, which they use to express thoughts concerning the object's relative location. In this context, the object is anchored in thought and language to an external referent to state its place or position relative to other objects in the environment or field of view (Meneghetti, et al., 2015). These two spatial types involve attention to either intrinsic or extrinsic object features, respectively under stationary conditions.

Mental rotation and spatial orientation also involve attention to either intrinsic or extrinsic features but under conditions where the object is in motion. Thought and language specific to the movement of a part or feature intrinsic to an object is indicative of mental rotation (Meneghetti, et al., 2015; Varzi, 2007). Parts may be moved in relation to the entire object by rotating, for example. Another manner of motion may convey transitional object motion like 'rolling' or 'flying', which intuitively involves travel from an origin to some other location (Chatterjee, 2008). Describing object motion as rotating, rolling, or flying requires attention to the motion of an object's constituent parts; that motion is intrinsic to either a specific part or the entire object (Kozhevnikov, Motes, Rasch, & Blajenkova, 2006). In contrast, spatial orientation relies on external referents to reason about or express an object's path of motion (Barton et al., 2014; Varzi, 2007; Yu & Zacks, 2017). The thought and language of spatial orientation concentrates on an object's path of motion based on external references in relation to the object. When people reason about an object's movement in relation to other objects, they need to orient it in relation to the location of other objects by their unique features, according to the Chatterjee (2008) framework.

A Typology of Spatial Tasks

Uttal et al. (2013) maintained the same general framework presented by Chatterjee (2008) to categorize four types of spatial reasoning thought to be necessary to perform tasks measured by spatial tests. In doing so, Uttal et al. (2013) hypothesized that the reasoning involved in solving spatial test items depended on reasoners' attention to specific aspects of object features and motion. Table 1.2 depicts the 2 X 2 typology of spatial type presented by Uttal et al. (2013) with each spatial type labeled by the category used in prior research, most notably by Linn and Petersen (1985) and later by Voyer et al. (1995).

The three spatial types Linn and Petersen (1985) proposed fit reasonably well into three of the categories of the model, as shown. For example, spatial visualization (Table 1.2, left upper quadrant), was described by Linn and Peterson (1985) using the same term, and was defined as a multi-step manipulation of spatially presented information that was specific to static object intrinsic features such as colour, shape, and size. In the literature, tests that measure spatial visualization may involve *disembedding* an object from distracting environmental information (Newcombe & Shipley, 2015), identifying or revealing a hidden object by its features, or completing an object by determining features that may be unclear or missing for some reason (McGee, 1979a; Carroll, 1993; Smith, 1964; Vernon, 1965). Spatial visualization primarily involves attending to the “what” visual information covered by intrinsic features to discover an object in a scene (e.g., finding a friend on a crowded train) or to create an accurate mental representation of the object (e.g., recognizing a friend by height or hair colour; Makovski, 2017).

Table 1.2: *A Typology of Spatial Processes by Object Feature and Motion*

Object Motion	Object Features	
	Intrinsic	Extrinsic
Static	Spatial Visualization	Spatial Perception
Dynamic	Mental Rotation	Spatial Orientation*

Note: Spatial orientation was not included in meta-analyses by Linn and Petersen or Voyer et al. (1995). Uttal et al. (2013) did not label the extrinsic-dynamic quadrant as *spatial orientation* either, thus, spatial orientation is my own term for this type of spatial process.

Spatial perception pertains to the attention paid to stationary object features in relation to an external referent (Table 1.2, top right quadrant). Tests measuring this spatial type involve comprehending the position and location of an object (Chan, Baumann, Bellgrove, & Mattingley, 2012). According to the typology, this spatial type involves consideration of external, environmental forces to determine an object's position and location (Carlson-Radvansky & Irwin, 1993; Robert & Harel, 1996). Environmental features as well as those of the object are held stationary in reality or in imagination to comprehend the locative relations between them. The viewer forms a spatial perception by attending to the “where” visual information based solely on its intrinsic features (Chatterjee, 2008). For example, tasks involving stationary pendulums and liquids for

example that are vertically and horizontally invariant fall into this quadrant of the typology. Their resting position or location is not dependent on the resting angle of the structures that support or contain them (Pulos, 1997; Robert & Harel, 1996).

Tests of mental rotation (Table 1.2, bottom left quadrant) measure the spatial reasoning due to focused attention on intrinsic motion displayed or imagined by an object without regard to an external referent. The typology implies that viewers develop a mental representation of an object to track the manner of motion of its intrinsic features through an imagined trajectory. Motion may occur on one, two, or all three of the object's feature axes. Attention is focused exclusively on the imagined motion of the object's intrinsic features and is not connected to any external referent.

Spatial orientation describes the processing that occurs when viewers pay attention to extrinsic features acting on an object in motion (Table 1.2, bottom right quadrant). Spatial orientation tasks were not included in Linn and Petersen's typology. Chatterjee (2008) indicated semantics describing an object's path of motion was expressed when attention is paid specifically to the sequential change in position of an object relative to other objects. The imagined or actual path of motion of the object must be considered to resolve tests of spatial orientation. Such reasoning implies the need for a three-dimensional, global perspective of the object relative to other objects along its path of motion (Kessler & Thomson, 2010). Maps, for example, provide a two-dimensional representation of the spatial relationships among objects from a global perspective that can be used to describe, explain, or predict a path between any object depicted (Harrell,

Bowlby, & Hall-Hoffarth, 2000; Kessler & Thomson, 2010; Meneghetti, Labate, Pazzaglia, Hamilton, & Gyselinck, 2017).

The spatial relationships depicted on a map guide one's actual pathway through three-dimensional space by orienting progress relative to landmarks along the way. A person could construct a mental map when given directions on how to proceed to a designation (Meneghetti, Pazzaglia, & De Beni, 2015; Sanchez & Wiley, 2017). An *egocentric* perspective of spatial orientation occurs when an object is viewed from the observer's current location. Alternatively, observers use an *allocentric* perspective when an object is imagined from the viewpoint of another object. Extrinsic features are integral to recognizing objects as they proceed along their pathways; extrinsic features provide reference points to track an object's movement when an egocentric perspective is involved. The projection of oneself to the location of another object to imagine a perspective of a third object signifies the figurative, dynamic movement in *allocentric* spatial orientation. The path of motion in either perspective is determined by transforming actual or imagined visual information to reposition an array of objects from the required global viewpoint.

Spatial orientation involves a complex transformation and integration of visual or imagined information to resolve the path of motion relative to multiple external referents, according to the Uttal et al. (2013) application of the Chatterjee (2008) framework. Uttal et al. (2013) do not specifically label the lower right quadrant of their typology as *spatial orientation*. However, the literature does provide some indication that spatial tasks requiring attention to an object in motion in relation to external referents may be labeled

as *spatial orientation* (Barton et al., 2014; Bosco, Longoni, & Vecchi, 2004; Coluccia & Louse, 2004; Lackner & DiZio, 2005; Kozhevnikov & Hegarty, 2001; Lohman, 1988; Sanchez & Wiley, 2017; Yu & Zacks, 2017).

Spatial Thought, Language and Task Performance

Verbal and spatial ability are highly correlated (Gabrieli & Norton, 2012; Hyde & Linn, 1988; Lohman, 1996; Wai, Lubinski, & Benbow, 2009). It is reasonable to suggest that expression of thought on spatial relations through language is indicative of the cognitive processes used to process visual information. By applying the Chatterjee (2008) framework to spatial categories, Uttal et al. (2013) provided a theoretical and evidential basis for distinct spatial types that were previously and arbitrarily labeled as *spatial perception*, *mental rotation*, and *spatial visualization* by Hyde (1981) and Linn and Petersen (1985). The Chatterjee (2008) framework and its utility for categorizing spatial tests by focused attention on objects' intrinsic or extrinsic features and by objects' static or dynamic motion, heeded the calls made by French (1951) and by Voyer et al. (1995) to operationally define spatial categories by grouping spatial tests that measure common components. The rationale for types of spatial reasoning had been muddled by a lack of consensus on the structure of spatial tasks – since the 1930s, over 150 spatial factors were identified and measured by a plethora of spatial tests (Carroll, 1993; Eliot, 1980; McGee, 1979a; Mirman, Landrigan, & Britt, 2017; see Yilmaz, 2017 for review). Accordingly, in this dissertation I tested the spatial typology proposed by Uttal et al. (2013). The paper describing the typology has been cited over 750 times (scholar.google.ca) and thus it is

important to determine whether there is empirical support for this model of spatial abilities.

No discussion of spatial abilities is complete without considering gender differences. On many different spatial measures, men perform better than women (Voyer et al., 1995). However, Hyde (1981) questioned the commonly accepted findings of substantial gender differences in verbal, quantitative, and visual-spatial abilities. For example, Hyde noted the effect sizes for the differences between males and females were moderate, such that $d = .24$, $.43$, and $.45$, for verbal, qualitative, and spatial abilities, respectively. Researchers since Hyde have provided further insight into gender differences in spatial processing (Caplan, MacPherson, & Tobin, 1985; Halpern, 2000; Linn & Petersen, 1985; Reilly & Neumann, 2013; Voyer, Voyer, & Bryden, 1995; Uttal et al., 2013). In my analyses, I consider the question of whether the 2x2 spatial typology proposed by Uttal et al. (2013) applies similarly to men and women.

Visual Search

In this dissertation, a visual search measure was developed to simulate a complex, real-world task that was expected to involve spatial processing. Thus, for the present purposes, visual search is assumed to require an active scan of the visual environment for a particular object, commonly referred to as the target, or for the features of a target among distractor objects and their features (Donnelly, Cave, Greenway, Hadwin, Stevenson, & Sonuga-Barke, 2007; Eckstein, 2011; Wolfe, 1998). Although there are many visual search paradigms in the experimental literature, I wanted to use a task that had some face validity as a task relevant for military personnel.

In general, spatial reasoning is likely required to complete visual search tasks (Eimer, 2014; Feng, Spence, & Pratt, 2007). Searchers need to focus on objects and their features as they visually scan the environment (Horowitz, 2017; McLeod, Driver, & Crisp, 1988; Wolfe, 1994; 1998). Searchers may rely on mental representations of objects and/or mental manipulations of those objects in order to recognize a target amongst distractors (Ecker, Maybery, & Zimmer, 2013; Eckstein, 2011; Weber, 2015; Wolfe & Horowitz, 2017). Accordingly, if this view of spatial reasoning involves searchers recognizing objects by their features and manipulating objects by imagining some motion, then spatial reasoning should explain some of the individual differences in visual search performance (Kim & Cave, 1995; Liu & Schunn, 2016; Wolfe, 1998).

Furthermore, the relations between spatial reasoning and visual search will be attenuated by the complexity of the target, its distractors, and scene complexity (Aydemir, Pronobis, Göbelbecker, & Jensfelt, 2013; Ericsson, 2014; Ericsson & Pool, 2016; Geng & Behrmann, 2005; Wolfe & Horowitz, 2017).

In general, we might expect that spatial abilities will predict performance on any task that involves spatial processing; visual search is simply an example of a task that seems very likely to require spatial processes. We might also expect that specific aspects of spatial reasoning enable individuals involved in disciplines such as geology and engineering to advance the theoretical and applied research of those disciplines. Spatial reasoning is generally higher for STEM students than for non-STEM students (Baenninger & Newcombe, 1995; Else-Quest et al., 2010; Wai, Lubinski, & Benbow, 2009), particularly on complex tasks (Lubinski, 2010; Nagy-Kondor, 2017; Shipley et al., 2013;

Uttal & Cohen, 2012). Predicting which spatial abilities will be most important for a given discipline is only possible if researchers analyze the details of the spatial processes required in these disciplines. Thus, although researchers might agree that visual search by these and other scientists is aided by the specific ways they process visual information to make sense of space, there is no consensus on the set of specific types of spatial reasoning required in any one occupation or in any particular spatial task. Notably, individuals' spatial processes improve with consistent training and practice (Ackerman, 1988; 1992; Ericsson & Pool, 2016; Guznov, Matthews, Warm, & Pfahler, 2017; Kass, Ahlers, & Dugger, 1998; Meneghetti, Cardillo, Mammarella, Caviola, & Borella, 2017; Müller & Krummenacher, 2006; Song & Nakayama, 2008).

Spatial reasoning and visual search are critical aspects of certain jobs.

Radiologists demonstrate expertise in spatial reasoning and visual search in the detection of anomalies in various anatomical structures like the brain, lung, and breast (Krupinski, 2010; Nakashima, Kobayashi, Maeda, Yoshikawa, & Yokosawa, 2013; Torralba, Oliva, Castelhana, & Henderson, 2006). Similarly, visual search performed by aircraft technicians who check for airframe cracks and other indicators of metal fatigue before certifying an aircraft's airworthiness and ensuring the flight safety of aircrew and passengers may reduce to specific types of spatial reasoning. Scrutiny of airport luggage (Meuter & Lacherez, 2016) and satellite surveillance imagery by trained personnel for possible threats to national security or safety appears to also involve highly-developed spatial reasoning gained through years of training and work experience to support the primary task of visual search in their jobs (Guznov, Matthews, Warm, & Pfahler, 2017;

Saad, Muda, Ashaari, & Hamid, 2015). Accordingly, individual differences in spatial abilities should be related to performance on complex tasks that require visual and spatial processing.

In visual search, complex tasks are likely to involve greater processing time to visualize, rotate, perceive, and orient objects as either distractors or the target (Eckstein, 2011; Eriksen & Schultz, 1979; Plumert & Spencer, 2007). The type of spatial reasoning required to complete complex visual search is also likely to depend on the object features and motion required. Even so, only certain types of spatial reasoning may be necessary to resolve a visual search. Individual differences in the spatial types framed by the underlying dimensions of the typology proposed by Uttal et al. (2013) may predict visual search if it requires viewers to process the interaction of one of two types of object features and motion that are necessary to recognize a target among distractors. The 2x2 typology posits that object features and motion are processed to form a mental representation, with one of four types of spatial reasoning coming to the fore when attention is paid to either one of an object's primary features and either end of the range of its motion.

The visual search task set created for this study was designed to include all four spatial types contained in the typology. Many objects were included in a set of scenes depicting vehicles parked or travelling around on city streets. These scenes set the conditions for the plausible activation of spatial visualization (intrinsic-static), mental rotation (intrinsic-dynamic), spatial perception (extrinsic-static), and spatial orientation (extrinsic-dynamic) reasoning. Conversely, the set of visual search tasks were not created

to induce any one spatial type contained in the typology. Given goodness of fit in the study's measurement model of spatial types implied by the typology, then indicators of visual search would be regressed on to the four spatial types, with the expectation that one or more spatial types would predict visual search task performance.

Overview of the Dissertation

The goals of the present research were to (a) evaluate the structure of the typology as proposed by Uttal et al. (2013) for adults and (b) investigate the four spatial types as predictors of visual search performance. Currently, only one published paper (that I know of) evaluated the 2x2 typology (Mix et al., 2018) and the participants in that paper were children. To evaluate the 2 x 2 typology in the present research, people performed 14 spatial tasks expected to indicate one of the four spatial types identified by the typology. I analyzed their performance on these tasks with a confirmatory factor analysis (CFA) to test whether a structural equation model implied by the typology captured the expected variability across the 14 spatial tests. Latent cognitive variables representing spatial visualization, spatial perception, mental rotation, and spatial orientation were then generated for each participant based on the CFA. These latent spatial variables were used to predict performance on a set of visual search tasks hypothesized to involve relevant spatial processing. An outline of the remaining chapters in this dissertation is provided below.

Chapter 2 provides a literature review of spatial reasoning and visual search. Early spatial research is presented to rationalize the object-centric focus of the typology and its application in visual search task performance. Factor and meta-analytical findings

on spatial processes that were reported over the years are briefly summarized leading to the more recent typologies proposed by Linn and Petersen (1985) and Voyer et al. (1995). The findings of these two key studies are discussed pertaining to the literature on psychometric, neuropsychological, cognitive, and differential perspectives on spatial reasoning processes and visual search.

Chapter 3 presents the methods, instruments, and procedure used to collect spatial test and visual search task data, resulting in a final sample of 304 undergraduate students.

Chapter 4 discusses the statistical criteria commonly used in structural equation modelling to demonstrate normality, reliability, and ultimately implied model fit with observed data. Measures of normality, reliability, and goodness of model fit are presented, along with theoretical and applied research findings to support their use in this study.

Chapter 5 presents the descriptive statistics and reliability, confirmatory and exploratory factor analyses, and regression modelling conducted to address the theoretical and practical utility of the typology and the statistical model of visual search. The statistics used to determine the fit between each implied model and the observed data collected in this study are also presented in Chapter 5.

The theoretical and practical implications of the current research are discussed in Chapter 6. This dissertation is unique in that it seeks to evaluate whether the four spatial types specified by the typology account for individual differences in spatial processes and predict individual differences in visual search among adults (cf. Mix et al., 2018).

Evaluation of the typology and its utility in explaining individual differences in visual

search support research on the theory, structure, and application of spatial reasoning in visual search performance.

Chapter 2: Literature Review

Overview

This synopsis provides an overview of the current knowledge base pertaining to individual differences in spatial reasoning and visual search task performance. Spatial reasoning is used throughout the chapter to connote a cognitive process specific to thinking about space in a logical, sensible way. Such reasoning reflects a distinct spatial ability, demonstrated by a specific cognitive skillset that frames contextual cues about a specific space. Like any skillset, spatial skills develop through training, practice, and experience (Hoyer & Ingolfsson, 2003; Kass et al., 1998). I use the term visual search to refer to a type of perceptual task requiring attention to actively scan to recognize the presence or absence of a particular object among others within a confined space. The literature offers common ground between spatial reasoning and visual search in that both psychological constructs are specific to objects. The goal of visual search is to determine whether an object is present or absent in a defined space. Spatial reasoning involves the gathering of visual input from a defined space to allow the searcher to construct and manipulate a mental representation of the objects in that space. I posit in this chapter that visual search in turn, is dependent on spatial reasoning to some degree such that an individual's spatial ability will explain variation in visual search.

This literature review serves as a rationale for identifying four spatial types as theoretically framed by two intersecting and primary dimensions of spatial reasoning about *object features* and *object motion*. Although the literature on spatial research has consistently identified these two primary dimensions (Grezes & Decety, 2001; Wurm,

Cramon, & Schubotz, 2012), empirical support for the 2 x 2 typology proposed by Uttal et al. (2013) is sparse. Mix et al. (2018) tested the 2 x 2 model with children in kindergarten, grade 3, and grade 6. However, the four-factor model did not converge for kindergarten and grade 3; only 1 and 2 factor models could be tested for the older children. Thus, the present research was an attempt to test the complete 2 x 2 model, using adults and a full range of tasks specified in the Uttal et al., framework.

In this literature review, findings on gender differences, along with cognitive strategies used to reason about space and complete visual search are also presented. The literature is reviewed to show spatial skills and visual search share a common process dependent on attention paid to a defined space to recognize and manipulate objects based on their features and motion. The literature has long reported that males and females go about solving spatial tasks and visual search in distinct ways. The cognitive strategies and gender differences that shape spatial skills and visual search by gender are also presented and discussed.

Theoretical Basis for a Framework of Spatial Reasoning

Chatterjee (2008) framed a typology of spatial thought and language as sequential behavioral outcomes of a cognitive process focused on thinking about space in a logical, sensible way. Language is a direct expression of thought (Bruner, 1985; Chomsky, 1986; Chomsky, 2006; Goodman & Goodman, 2014; Hauser & Chomsky, 2002; Vygotsky, 1985). Language indicates breadth and depth of knowledge on a particular topic or domain (Alexander & Judy, 1988; Billett, 2001; Carey & Spelke, 1994; Gentner, 2014; Grezes & Decety, 2001; Wai, Lubinski, & Benbow, 2009). Semantics used to convey

spatial thought represent artifacts that stem from reasoning about space (Holmes, 2012; Olson & Bialystok, 2014; Munnich & Landau, 2003).

The typology posits semantics derived from spatial thought and expressed by spatial language as object-oriented, such that spatial reasoning is dependent on attention to specific object features and motion. Spatial thought and language express specifics concerning the nature of knowledge, reality, and the existence of objects (Bloom & Keil, 2001; Fernandino, Binder, Desai, Pendl, Humphries, Gross, Conant, & Seidenberg, 2015; Herskovits, 1997; Smith & Ceusters, 2010). Spatial thought and language convey the fundamental connections between knowledge, reality, and the existence of objects in the context of a defined space (Choi & Bowerman, 1991; Mix, Levine, Cheng, Young, Hambrick, Ping, R., & Konstantopoulos, 2016; Smith & Ceusters, 2010). Recognition of an object involves parsing it from its context by features that are intrinsic or innate to the object and those that are not or extrinsic (Chatterjee, 2010; Herskovits, 1997; Newcombe, Uttal, & Sauter, 2013; Waller, 2014). A classic figure-ground configuration emerges, separating features intrinsic to the object from those that are extrinsic relative to the field of view (Halligan, Fink, Marshall, & Vallar, 2003; Hoffman & Richards, 1984; Johnson, Spencer, & Schöner, 2008; Vecera, Flevaris, & Filapek, 2004).

Objects and reasoning about space.

All that we see is composed of matter; objects represent structures of matter, each with unique intrinsic properties and features. Matter is anything that has mass and takes up space. All objects from a sub-atomic particle to the entire universe represent structures of matter. All matter has energy that is either static - stored within the structure as

potential energy - or kinetic and dynamic, when it is released and conveyed in movement or motion. Chatterjee (2008) proposed that thinking with the intention of expressing thought about space reduced to semantics that described the features and motion related to the matter recognized within a defined space (i.e., an object). Spatial language then expresses thought related to the nature of matter in terms of its features and motion, within a defined space or environmental context (Broad, 2014; Hinze, Williamson, Shultz, Williamson, Deslongchamps, & Rapp, 2013; Jackendoff, 1991).

Parts of parts of wholes.

Under this paradigm, matter contained in an object can be deconstructed into constituent parts to a sub-atomic level. How those constituent parts relate to one another is determined in part by the properties of the matter and energy that is contained within them. The matter contained in an object is also effected by the matter not contained in it, in other objects that are somehow in relation with an object. Individual understanding of the nature of things in the form of objects is conveyed by the semantics used in language that describe the interaction between object intrinsic and extrinsic features and their range of static to dynamic motion (Meneghetti, Pazzaglia, & De Beni, 2015).

The Chatterjee (2008) typology proposed that semantics specific to an *object*, *proper* are conveyed through language conveying attention focused on its intrinsic features while stationary or in static form (Meneghetti et al., 2015). The *manner of an object's motion* is conveyed through language when thought is concentrated on the nature and range of plausible motion inherent in an object's constituent parts. An object's *locative relations* are expressed when the extrinsic features of its environment are

considered while an object is in a static or resting position. Its location is communicated when a stationary object in its environmental context is considered (Carlson-Radvansky & Irwin, 1993; Kessler & Thomson, 2010; Pulos, 1997). The nature of an object's movement is central in the use of semantics and language to describe extrinsic features of objects while one or more objects are in dynamic motion.

Uttal et al. (2013) extrapolated on the Chatterjee (2008) framework by proposing its four spatial types could also convey the spatial reasoning necessary to perform spatial tasks. If spatial language was dependent on thought concentrated on object features and motion, then the same reasoning was necessary to demonstrate understanding of the nature of things through spatial tasks (Baenninger & Newcombe, 1989; Harris, Hirsh-Pasek & Newcombe, 2013; Newcombe, Uttal, & Sauter, 2013; Pruden, Levine, & Huttenlocher, 2011). The literature supports the nexus between spatial thought, language, task performance, and attention to objects (Bateman, 2010; 2013).

Verbal and spatial ability and object frame of reference.

Early research on the distinction between spatial visualizer and object verbalizer demonstrated the association between verbal and spatial ability in reasoning about space (Kirby, Moore, & Shofield, 1988; Paivio, 1971; Richardson, 1977; Riding & Cheema, 1991). Spatial visualizers tend to see the larger picture by focusing on extrinsic features, while object verbalizers tend to focus on specific objects, with less regard for the overall environmental context (Kozhevnikov, Kosslyn, & Shephard, 2005). Group membership found visualizers as more field independent and holistic, with verbalizers as more field dependent and analytical (Kozhevnikov, Hegarty, & Mayer, 2002). Membership in either group depended on spatial and verbal ability and performance on spatial and object imagery tasks. When spatial and verbal ability were placed along a continuum, spatial visualizers tend to have higher spatial ability and object verbalizers higher verbal ability relative to each other (Pitta-Pantazi, Sophocleous, & Christou, 2013). Research on spatial and verbal ability and object frame of reference report that scientists, engineers, mathematicians, and technologists tend to demonstrate higher spatial ability and identify as spatial visualizers than students, artists, and other workers educated in the social scientists and humanities who tend to demonstrate higher verbal ability and identify as object verbalizers (Lubinski, 2010; Uttal & Cohen, 2012; Wai, Lubinski, & Benbow, 2009).

More recently, Blazhenkova and Kozhevnikov (2009) showed that spatial and verbal reasoning were correlated with cognitive styles used to interpret object imagery. Cognitive styles in terms of consistencies and preferences in processing visual versus

verbal information to resolve cognitive tasks have been shown to depend on the type of object imagery provided. Visualizers rely primarily on object imagery, while verbalizers rely primarily on verbal analytical strategies. Object features and motion appear to be instrumental in the cognitive style used by visualizers and verbalizers. Object features and motion further clarified the former bipolar dimension of Visual-Verbal cognitive style proposed by Richardson (1977). A close relation between cognitive style and area of work specialization was reported by Blazhenkova and Kozhevnikov (2009): Scientists tend to demonstrate higher spatial imagery; humanities professionals tend to demonstrate higher verbal ability; and visual artists tend to demonstrate higher object imagery. The verbal ability of scientists did not differ significantly from visual artists. Visual artists and scientists tend to prefer cognitive styles that focus on object imagery or spatial information processing, while humanities professionals rely on semantic analytical or verbal imagery information processing to resolve cognitive tasks (Blazhenkova & Kozhevnikov, 2009).

Measuring spatial task performance.

The Chatterjee (2008) typology theoretically mapped to spatial tests identified by Linn and Petersen (1985) and Carroll (1993; see Table 1 and Appendix 1 in Uttal et al., 2013 for review). Linn and Petersen (1985) meta-analyzed gender differences in spatial reasoning based on samples that completed measures of spatial visualization (i.e., intrinsic-static), spatial perception (extrinsic-static), and mental rotation (intrinsic-dynamic). Linn and Petersen (1985) did not include a measure of extrinsic-dynamic in their meta-analysis. It should also be acknowledge that Linn and Petersen (1985) did not

clearly distinguish *mental rotation* as specific to thought on intrinsic features and dynamic motion. Their analysis indicated some aspects of the nature of objects measured by *spatial visualization* were also necessary to resolve tests meant to measure intrinsic features and dynamic motion of objects.

The Linn and Petersen (1985) study followed a similar study by Hyde (1981) who showed that the magnitude of gender differences in spatial reasoning favouring males was much smaller than previously had been reported by Maccoby and Jacklin (1974) and Sherman (1978). Hyde (1981) reported the effect size by gender in spatial ability was $d = .50$. Similar effect sizes were reported by Uttal et al. (2013) on male ($g = .54$) and female ($g = .53$) improvement with spatial training. Linn and Petersen (1985) reported small gender differences on spatial visualization and spatial perception measures and large gender differences on measures of mental rotation. However, they did not use standard statistics such as Cohen's d (as did Hyde, 1981) or the slightly more conservative Hedge's g (used by Uttal et al., 2013), which corrects for biases due to sample size, to compute effect sizes. Linn and Petersen (1985) used a methodology based on a weighted estimator of effect sizes and did not clearly state the effect size of spatial type by gender (Voyer et al., 1995). Voyer et al. (1995) re-analyzed the data gathered by Linn and Petersen (1985) to show the smallest and largest effect size by spatial type occurred in mental rotation ($d = .56, p < .05$) and spatial visualization ($d = .19, ns$) respectively, with the spatial perception effect size ($d = .44, p < .05$) falling in between. Voyer et al. (1995) re-iterated the difficulty of evaluating the significance of the spatial visualization type, possibly because of its lack of unidimensionality among measures

used. These meta-analyses were focused on gender differences in spatial reasoning without benefit of a system of classifying spatial reasoning by some underlying dimensions (Mirman et al., 2017).

Factor analyses conducted by Carroll (1993) revealed three spatial types. Uttal et al. (2013) placed Carroll's (1993) *visuospatial perceptual speed* along with Linn and Petersen's (1985) *spatial visualization* within the typology's intrinsic-static spatial type. Like Linn and Petersen (1985), Carroll's (1993) *spatial visualization* factor was also placed in the intrinsic-dynamic spatial type, along with measures he labelled *spatial relations/speeded rotation*. Other researchers have commented on the possible overlap between spatial measures of intrinsic-static and intrinsic-dynamic spatial types (Baenninger & Newcombe, 1989; Newcombe & Shipley, 2015). The distinction between *spatial visualization* and *mental rotation* by intrinsic object features and static or dynamic object motion respectively seems tenable but untested to date.

Newcombe and Shipley (2015) for instance frame intrinsic-static thought as *disembedding*, concluding that both spatial visualization and mental rotation processes involved reasoning about object intrinsic features and dynamic motion. Much earlier factor analyses of spatial tests administered to United States Air Force personnel during the Second World War identified two clusters of tests measuring *spatial relations* and *spatial visualization* (Anderson, Fruchter, Manuel, & Worschel, 1954). The *spatial visualization* test cluster required an ability to imagine the rotation of depicted objects, the folding and unfolding of flat patterns, and the relative changes of positions of objects in space, clearly indicating that more than attention to the intrinsic-static dimension of

object recognition and motion was involved (Guilford & Lacey, 1947). Carroll's (1993) factor analyses identified only two intrinsic spatial types. Carroll (1993) did not identify spatial factors that captured spatial reasoning specific to the locative relations between objects, their pathways, or other forms of dynamic motion that may occur in any array of objects; spatial perception and spatial orientation were not identified by Carroll (1993).

Object recognition and object manipulation.

Carroll's (1993) factor analyses were the culmination of a long series of comprehensive studies on spatial factors. Years of research had improved factor analysis, with a number of spatial factor studies seeking to establish a discreet set of latent spatial factors. Early spatial research supported Kelley's (1928) hypothesis that recognition of forms and mental manipulation of shapes were the two critical cognitive processes in working spatial tests (Brown & Stephenson, 1933; Egan, 1977; El Koussy, 1935; see Harle & Towns, 2010 for review; Slater, 1940). For Kelley (1928), spatial reasoning about space spatial reasoning, ability, and skill depended on *object recognition* and *manipulation*. For Kelley (1928), logical thought about space reduced to the cognitive processes involved in recognizing and manipulating objects to determine how they might have appeared in the past, appear in the present, or might appear in the future, given the natural tendency of one object's properties and motion in relation to one other objects. For Kelley (1928), object recognition estimating, predicting, and making judgments about the relationships of objects in different configurations was a natural operation of the mind. Even an intuitive, naive understanding of an object's ontology and physics facilitated recognition of the logical relations between an object's intrinsic and extrinsic

features. An object could be recognized initially by its intrinsic features such as colour, shape, and size to be mentally manipulated in such a way as to recognize it in an alternative position or place, given a reasonable understanding of the object's being or makeup and mechanics in relation to the features inherent in other objects (Eliot & Hauptman, 1981; Slater, 1940; Smith & Ceusters, 2010).

Early spatial research also identified object motion as an important characteristic of spatial reasoning. Performance on entry-level spatial ability tests administered to United States Navy recruits during the Second World War depended on an ability to visualize stationary solid objects and the ability to visualize solid objects moving through space, according to a factor analysis completed by Thurstone and Thurstone (1949). Their factor analysis of 25 individual spatial tests administered to 350 American high school boys identified two spatial factors representing an ability to visualize a rigid configuration when it was moved into different positions and an ability to visualize a configuration when there was movement or displacement among the parts of the configuration (Thurstone & Thurstone, 1949). Eliot and Smith (1983) later suggested recognition and manipulation of the static and dynamic quality of the imagery depicted in spatial test items was a fundamental aspect of spatial reasoning. Object recognition and motion seemed to indicate primary factors measured by spatial tests in the much the same way as *primitives* underlie the phonemes, semantics, and language derived from spatial thought (see Hayward & Tarr, 1995 for review).

Spatial primitives.

A number of researchers have identified a discreet set of essential concepts upon which a range of simple to more complex spatial concepts can be derived. These primitives generally include primitives of identity, location, magnitude, and time that are specific to object recognition and motion (Carlson-Radvansky & Irwin, 1993; Mandler, 2010; 2012). Such a discreet set of primitives is hypothesized to become embedded soon after birth to guide spatial reasoning and language development (Mandler, 2010; Talmy, 2005). Soon after birth, a taxonomy of concepts begins to develop to frame general categories of objects (e.g., animal, vehicle, furniture) by recognition and their motion, with more detailed groupings forming therein as nuances concerning the nature of objects are learned or recognized (Mandler, 2010; 2012).

Kelley's (1928) description of spatial reasoning generally captured the semantics often used by researchers to describe a very discreet set of spatial primitives identified by Hayward and Tarr (1995) and Mandler (2010; 2012). For Kelley (1928), spatial reasoning involved the perception of visual forms and the mental manipulation and reconstruction of visual shapes. His description incorporated a distinction between figurative and operative imagery (Amin & Valsiner, 2014) expressed by Vygotsky (1936) and later by Piaget and Inhelder (1971) described by French (1951) as emphasizing the perception and comparison of spatial patterns and comprehension of imagery movement. Developmental theorists like Piaget and Inhelder (1971) distinguished the mental imagery of children by specifying younger children's *figurative* thinking, which involved the perception of static patterns and the formation of static images, from that of older children's *operative*

thinking, which concerned the perception of pattern in the movement of figures or objects as well as the manipulation of images (Olson, Bialystok, & Liben, 1986). With age came a maturation and complexity in terms of depth and breadth of reasoning about objects, starting with a basic recognition of objects (intrinsic-static) to include their range of motion (intrinsic-dynamic) in relation to a defined space (extrinsic-static) and other objects (extrinsic-dynamic) as indicated by language and spatial task performance.

A discreet set of spatial factors.

Spatial research has long suffered from a lack of nomenclature and taxonomy (see Yilmaz 2017 for review). Its history is marked by various attempts at various times to organize the interrelationships among up to 150 reported spatial skills abilities as measured by spatial tests (Guilford, 1967; 1971; Guttman, 1969; Cattell, 1971; Royce, 1973). Such a catalogue of spatial tests prompted the *Educational Test Service* to offer a range of tests measuring a variety of spatial factors in its *Kit of Cognitive Reference* throughout in the 1960s and 1970s (French, Ekstrom, & Prince, 1963; 1976). Spatial measures were included if their underlying construct was found in at least three factor analyses performed in separate laboratories by different investigators. Both the 1963 (French, Ekstrom, & Prince, 1963) and 1976 editions of the *Kit of Cognitive Reference* were organized by factorially similar tests but not in terms of a hierarchical model or any structure resembling the typology examined in this dissertation.

Likewise, those researchers who considered object recognition and manipulation as instrumental in reasoning about space tended to identify three factors. For instance, French (1953) reviewed the early and military literature on spatial factors and identified

three separate spatial factors namely *spatial visualization*, *spatial perception*, and *spatial orientation*. To him, *spatial visualization* captured an ability to comprehend imaginary movement in three-dimensional space or to manipulate imaginary objects. *Spatial perception* represented an ability to perceive and compare spatial patterns accurately. *Spatial orientation* involved an ability to remain unconfused by spatial patterns presented in varying orientations. Like Thurstone and Thurstone (1949) and French (1953), Michael, Guildord, Frechter, and Zimmerman (1957) identified three spatial factors but in the form of a visualization factor, a kinaesthetic imagery factor (i.e., mental rotation), and in a combined spatial relations (i.e., perception) and orientation factor. McGee (1979a) found there was strong and consistent support for the existence of two distinctive spatial factors namely, *orientation* and *visualization* but cautioned that despite the fact that these two spatial factors are highly correlated with one another, their descriptions by different analysts were frequently overlapping, vague, and even contradictory. Three spatial factors tended to appear in the literature over the course of the first 30 years of spatial research. The distinction between them, depended on the quantity, complexity, and exclusivity of spatial tests administered to participants. Object position rather than its two- or three-dimensional presentation or representation appeared to further distinguished spatial factors from one another (Cattell, 1993; McGee, 1979a).

Lohman (1979) re-analyzed datasets from Thurstone (1938; 1941; 1949), Guilford and Lacey (1947) and Guilford and Hoepfner (1971) in an attempt to identify a discreet set of spatial factors, despite often inconsistent descriptions by different analysts.

Lohman (1979) identified three major spatial factors, along with some minor ones. His

spatial relations factor defined by performance on tasks requiring mental rotation of figures or objects. The *spatial orientation* factor captured ability to imagine how a stimulus array would appear from a different perspective. Lohman's (1979) *spatial orientation* was similar to the latent variable reported by French (1953) and Michael et al. (1957) but he conceded it could be confounded by the possibility of solving the same task by mentally rotating the stimulus instead of re-orienting one's perspective. His *spatial visualization* was complex in that it was identified only by performance on non-speeded tests and two-dimensional surface development tests, in particular. Lohman (1979) also noted that *visualization* only appeared when complicated or more difficult tests were administered than those used to identify either the *spatial relations* or *orientation* factor. The minor spatial factors he identified only appeared when extremely similar items that emphasized visual memory, matching visual stimuli, and speed during left-right discriminations were included in a test battery. Again, Lohman (1979) distinction between major and minor spatial factors echoed the basic factors of spatial ability made by Kelly (1928) as the perception and retention of object form and the mental manipulation of visual shapes. Eliot and Hauptman (1981) suggested that it may be that combinations of operations required for minor spatial factors are necessary but not sufficient to perform well on tests compared to those that load on major spatial factors. These researchers made no mention of whether object features and motion determined object recognition and manipulation on minor spatial factors.

Task difficulty and complexity.

Past research has shown that the cognitive process by which object manipulation and recognition occurs is dependent on the degree of task complexity and difficulty. Zimmerman (1954) showed that perceptual speed decreased as spatial test items became more difficulty and complex by manipulating the degree of rotation from zero of test figures, for example. Successive factor loadings labelled perceptual speed, spatial orientation, and spatial visualization were identified from a single spatial test by Zimmerman (1954) who varied in the number of maneuvers per item the examinee was required to visualize in order to estimate the final position of the airplane. Test item complexity and difficulty could be augmented by presenting figures in two- or three-dimensions to distinguish between spatial factors (Zimmerman, 1954; Lohman, 1979; Yilmaz, 2017). Greater thought was required to manipulate and recognize objects depicted in increasingly difficult and complex spatial items. Fleishman (1957) suggested that spatial tasks essentially measured perceptual speed, with unidimensional factor loadings such as spatial orientation and spatial visualization identified as task item complexity and difficulty increased.

Sole purposed testing.

Past researchers encouraged testing specifically for spatial reasoning as necessary to determine spatial factors. French (1951) commented on the challenge of identifying spatial factors, which was possible only when many spatial tests were administered. Other researchers noted that multiple spatial test administrations facilitated the resolution of issues related to dimensionality, imagery, and the distinction between spatial factors

(Burton & Fogarty, 2003; Eliot & Hauptman, 1981; Lopes, Gamerman, & Salazar, 2011). The literature cautions that it can be difficult to identify spatial factors when testing is not solely concentrated on spatial abilities. French (1951) found it difficult to discriminate between spatial factors when spatial test administration was mixed with other cognitive tests or when too few spatial tests were administered.

These early observations support the use of structural equation modelling to confirm the proposed spatial framework and determine its utility to explain variance in visual search task performance. Measurement and structural models imply the basic structure and association between such latent constructs as those contained in the typology as indicated by observed data collected from multiple measures (Bollen, 2005; Kline, 2015). Structural equation modelling relies on multiple administrations of spatial tests for the purpose of conducting factor analyses to determine test reliability and latent construct dimensionality, with the intent of testing the structure of a model implied by the Chatterjee (2008) framework (Kline, 2015; Schreiber, Nora, Stage, Barlow, & King, 2010). The effect of task complexity and difficulty on unidimensionality was also applied to the visual search tasks designed for this study. I relied on the item difficulty of spatial tests commonly used in research and cited in Appendix 1 of Uttal et al. (2013), expecting that greater perceptual processing time also would be required to resolve the set of complex visual search tasks designed for this study. Goodness of fit between the implied model of spatial types as well as the implied model of visual search and the observed data collected from the measures selected and designed for this study, would permit testing of models that regressed visual search performance on spatial types contained in the

Chatterjee (2008) framework. The resulting fit statistics would indicate whether the theory and structure of the typology should be retained, along with structural regression models of visual search on spatial types.

I turn now to summarize the literature on spatial reasoning from different perspectives related to the importance of object recognition and manipulation in processing visual information. The summary of this information is meant to demonstrate the converging support for the underlying focus of attention in reasoning about space realized early in spatial research and confirmed over time by research on understanding how individuals make sense of any defined space.

A Neurological Basis of Object Recognition and Manipulation

The basic tenets of spatial reasoning implied by the Chatterjee (2008) framework namely, object recognition and manipulation by attending to object features and motion are supported by findings in the neurological literature (Wurm, Cramon, & Schubotz, 2012). Visual recognition of objects is dependent on the activation of specialized neuronal areas distributed throughout the visual system (Bartels & Zeki, 2006; see Table 1 in Blazhenkova & Kozhevnikov, 2009 for a comparison between verbal, object, and spatial processing systems; Felleman & van Essen, 1991; Goodale & Milner, 1991; 1992; Goodale, Westwood, & Milner, 2004; Milner & Goodale, 2006; 2008; 2013). Responses to basic object features and orientations originate in neurons located in the V1 and V2 areas of the brain (Grosz, Shapely, & Hawken, 1993; Milner & Goodale, 2006). Certain object orientations activate inhibitory or excitatory responses when the receptive field properties of V1 neurons are stimulated to recognize objects (Farivar, 2009; Milner &

Goodale, 2006). Structurally, visual information about an object is fed forward to specialized areas in either the ventral and dorsal pathways, which are commonly referred to as the ‘what’ and ‘where’ brain systems, respectively (Atkinson, 2013; de Haan & Cowey, 2011; Milner & Goodale, 2006; Mishkin, Ungerleider, & Macko, 1983; Spreng, Mar, & Kim, 2009).

Visual information concerning an object’s intrinsic features such as colour, texture, and shape is processed via the ventral system’s neuronal pathway (Milner & Goodale, 2006; 2008; 2013; Kozhevnikov, Kosslyn, & Shephard, 2005). Alternatively, extrinsic object features such as momentary location and size relative to a frame of reference are processed by the dorsal system’s neuronal pathway (Goodale & Milner, 1991; 1992; Goodale, Westwood, & Milner, 2004; Kroliczak, McAdam, Quinlan, & Culham, 2008; Newman, Atkinson, & Braddick, 2001). The middle temporal and middle superior temporal lobes process information gathered on object movement (intrinsic-dynamic; mental rotation) and collections of objects (extrinsic-dynamic; spatial orientation) (Gallese, 2000; Goodale & Humphrey, 1998). In various combinations of brain modalities, visual information processing in the inferior temporal lobe, parietal lobe, middle temporal, middle superior temporal lobes, and VI through V4 neurons facilitate spatial visualization, spatial perception, mental rotation, and spatial orientation of mental representations to accomplish tasks such as throwing a ball, operating a vehicle, or finding a ladle in a drawer full of kitchen utensils (Deubel, Schneider, & Paprotta, 1998; Karnath, 1997; Goldstone, de Leeuw, & Landy, 2015; Kosslyn & Koenig, 1995). The human brain is organized to function such that making sense of space occurs

through different modalities and along different pathways to recognize and manipulate objects by their features and motion (Berthoz, 2017; Neubauer & Fink, 2009; Spreng et al., 2009), as outlined by Chatterjee (2008).

Current neurological theory adheres to a two-stream model of visual and auditory processing. The same areas of brain that are involved in visual-spatial processing are also involved in auditory processing as well. The brain's spatial and phonological networks map on to the same processing structure (Hickok & Poeppel, 2000; 2004; Vigneau, Beaucousin, Herve, Duffau, Crivello, Houde, Mazoyer, & Tzourio-Mazoyer, 2006). Verbal and spatial reasoning are supported by the same neurological structures and processes. The spatial network of the ventral system defines object identification and recognition via mental representations, while the phonological network processes phonemes into syllables, and environmental sounds (i.e., language) that are paired with mental representations into auditory objects, producing audio-visual representations (Schwartz, Faseyitan, Kim, & Coslett, 2012; Vigneau et al., 2006). Mental images are paired with sounds to recognize objects in space and in relation to one another. Likewise, specific sounds can evoke mental images. For instance, the sound of dog barking, a car's horn can activate a mental representation in the same way that describing an aircraft's landing, a dog sitting by a tree, or directions from one location to another can assist in thinking about the relation between objects in a defined space (Meneghetti, Labate, Pazzaglia, Hamilton, & Gyselinck, 2017). The Chatterjee (2008) framework generalizes to spatial thought, language, and task performance based on findings from the neurological literature.

Thought, language, and tasks associated with recognizing and manipulating objects originate in the ventral system so that attention on an object's intrinsic features and movement innate to the object are learned and reinforced by thinking, speaking and doing (Indefrey, 2011; Jackendoff, 2012). Further, the spatial network is supported by the dorsal system as it processes an object's location, while mapping auditory sensory representations onto articulatory motor representations based on a system of coordinates between objects, anchored primarily by the viewer point of view (Ben Shalom & Poeppel, 2008; Just & Carpenter, 1985; Chatterjee, 2008; Noordzij, Neggers, Ramsey, & Postma, 2008; Tranel & Kemmerer, 2004). The dorsal system is also responsible for speech repetition in language development (Hickok & Poeppel, 2004). Speech is considered a motor learning activity integral to the sensorimotor functions of the brain's dorsal system (see Hickok & Poeppel, 2007 for review). Sub-lexical tasks involve dorsal processing, with locative and navigational semantics involve neuronal mechanisms located in brain areas along the dorsal system to guide locative and transitory information about objects relative to others in a confined space (Griffiths, Marslen-Wilson, Stamatakis, & Tyler, 2012; Kozhevnikov et al., 2006; Zaehle, Geiser, Alter, Jancke, & Meyer, 2008). The dorsal auditory pathway also supports sensorimotor control and integration to establish the location of stationary objects and those in motion relative to the viewer's viewpoint (Rauschecker, 2011; Watson & Chatterjee, 2011). Hearing also involves dorsal information processing to establish the location and pathway of an object relative to others in a defined space (Rauschecker, 2012; 2018). Certain sounds can help

recognize objects (e.g., a train's whistle, an approaching car, a plane travelling overhead) and establish their location or course of travel.

In summary, past research support the earliest reasoning about space made by Kelley (1928) on object recognition and manipulation. Factor analyses since have identified a discreet set of latent spatial constructs under various labels, with little investigation on the dimensions that define one spatial factor from another. Factors such as spatial relations, spatial perception, spatial visualization, mental rotation, and spatial orientation have been defined and re-defined over the years but appear to fit within one of four quadrants of the Chatterjee (2008) framework in terms of recognizing and manipulating objects as figures on tests or mental representations by their features and motion. Language convey and tasks require attention to object features and motion when space is recognized and manipulated via these spatial processes also adheres to the framework's dimensions and Kelley's (1928) tenets.

I turn now to discuss gender differences in spatial reasoning as research in this area supports the theoretical considerations of the Chatterjee (2008) framework. Lawton and Morrin (1999) reported that spatial abilities are considered among the largest gender differences in all cognitive abilities. Findings related to gender differences in object recognition and manipulation based on object features and motion may substantiate tests of the spatial model implied by the Chatterjee (2008) framework by gender.

Spatial Ability and Gender

It was not until Hyde and Linn (1988) and Voyer et al. (1995) meta-analyzed gender differences in verbal and spatial abilities, respectively that the magnitude in effect

size was accurately reported. Men perform better substantially than women on mental rotation; with a medium effect size for spatial perception, and a small effect size for spatial visualization. Over time, gender differences in verbal abilities favouring girls diminish with age (Hyde & Linn, 1988) whereas gender differences in spatial abilities are evident throughout the lifespan (Linn & Petersen, 1985). Gender differences decrease with spatial training (Uttal et al., 2013).

Gender differences in adolescence decrease when individuals' preferences for work and play require sophisticated spatial skills (Coluccia & Louse, 2004; see Baenninger & Newcombe, 1989 for review; Halpern, 1989; Höffler, 2010; Hoyer & Ingolfssdottir, 2003; Hyde, 2005; Uttal et al., 2013; Wai, Lubinski, & Benbow, 2009). Gender differences in spatial ability were reported by Burt (1949) who identified a practical ability factor, consisting of a spatial and mechanical factor that distinguished males from females around the age of 11, favouring males more distinctly until age 15, and that was most pronounced thereafter by male occupational interests and job requirements. Burt (1949) also distinguished two factors focused on static and dynamic by factor analyzing *spatial relations* data obtained from adolescent males and older engineering apprentices. Eye movement determined the static and dynamic sub-factors of *spatial relations*. Recognition of an object's static relations depended on ability to visualize and perceive intrinsic object features in two as opposed to three dimensions. Object recognition under dynamic motion depended on individual ability to mentally rotate and orient intrinsic features in three dimensional form. A similar structure of *spatial relations* as indicated by static and dynamic sub-factors was also later reported by

El Koussey (1955). Although this area of research did not investigate whether the structure of spatial relations generalized to women, it did lend partial support for a framework of object recognition and manipulation based on object features and motion.

Recognition and Manipulation of Gestalts

Werdelin's (1961) factor analysis and description of spatial abilities confirmed Kelly's (1928) distinction between recognition and manipulation of objects and sparked research through the 1970s and 1990s on spatial task performance and gender differences (Buffrey & Gray, 1973; Harris, 1978; Horowitz, 1981; Linn & Petersen, 1985; McGee, 1979b; Potegal, 1982; Vandenberg, 1975; Voyer et al., 1995; Wittig & Peterson, 1979). Thurstone's (1938) analysis of 23 tests to 453 high school students confirmed a two-factor model of spatial ability but from a Gestalt perspective. The first factor was interpreted as an ability to see a whole gestalt and to manipulate it as a whole. The second factor involving an ability to deconstruct a gestalt and manipulate its different parts. Werdelin noted that both spatial factors were highly correlated and consistently identified among male samples. However, only the first spatial factor was identified among female samples (Werdelin, 1961). Gender differences in ability to manipulate visual objects and structures were not significant. However, boys outperformed girls in their ability to comprehend, organize, and re-organize visual structures.

Werdelin's (1961) research provided a unique (Gestalt) perspective on gender differences in spatial reasoning using Thurstone's (1938) spatial factors. One of Thurstone's factor identified an ability to perceive a whole gestalt and to manipulate it as a whole. The second factor involving an ability to deconstruct a gestalt and manipulate its

different parts. Even so, both factors involved an interaction between object features and motion to recognize a gestalt as a whole or by its constituent parts. A gestalt perspective under these conditions does not fit easily into the four quadrants of the Chatterjee (2008) framework. Yet, the study's findings on these spatial types did reveal gender differences when objects were recognized and manipulated as gestalts.

At the same time, research on age-related differences in spatial ability were inspired in large part by Piaget's developmental account of spatial representation. Piaget and Inhelder (1967) proposed that children evolved from a static perceptual space to a dynamic conceptual space, as they discovered their own point of view. By age nine and older, children developed an ability to maintain the relative position of parts of a figure, of figures relative to one another, and of whole configurations relative to different points of view (Gersmehl & Gersmehl, 2007; Olson et al., 1986). Piaget and Inhelder (1967) emphasized that the achievement of this cognitive development depended upon children having repeated experiences with task requiring static perceptual space. In summary, developmental psychology also recognized the importance of spatial reasoning in child development. Developmental theory in the 1960s made a point of proposing possible dimensions related to object recognition and manipulation. Developmental psychology also recognized the early onset of gender differences in spatial reasoning, which were incorporated into theory and research on child development.

Biological Basis for Gender Differences

Developmental differences that occur at the hormonal levels also affect the development of verbal and spatial ability in females and males. Neurological studies

show that a strong left-hemisphere-dominant cerebral pattern for language has a negative influence on spatial ability development (Annett, 1992; Chatterjee, 2001; Hellige, 1990). Accordingly, the restricted development of spatial ability in females is generally attributed to early development of their left-hemisphere language abilities (Flöel, Buyx, Breitenstein, Lohmann, & Knecht, 2005; Vigneau, Beaucousin, Herve, Duffau, Crivello, Houde, Mazoyer, & Tzourio-Mazoyer, 2006; Vogel, Bowers, & Vogel, 2003). This neural difference may account for the finding that females tend to favour verbal strategies to solve spatial problems (McGee, 1979b; Witelson, 1976).

Environmental context for gender differences.

Experience and learning also account for variation in individual differences in spatial ability (Gaulin & Hoffman, 1988). In a meta-analysis, Baenninger and Newcombe (1989) reported positive correlations between spatial test performance and participation in various spatial activities, such as (a) sports (Alves, Voss, Boot, Deslandes, Cossich, Inacio Salles, & Kramer, 2013; Devlin, 2004; Fajen & Phillips, 2013; Memmert, 2009; Voss, Kramer, Basak, Prakash, & Roberts, 2010), (b) occupations (Lubinski, 2010; Wai, Lubinski, & Benbow, 2009), (c) dance (Bläsing & Schack, 2012), and (d) musical fields (Moreno, 2009; Wong & Gauthier, 2012). Lawton and Morrin (1999) reported that males accumulate more experience in activities that enhance spatial skills development relative to females. Early in childhood, males tend to play games with high spatial components, like exploratory games, team sports, play fighting (Beatty, 1984), LEGO-construction (Brosnan, 1988; Baenninger & Newcombe, 1989; Goldberg & Lewis, 1969) and video games (Barnett et al., 1997; Quaiser-Pohl, Geiser, & Lehmann, 2006; Subrahmanyam &

Greenfield, 1994). Such activities may expose males to more spatial experiences than females (Hoyer & Ingolfsson, 2003). Other researchers have suggested that gender differences in spatial reasoning may also be related to the frequency with which boys are allowed to explore new environments relative to girls (Iachini, Ruotolo, & Ruggiero, 2009; Lawton, 1994; Momsen, 2009; Webley, 1981).

Biology and environment interactions and gender differences.

Biological and environmental factors may interact to influence the spatial abilities demonstrated by males and females. Individual experience and natural predispositions may account for the gender differences displayed in spatial abilities. For example, biological factors may direct males and females towards particular activities (Baenninger & Newcombe, 1995; Voyer, Nolan, & Voyer, 2000). Gender differences in spatial visualization (Burnett, Lane, & Dratt, 1979; Höffler, 2010), spatial perception (Jahoda, 1980; Robert & Harel, 1996; Vasta, Knott, & Gaze, 1996; Vasta & Liben, 1996), mental rotation (Casey & Brabeck, 1990; Collins & Kimura, 1997; Devlin, 2004; Vandenberg & Kuse, 1978), and spatial orientation (Linn & Petersen, 1985; Yılmaz, 2017) may support the *bent twig* theory in which activity choice is influenced by predispositions innate to males and females (Casey & Brabeck, 1990; Casey, 1996). Accordingly, males may be more actively search for and time spent in high-spatial experiences compared to females (Su, Rounds, & Armstrong, 2009). Such interest and involvement in spatial activities, in turn, speeds the development of spatial abilities, thereby widening the gap between males and females in spatial reasoning.

Section Summary

The literature supports a framework of spatial reasoning based on object features and motion. Reasoning about space involves cognitive processes that facilitate object recognition and manipulation by imagining objects by their intrinsic or extrinsic features in either a static or dynamic state. Factor analyses since the late 1930s and meta-analyses since the early 1980s have identified a discrete set of spatial factors under an assortment of labels that theoretically fit within the quadrants of a recently proposed spatial typology framed by object features and motion. Meta-analyses since the early 1980s have confirmed three spatial factors and that there are gender differences in spatial reasoning favouring men. Neurological, biological, and environmental research on spatial reasoning have enhanced the scientific understanding of gender differences in spatial reasoning (Deary, Penke, & Johnson, 2010), while supporting the typology and its tenets of object recognition and manipulation by object features and motion. These findings demonstrate theoretical support for the typology. I turn now to review the literature on visual search as one criterion for evaluating the typology and its four spatial factors.

Visual Search

In this thesis, I use the term **visual search** to refer to a type of perceptual task requiring attention that typically involves an active scan of the visual environment for a particular object among other objects (Quinlan, 2003; Treisman & Gelade 1980; Wolfe, 1994). Visual search is a primary purpose of vision (Biederman & Ju, 1988; Mann, Williams, Ward, & Janelle, 2007; Muggleton, Juan, Cowey, & Walsh, 2003). The visual search literature is extensive, so much so that common categories of visual search tasks

are frequently discussed (Duncan & Humphreys, 1989; Wolfe, 1998). The basic physiology of visual search is well-documented (Duncan, Ward, & Shapiro, 1994; Nothdurft, 1993; Treisman & Gormican, 1988) but how individuals efficiently perform visual search remains elusive in that the science of visual search still cannot fully explain how people find needles in haystacks or friends in a crowd (Andersen, Fuchs, & Müller, 2011; Rabbit, 2017). The general principles of visual search are contained in two complementary theories, which I discuss below.

The basic principles of visual search.

Feature integration theory and more recently guided search have guided research in visual attention since the early 1980s (Quinlan, 2003; Treisman, 2016; Treisman & Gelade, 1980; Wolfe, 1994; 2014). Treisman and Gelade (1980) proposed a feature integration theory suggesting that visual information is perceived in terms of features that are processed early, automatically, and in parallel during a pre-attentional stage to recognize separate and unique objects at a later, attentional state of processing. Wolfe (1994) later proposed that certain intrinsic object features guided visual search. Recognition of object features is central in both theories. Both theories present a two-stage process of visual search, initiated by an unconscious or pre-attentional phase and a conscious or attentional phase. Feature integration theory claims visual cues concerning object features and motion are processed in parallel (De Brigard & Prinz, 2010; Desimone & Duncan, 1995; Huang & Pashler, 2005; Kruijne & Meeter, 2015; Posner & Rothbart, 2009; Theeuwes, 2018), concurrently during the pre-attentional and attentional phases and slowed only to a serial process as visual cues as the search is perceived as

more complex (Quinlan, 2003). Guided search is distinguished from feature integration theory in that the pre-attentive stage processes massive information about object intrinsic features and motion across large portions of the visual field to guide a subsequent limited-capacity stage during more complex operations like object recognition over more limited portions of the visual field (Wolfe, 2014). The spatial deployment of the limited-capacity process is thought to be under attentional control. The output of the initial parallel processes during the environmental scan guides attentional deployment of limited resources to resolve visual search (Oliva & Torralba, 2007; Riesenhuber & Poggio, 2000; Uijlings, Van De Sande, Gevers, & Smeulders, 2013). Serial processing does not occur theoretically during guided visual search (Quinlan, 2003; Wolfe, 2014). Nevertheless, resolution of visual search is dependent on object recognition by processing visual cues specific to object features and motion.

Under these paradigms, a typical visual search experiment presents an observer with a display containing a number of items. On each trial, the observer is asked to determine if a specific *target* item is present among a group of *distractor* items or absent. The number of items, known as the *set size* varies by trial. Reaction time is measured by the amount of time that is required to recognize whether a target is present or absent. Accuracy of response is also recorded as correctly identifying a target as present or absent when the test item is displayed. Results from such visual search trials show that changes in accuracy and reaction time are a function of set size (Duncan & Humphreys, 1989; Eckstein, 2011; Horowitz & Wolfe, 1998; Wolfe, 1994; 2014; Yantis & Jonides, 1984).

Ease of search is also a function of reaction times and set size (Liesefeld, Moran, Usher, Müller, & Zehetleitner, 2016; Logan, 2005; Ma, Navalpakkam, Beck, Van Den Berg, & Pouget 2011; Marti, Bayet, & Dehaene, 2015; Torralba, Oliva, Castelhana, & Henderson, 2006). Target-present and target-absent slopes are strongly and positively correlated, explaining 78.5 percent of variation in individual differences (Hommel, Li, & Li, 2004; Wolfe, 1998). The same process of evaluating target features with those of distractors under feature integration theory also guides attention to determine the presence or absence of a target in the search field. According to Wolfe (1998), visual attention allocation explained substantial differences in target-present and target-absent detection slopes. Comparison of target and distractor intrinsic features is a primary predictor of visual search outcome (Horowitz, Klieger, Fencsik, Yang, Alvarez, & Wolfe, 2007; Wolfe, 1998; 2017).

Types of visual search tasks.

Three types of visual search tasks are typically discussed in the literature. Target feature trials focus participants' attention on a single intrinsic feature such as orientation or colour. Conjunctive search trials measure visual attention to two different target features such as colour and orientation, for instance or curvature and size. Finally, spatial configuration visual search trials defined the target by the spatial arrangement of line segments rather than by any single or conjunction of its intrinsic feature properties. On their own, intrinsic features are conspicuous but become cryptic and harder to detect when bound with others to form conjunctions or involve motion. Such conjunctions

increase search complexity to a level where greater attentional focus and processing time is required to recognize a target's spatial configuration among distractors.

Difference search tasks produce different patterns of results (Godwin, Menneer, Riggs, Cave, & Donnelly, 2015; Kiss, Grubert, Petersen, & Eimer, 2012; Memmert, Simons, & Grimme, 2009). Counter-intuitively, task complexity is negatively correlated with visual search failure (Wolfe, 1998). Wolfe's (1998) analysis of the three most studied categories of visual search showed that subjects terminated unsuccessful feature searches more readily than unsuccessful conjunction searches and unsuccessful conjunction searches more readily than unsuccessful spatial-configuration searches. The extant literature reports more visual attention is required for spatial configuration than conjunctive or feature tasks given set size to recognize a target as present or absent among distractors (Hommel, Li, & Li, 2004). Visual search success may be unconsciously related to detecting the presence of targets. Detection of the absence of targets may be perceived as an inability to resolve a visual search, particularly when detection is dependent on single feature discrimination (Fleck & Mitroff, 2007; Todd & Kramer, 1994; Wolfe, Horowitz, Van Wert, Kenner, Place, & Kibbi, 2007). The complexity involved in resolving spatial configuration and conjunctive searches may require greater attentional focus and slower, more methodical (serial) processing of target and distractor features, relative to feature searches.

Task complexity.

Task complexity prolongs visual search, with mixed results concerning trial error rates (Molloy & Parasuraman, 1996; Wolfe, 2010). Laboratory search trials to detect

complex shapes (Kirchner & Thorpe, 2006) and facial matching (Crouzet, Kirchner & Thorpe, 2010) result in higher visual search success and greater efficiency compared to feature trials containing simple content such as Ts and Ls (Wolfe, 1998). Search complexity increases reaction time but not to the benefit of higher success rate in correctly identifying the search target. Differences in search termination are not due to a speed-accuracy trade-off, since the opposite outcome is commonly reported where error rates tend to be highest for feature searches and lowest for spatial-configuration searches (Chittka, Skorupski, & Raine, 2009; Humphreys, Quinlan, & Riddoch, 1989; see Ruskin & Kaye, 1990 for review; Pylyshyn & Storm, 1988; Rensink, 2000; Thornton & Gilden, 2007). Search complexity further increases when the spatial configuration of the search target and scene is required compared to search trials where attention can be focused on a conjunction of features or a specific feature of the target. Broadening the search field increases the array of objects that must be recognized as either a target or distractor, further prolongs the search time due to the need to detect unique object features and conjunctions within a more complex spatial configuration. Response times tend not to vary with target-prevalence (Wolfe, 1998). Laboratory and field studies show that error rates increase with target-absent trials prevalence (Godwin, Walenchok, Houpt, Hout, & Goldinger, 2015; Wolfe & Van Wert, 2010). Research participants, sonar and radar operators, baggage handlers, airport security personnel, and x-ray technicians alike typically complete successful visual searches when at least half of trials include target-present tasks (Eckstein, 2011; Horowitz, 2017).

A common perceptual system.

Horowitz (2017) shows that, despite large variations in the complexity of the stimuli and the expertise of the observers, the primary effect of target prevalence is to shift response criterion. Under low target prevalence conditions, observers become more conservative, so that miss rates go up and false alarms go down. As target prevalence rises, criterion becomes more liberal, with fewer misses and more false alarms. Across cognitive and medical studies, target detectability remains roughly constant, regardless of respondent's education, occupation status, training, or skill. The larger message is that highly controlled studies with naïve observers in cognitive psychology laboratories uncovered the same mechanisms that operated in the radiology or pathology clinic. Radiologists, cytologists, pathologists, and nuclear medicine physicians face incredible challenges to help detect and diagnose diseases. They face these challenges armed with years of training and experience but rely on a common human perceptual system as undergraduate research participants.

Hypotheses.

Visual search is a perceptual task supported in part by spatial reasoning to recognize targets by their unique intrinsic features and motion among a set of distractors. The pre-attentive environmental scan prepares a mental representation in the form of cognitive maps layered (Quinlan, 2003) by as much visual information as possible on the intrinsic features of each object's topology to detect the presence or absence of a target during the attentional phase of guided search. Object motion is also mentioned in the visual search literature as a primary feature (Wolfe, 1994; Wolfe & Horowitz, 2017).

However, intrinsic features such as colour, shape, and size are much more prominent search criteria.

Spatial visualization and mental rotation.

Based on the literature described above, I expected that spatial visualization and mental rotation will predict visual search performance in this study. According to the Chatterjee (2008) framework, these two spatial types involve reasoning about intrinsic features of objects. However, the visual search task involved in this study occurred under static conditions in that targets and distractors are stationary within each trial set (Quinlan, 2003; Wolfe & Horowitz, 2017). Therefore, individual differences in spatial visualization, which is linked to processing of the static intrinsic features of objects, may be more strongly related to visual search than individual differences in mental rotation, which according to the framework, involves reasoning about object intrinsic features and their manner of movement.

Spatial perception.

Further, spatial perception may also predict visual search performance. Spatial perception occurs when the static features of other objects are considered to determine the relative position or location of the target object. Visual search involves recognizing a target among its distractors by its distinguishing features. Feature comparison is essential as is determining the location of a target in visual search. Confirming the presence or absence of a target among its distractors resolves the visual search task. Locating the target among distractors will be necessary to resolve the visual search tasks in this study.

For these reasons, spatial perception may be related to performance of the visual search task in this study.

Spatial orientation.

The visual search literature does not report on findings related to spatial orientation as defined by the Chatterjee (2008) framework (i.e., recognition of targets as they move or transit along a pathway, using the position of other objects as extrinsic features as waypoints to define the pathway). The pathway that a particular target may have taken among distractors is not relevant to the resolution of visual search tasks by type. Perspective-taking as well does not appear relevant in the visual search literature. However, dynamic movement and alternate perspectives are features included in the visual search task used in the present study. For participants to comprehend the driver's perspective in the target vehicle, they may need to consider its location relative to extrinsic features along its pathway. Thus, individual differences in spatial orientation are expected to predict visual search performance in this study.

Gender differences.

Research on visual search supports a U-shaped, reaction time curve related to visual search for both men and women (Dye & Bavelier, 2010; Lobaugh, Cole, & Rovet, 1998; Plude, Enns, & Brodeur, 1994; Scialfa, Jenkins, Hamaluk, & Skaloud, 2000). Search practice gained by playing action video games (Feng, Spence, & Pratt, 2007; Quaiser-Pohl, Geiser, & Lehmann, 2006), fast-action sports, and driving (Silverman, 2006) has been shown to benefit both men and women (Kass et al., 1998). The visual search performance of young adults therefore, likely varies by the spatial skills they use

and develop in support of their daily activities and leisure pursuits. However, this study can only hypothesis on the basis of previous findings that men demonstrate higher spatial reasoning than women and twill significantly predict visual search performance by gender.

Reports on visual search performance and reaction time by gender are mixed. Silverman (2006) reported no gender difference in reaction time on visual search tasks. A meta-meta-analysis by Roivainen (2011) showed significant gender differences in processing speed favouring females in alphabet and number recognition, and naming tasks, while males performed better than females on reaction time tests and finger tapping tasks. It is expected that reaction time in response to spatial test items will predict visual search performance by gender in this study. It is expected that the higher spatial reasoning of men as measured by quicker reaction time compared to women will result in higher target recognition during the study's visual search tasks compared to women.

In general, it is hypothesized that males will outperform females on measures of spatial reasoning and visual search in this study. However, it is unlikely the same pattern of spatial reasoning will predict visual search performance for both genders. Linn and Petersen (1985) and Voyer et al. (1995) discussed how males and females applied different cognitive strategies to reason about spatial tasks. Gender differences were small for spatial visualization. Therefore, it is likely that spatial visualization will predict visual search performance equally for both women and men. As previously mentioned, visual search tasks commonly focus on stationary intrinsic features, which is also likely to explain variation in visual search performance by spatial visualization.

The effect size for gender was largest on mental rotation measures, favouring males (Linn & Petersen, 1985; Voyer et al., 1995). The manner of motion is not usually considered in visual search tasks, given the static nature of targets and distractors in lab and field studies. Object motion was involved in the study's visual search tasks. Given that manner of motion is measured by the study's mental rotation tasks and it is involved in the visual search tasks, with consideration of the performance on mental rotation tasks by men compared to women, it is hypothesized that gender differences in mental rotation will predict visual search performance.

Linn and Petersen (1985) reported a medium effect size favouring men on spatial perception. Linn and Petersen (1985) found women used a strategy of correcting for distracting information, which may explain variation in their visual search performance in this study. Men tended to rely on gravitational and kinaesthetic cue to resolve spatial tasks, according to Linn and Petersen (1985). The study's visual search tasks included a significant amount of pertinent but distracting information. Visual search relies on correcting for distracting information to recognize the presence or absence of a target among its distractors. Therefore, the parameter estimate of visual search on spatial perception is likely to be significant if participants use this cognitive strategy to complete visual search and spatial perception tasks in this study. The research literature suggests women use a cognitive strategy of correcting for distracting information more so than men. For this reason, spatial perception is likely to predict the visual search performance women more so than men.

Chapter 3: Method

This chapter describes the methods used to gather spatial test, training and visual search data to confirm the typology and examine its application to explain performance criteria. Participants completed spatial tests and visual search performance activities through a game-like interface designed and hosted on a website. Information regarding the spatial skills of participants was collected via 14 spatial tests (described below in Part I). The web-hosted game (described below in Part II) included a basic, intermediate, and advanced module designed to provide spatial training to participants. The web-hosted game also included a set of ten tasks to measure visual search performance (Part III). The procedure participants followed to complete the study's requirements is then presented at the end of this chapter.

Participants and General Procedure

Participation in the study was announced through an online psychology experiment sign-up system at Carleton University. Participants read a brief description of the purpose and requirements of the study and clicked a link to connect to a website. Completion of the study took participants approximately one hour and 13 minutes. Study participation was voluntary and anonymous. Participants received partial course credit in their introductory cognitive science or psychology classes for participating. The Research Ethics Board of Carleton University approved the study. Statistical analyses were based on the responses of 305 students (199 women; 106 men) who completed the study.

Participants

Participants were recruited from introductory psychology or cognitive science classes and received course credit for agreeing to take part in the study. A total of 1,256 individuals started the study. Participants were excluded from the current analyses if they did not complete any of the 18 study requirements ($n = 757$) or completed between one and 14 of the study requirements ($n = 195$). Application of these exclusion criteria produced a final sample of 304 participants who had completed the 14 spatial tests and the set of visual search tasks (i.e., 24% of the original sample who had agreed to participate). Only six of the 304 participants had also completed the spatial training. The length of the study apparently discouraged people from completing the training module. Accordingly, the spatial training data are not discussed further in this thesis.

Demographic information.

Of the 304 individuals included in the analysis, 64% were women ($n = 195$) and 36% were men ($n = 109$). These frequencies represent typical gender distributions for social science programs. Eighty-six percent of participants ($n = 261$) were undergraduate students enrolled in non-STEM programs (i.e., cognitive science or psychology); the rest ($n = 43$) were enrolled in STEM programs (i.e., physics, chemistry, engineering, biology, industrial design, or mathematics). More of the men were registered in STEM disciplines ($n = 25$; 23%) compared to women ($n = 18$; 9%), $\chi^2(1, N = 304) = 9.72, p = .0018$.

Participants ranged in age from 18 to 29 years, with a mean age of 21.4 years ($SD = 2.5$). In terms of education beyond high school, 12% of participants had completed a previous undergraduate degree ($n = 37$), 8% had completed a college degree ($n = 24$), and

one had completed a Master's degree. Participants indicated which language they spoke most often. English was most often spoken by 86% of the participants ($n = 261$), one participant spoke French most often, and 13.5% of the participants ($n = 41$) regularly spoke a language other than either French or English.

The study was designed to run equivalently on all browsers and operating systems. The internet browser used by participants varied: 53% had used Firefox ($n = 163$), 42% had used Google Chrome ($n = 124$), and 6% had used Safari ($n = 17$). Five participants did not indicate which browser they had used. In terms of the computing equipment, 58% of participants ($n = 175$) had used a personal computer operating on Mac IOS, 41% used Microsoft® Windows ($n = 125$), and 1% used Linux ($n = 4$).

Measures

Part I: Spatial Abilities

In Part I, participants completed 14 spatial tests that are frequently used by researchers to measure spatial skills. The tests were selected as representative measures of one of the four spatial skills identified by Uttal et al. (2013). The 14 spatial tests were designed to be administered in paper-and-pencil form and thus online versions were created for this study.

Participants were allowed to attempt each test once. A timer was displayed on the participant's computer screen, counting down the time limit for each spatial test. However, the computer script attached to the test timer failed to return the participant back to the testing menu once the individual test time limit was reached. Subsequently, participants were allowed unlimited time to attempt each of the questions on each test.

Participants who took longer than the indicated time limit or unusually less time to complete a test were retained along with all other data. Records were only removed from the study data when outliers were identified by score attained compared to the normal distribution.

The timer glitch experienced in this study meant that the test performance is not directly comparable to other uses of these tests where the actual time limits were imposed. The number of test items, reported reliabilities from the study's sample, test time descriptive statistics, and sample distribution by test are presented in Chapter 4 (Results). Each of the spatial ability tests, maximum time allotment, scoring method, and reliability as reported in the literature is described below. Spatial test descriptions are presented by spatial type framed by the typology.

Intrinsic-Static Measures.

The intrinsic-static spatial type (i.e., spatial visualization according to Uttal et al., 2013) was measured with three tests: The Card Rotation Test, Hidden Figures Test, and the Figure Completion Test. These tests are briefly described below.

Card rotation.

The Card Rotation Test (Ekstrom, French, Harman, & Derman, 1976) measures participants' ability to match two-dimensional shapes based on a target figure and a series of alternates using geometrical reflection (i.e., 'flip') or rotation. The test consisted of 14 items. Each item depicted a target shape to the left of a vertical line and eight identical alternate shapes on the right. These alternate shapes had to be rotated and some of the shapes had to be flipped over to match the target shape. Participants check the box below

an optional shape that needed to be rotated; the box below alternate shapes that had to be flipped to match the target shape were not checked. Participants completed as many questions as possible within three minutes. Hughes & Ensor (2009) reported a Cronbach's alpha of .73 for the Card Rotation Test. Items 2, 3, 6, and 8 are the correct responses in the Card Rotation Test sample item from the shown in Figure 3.1.

Figure 3.1: Sample of an item on the Card Rotation test

Hidden figures.

The Hidden Figures Test (Kepner & Neimark, 1984; Witkin, 1971) consisted of 13 test items. Participants were asked to look for a simple figure in a complex drawing. Above each group of questions were five figures, lettered A, B, C, D, and E as shown in Figure 3.2. Below and to the right of the set of lettered figures was a complex drawing. Participants selected one of the five lettered figures contained in the complex drawing in each test item. Each numbered drawing contained only one of the lettered figures. The correct figure in each drawing was similar and in the same position as it appeared in the set of lettered figures. Participants were given five minutes to correctly identify as many

test items by checking the box below the letters A through E directly opposite the complex drawing on each test item. Stankov, Danthiir, Williams, Pallier, Roberts, and Gordon (2006) reported Cronbach's alpha of .80 and Eliot (1980) reported a similar value of .82. Kepner and Niemark (1984) reported reliabilities in the range between .78 and .92. The correct response to the sample item from the Hidden Figures Test shown in Figure 3.2 is 'C'.

Figure 3.2: Hidden Figures Test Item Sample

Figure completion.

The Figure Completion Test (Torrance, 1963) consisted of 17 items. Figure 3.3 depicts a sample item from the Figure Completion Test. Each test item has a large figure on the left consisting of four parts. Three of the parts were given immediately to the right of the large figure. One of the four parts in each test item was missing. The object of this test was to discover the missing part that would complete the figure when it was assembled with the three given parts. Some of the alternate parts on the right must be

rotated to complete the figure correctly; others were already in the right position.

Participants were instructed to rotate a part only if it was necessary. Participants selected the missing part in each case from among the four choices below the figure and its three alternate parts that were labeled 'A', 'B', 'C', and 'D'. Alternate part 'C' completed Figure 3.3.

Figure 3.3: Figure Completion Test Sample

Measure of the Ability to Form Spatial Mental Images.

The *Measure of the Ability to Form Spatial Mental Images* (MASMI; Campos, 2012a; 2012b) which consists of a series of unfolded cubes that participants mentally refolded for each of 22 questions. Each mental imagery question provided four response options; two were correct and two were incorrect. Adding correct responses and subtracting the incorrect responses results in a minimum and maximum test score in the range from - 44 to 44, respectively. The correct responses to the sample spatial imagery item shown in Figure 3.4 are 'B' and 'C'. Campos (2012a) reports an alpha of .93.

Figure 3.4: Item Sample of the Measure of Ability to Form Spatial Mental Imagery

Intrinsic-Dynamic Category.

The Intrinsic-Dynamic category (i.e., mental rotation according to Uttal et al., 2013) was measured using the Measure of the Ability to Form Spatial Mental Images, Mental Rotation Test, the Rotated Blocks Test, and Revised Purdue Spatial Visualization Test.

Mental rotation test.

The Mental Rotation Test consisted of 24 items (Vandenberg & Kuse, 1978). Each item consisted of a target figure on the left and two correct and two incorrect alternate figures on the right. The task required participants to mentally rotate each alternate figure and determine if it matched the target figure. Alternate figures did not match the target figure when reflection (i.e., ‘flipping’) vice rotation was used. Participants received a point for each correct response. Participants were given three minutes to complete the

test. Shape rotation showed good reliability (i.e., Cronbach's $\alpha = .83$) as reported by Sharps, Price, and Williams (1994). Responses 'A' and 'D' were the correct responses to the sample item depicted in Figure 3.5.

Figure 3.5: Item Sample of the Shape Rotation Test

Rotated blocks.

The Rotated Blocks Test (Carretta & Ree, 1996) measured participants' ability to mentally manipulate objects in space along its three-dimensional axis. (Dragow, Nye, Carretta & Ree, 2009). The test consisted of 12 items. Each test item presented a target figure to the left and five similar figures at various angles to the right. Participants were instructed to select the block to the right that matched the target block on the left by rotation. The correct answer for the Rotated Blocks sample item displayed in Figure 3.6 is 'A'.

Figure 3.6: Rotated Block Test Item Sample

Revised Purdue test of visualization of rotations.

The Revised Purdue Test of Visualization of Rotations (Visualization of Rotations) consisted of 30 items arranged in order of increasing difficulty to measure individual differences in visualizing the rotation of three-dimensional objects (Yoon, 2011). Test items were presented in an analogy format depicting a target object before and after rotation and asked participants to correctly select one of four optional objects that had undergone the same rotation. Participants were given five minutes to complete as many items as possible on the Visualization of Rotations. Yazici (2014) reports an alpha reliability of .79 for the Test of Visualization of Rotations. The correct response to the Visualization of Rotations sample item shown in Figure 3.7 is 'B'.

Figure 3.7: Sample Item from Visualization of Rotations

Extrinsic-Static Category.

The Extrinsic-Static category (i.e., spatial perception type according to Uttal et al., 2013) was measured by the following four tests: The Water Level Test, and the Plumb Line Test, the Crossbar Horizontal Test, and the Crossbar Vertical Test.

Water level.

Each Water level Test (Wittig & Allen, 1984) displayed an empty drinking glass to the left of a vertical line and four optional figures on the right of the vertical line depicting a liquid's possible level in the drinking glass at various angles. The test consisted of six test items. Participants were asked to correctly identify the resting water level in the target figure as shown in the optional figures within a three-minute test time limit. One point was awarded for each correct response. No points were awarded for incorrect responses. The third alternate figure in Figure 3.8 depicts the resting level of the liquid.

Figure 3.8: Sample Item from the Water Level Test

Plumb line.

The Plumb Line Test (Vasta, Knott, & Gaze, 1996) used a test format similar to the Water Level Test (Wittig & Allen, 1984). Instead of assessing horizontality, the Plumb Line Test assessed verticality by displaying a cube van as a target figure on an incline containing a visible plumb line attached to the inside of the cube van's roof. Participants were instructed to select the correct angle of the resting plumb line from among the four optional figures. The test consisted of ten items. Participants were given three minutes to complete the test. One point was awarded for each correct response. No points were awarded for an incorrect response. The second figure on the right of the blue line is the correct response to the Plumb Line Test item presented in Figure 3.9.

Figure 3.9: Sample Plumb Line Item

Crossbar horizontal.

The Crossbar Horizontal Test (Nyborg, 1977) contained 17 items each showing a target figure to the left of a vertical line. The target figure depicted a fixed blue vertical support bar a red horizontal bar that was free to vary. Four alternate figures were presented to the right of the vertical line. The test instructions showed the red crossbar in a horizontal resting position. Participants were instructed to select the optional figure that presented the red bar in the target figure in its resting position (i.e., parallel to the top and bottom of the figure frame). The correct response to the crossbar horizontal sample item shown in Figure 3.10 is ‘C’.

Figure 3.10: Crossbar Horizontal Test Item Sample

Crossbar vertical.

The Crossbar Vertical Test (Nyborg, 1977) consists of 16 items. It applied the same test format as the Crossbar Horizontal Test to test participant perception of verticality. The Crossbar Vertical Test featured a target figure with a fixed blue support bar crossed by a red bar that was free to vary. Four alternate figures were shown to the left of a vertical line in each test item, with one alternate figure correctly showing the red bar at rest vertical to the left and right of the figure's frame. Participants were instructed to select the alternate figure in each test item that depicted the resting position of the red bar. The correct response to the crossbar vertical sample item provided in Figure 3.11 is 'D'.

Figure 3.11: Crossbar Vertical Sample Item

Extrinsic-Dynamic Category.

Three tests were selected to indicate the extrinsic-dynamic category (i.e., spatial orientation): Guay's Test of Visualization of Viewpoint, the Perspective-Taking Spatial Orientation Test, and the Map Perspective Test.

Visualization of viewpoints.

Guay's Visualization of Viewpoints consisted of 24 questions (Guay & McDaniel, 1976). The test assessed participant's ability to correctly identify the viewing position of a three-dimensional object. Each question presented a target object in three-dimensional form placed within a cube outlined by dashed lines. An optional object was also displayed in the same format below the cube outlined by dashed lines. The participant chose the corner of the cube from which the optional object view was presented by selecting a lettered response from 'A' to 'G' to the right of the alternate figure. One point was awarded for each correct response. No points were awarded for incorrect responses. Cronbach's alphas ranging from .72 to .86 are reported for this test (Yoon, 2011). The

correct response to the sample item from the Visualization of Viewpoints test shown in Figure 3.12 is 'B'.

Figure 3.12: Sample Test Item from Visualization of Viewpoints

Revised perspective taking/spatial orientation test.

The Revised Perspective Taking/Spatial Orientation Test (Alternative View Test) consisted of 12 questions (Hegarty & Waller, 2004). Five minutes were allotted to complete the test. Each question presented an array of arranged objects (e.g., car, stop sign, traffic light, a tree) within a circle. Each test item included a statement asking the participant to imagine standing at a referent object while facing another and pointing in the direction of a third referent object. The participant was then asked indicate the compass degree corresponding to third referent target object in the array under the statement's conditions. The Alternative View test has a reliability ranging between .79 and .85, as measured by Cronbach's alpha (Baber, Morin, Parekh, Cahillane, & Houghton, 2011). An average of the deviations from the correct angle in degrees

indicated the participant's spatial orientation on this test, with a smaller number indicating better performance. The correct response to the sample item from the Alternative View test shown Figure 3.13 is 83 degrees.

Figure 3.13: Revised Perspective Taking Spatial Orientation Test Sample Item

Map perspective test.

The Map Perspective test (Kozhevnikov & Hegarty, 2001) also consisted of 12 questions. Participants were allotted five minutes to complete the test. The Map Perspective test used a similar format as the Alternative View test. Each question presented a map displaying landmarks such as a church, a school, and an airport. In each question, a landmark and a referent object were identified, along with a third landmark. Each test item's statement asked participants to imagine they were standing beside a landmark in the direction of another referent object and indicate the compass angle by degree that would represent the angle by degree while pointing at a third landmark. An average of the deviations between the items 'correct degree and the participant's responses indicated spatial orientation on this test. The correct response to the Map Perspective test sample item is shown in Figure 3.14 is 55 degrees.

Figure 3.14: Map Perspective Test Item Sample

Part II: Spatial Training

Participants were asked to complete a spatial training task consisting of three graduated levels of spatial training. The basic level of spatial training provided introductory principles, while the intermediate, and advanced training provided more in-depth knowledge related the relations between objects. Participants were provided with a short informational text and then asked to identify the correct response found in the text among three multiple choice answers. No time limit was imposed on any aspect of the spatial training. However, participants were required to identify the correct response for each training item to advance to the next information panel and in turn, the next level of training.

Part III: Visual Search

Participants were asked to complete a set of ten different visual search tasks meant to simulate aerial surveillance. Each task required participants to visually search for a target vehicle using five aerial video displays of a cityscape. Figure 3.15 shows the participant's view while completing one of the study's visual search tasks. Each task presented a main camera view in the centre of the participant's browser window. Four

alternate camera views were also available, with two camera views located on the left side of the participant's browser window and two camera views located on the right side of the browser window. Camera views were provided from five separate cameras mounted on five separate drones continuously circuiting over a cityscape. The cityscape consisted of streets, buildings, and vehicles.

Figure 3.15: Sample Visual Search Task

One vehicle on the city streets contained a camera providing a viewpoint from the target vehicle's driver seat, which was displayed in the lower left hand corner of the participant's browser window. Four alternate vehicle models were presented under four buttons labeled as response 'A' through 'D' directly to the right of the target vehicle's viewpoint. Participants used the alternate camera views to determine which of the four vehicles provided the viewpoint from the target vehicle. The task was completed once the participant selected a response by selecting either alternate vehicle 'A', 'B', 'C', or 'D'. Participants were then informed by a message on their computer screen that the next task would begin in seven seconds, with a count-down timer indicating the remaining time.

The visual search tasks simulate a target identification task commonly performed during aerial surveillance operations. Typically aerial surveillance operations survey a known target vehicle such as a car or truck being pursued by local law enforcement. Likewise, a boat or ship under aerial surveillance in support of drug or fisheries interdiction is tracked until the operation is complete. For the purposes of this study, the surveillance task was modified so that participants were required to visually search for the target vehicle among a set of distractor vehicles and identify the target. The target vehicle was not identified for participants prior to each task as is standard operating procedure during aerial surveillance operations. Instead each visual search task required participants to identify a target vehicle from among four possible choices, given multiple video displays and the driver's viewpoint from the target vehicle. Multiple vehicle types were contained in the set; more than one taxi, firetruck, garbage truck, and ambulance were featured in the visual search trials. It was therefore, necessary to consider the driver's viewpoint from within the target vehicle to identify it as such, as displayed in the bottom left corner of the participant's computer screen during each visual search task.

Visual search tasks were designed from the same initial template. That is, an initial task was developed that contained the same location of city infrastructure and set of vehicles. A target was selected at random from the set of distractors for each visual search task. The remaining vehicles served as distractors and were placed at random on the city's streets.

A sequence of tasks and pauses (informed by message) continued until all ten visual search tasks were completed. The set of visual search tasks consisted of five static

and five dynamic scenarios. Static scenarios presented all vehicles as stationary on the city streets, while vehicles in the dynamic task scenarios were in motion, driving around on the city's streets. Scenarios were also presented in the following three different camera perspectives: A normal view where ambient colours of cityscape objects were presented ($n = 5$); an infrared view where cityscape objects were presented in grayscale tones ($n = 2$); and a night vision perspective where all cityscape objects were presented in hues of green ($n = 3$).

Figure 3.16: Initial Website Screen on Download

Procedure

A website was designed using Unity WebGL game development software (<http://www.unity3d.com/>). The study's website (www.surveilex.com) consisted of four sections: (a) Personnel Selection to gather participant spatial test data; (b) Training Development to provide spatial training; (c) Mission Performance to gather participant visual search performance data; and (d) Mission Debrief, to provide general personal

feedback on the participant's results. The website was designed to simulate an online assessment centre to process participants through concomitant personnel selection, training development, mission performance, and mission debrief phases by measuring their spatial and visual search skills. A full description of the study's requirements is provided after the following description of how participants registered online through the study's website.

Website Registration.

Participants initiated the study's requirements by entering the website address in an internet browser, which downloaded the game to their personal computer (Figure 3.16). The website's home page then displayed a Connect button allowing participants to login and a Registration button to access the game's registration system (Figure 3.17).

Figure 3.17: The Study's Home Page

First-time participants registered by clicking on the Registration button, declaring a valid email address, selecting a username and password, and declaring their participant

status (e.g., student, active military, retired military). A screenshot of the Registration page is provided in Figure 3.18. The website sent an activation email to the participant within five minutes of registration to the participant's declared email address on completion of the Registration page. The email contained a short description of the study and a validation link that opened a new tab in the participant's browser when it was clicked on, permitting the participant to begin the study. All information collected from participants was stored on a secure server by a host domain company (i.e., www.godaddy.ca) and transmitted with encryption software.

Figure 3.18: The Study's Registration Webpage

Study's website.

Upon logging in, participants were presented with the site's main menu consisting of an instructions, participate, language, and logoff button (Figure 3.19). The main menu displayed a Personnel Selection, Training Development, Mission Performance, and Mission Debrief button on the right side of the screen when participants selected the Instructions button on the main menu page. An instructional sub-menu was presented on the left side of the participant's computer screen when any one of the four buttons on the main menu were selected.

Figure 3.19: The Study's Main Menu

Participants received a general description of the spatial skills tests by selecting the Personnel Selection button, a general description of the study's spatial skills training by selecting the Training Development button, and a general description of the study's visual search tasks by selecting the Mission Performance button. Participants were

informed they would receive a general overview of their personal test, training, and performance outcomes when they selected the Mission Debrief button on the study's Instructions Menu. An example of the Personnel Selection instructional submenu is provided in Figure 3.20.

Figure 3.20: The Personnel Selection Instructional Menu

Participants accessed each of the four parts of the study by clicking on the Participate button and then the specific section of the study. The Mission Debrief section could only be accessed once the Personnel Selection (i.e., containing spatial skills tests), Training Development (i.e., containing spatial training modules), and Mission Performance (i.e., containing visual search tasks) were completed in that sequence. The Mission Performance section could only be accessed once the Training Development and Personnel Selection requirements were completed. Likewise, the Training Development

section could only be accessed once the Personnel Selection requirements were completed.

Figure 3.21: The Participant Demographic Information Webpage

Personnel Selection.

The participant's initial selection of the Personnel Selection button under the Participate button on the Main Menu webpage activated the demographic information webpage (Figure 3.21). The demographic information webpage asked participants to indicate their first language (i.e., French, English, or other), their gender (i.e., male, female), birth month and year, as well as the type and highest level of education they had completed to date. Providing this demographic information made the Next button available, permitting participants to access the spatial test sub-webpage of the Personnel Selections section of the website. Participants could complete the 14 spatial tests under the Personnel Selection section in any order. Participants reviewed the test's instructions

which appeared once a test was selected on the Instructions button on the Personnel Selection - General Instructions webpage shown in Figure 3.22. The instructions for Guay's Visualization of Viewpoint as seen by participants is provided in Figure 3.23. Test instructions and a test item example were provided in an information section, along with a "Previous" and "Next" button located at the bottom left of the computer screen, allowing the participant to return to the Personnel Selection menu or begin the current test, respectively. All 14 spatial tests were timed as displayed by a timer on the test page. Time taken per item was recorded along with whether or a correct or incorrect response was provided for each test item.

Figure 3.22: Personnel Selection / Spatial Test Instructional Menu

Participant data was transmitted by encryption software to the study's secure server and stored by participant's id number within individual tables by spatial test name. Once the participant completed all test items the website returned the participant to the

Personnel Selection menu and redacted the completed test button, making further spatial testing unavailable to the participant.

Figure 3.23: Sample Test Instructions (Visualization of Viewpoint

Training development.

The website included a Training Development section designed to provide participants with basic, intermediate, and advanced spatial training information. Each level consisted of a sequence of webpages containing panels of spatial information, along with a question based on the information provided followed by three multiple choice responses. An example of a basic spatial training information panel is shown in Figure 3.24. Participants read the information on the panel and identified the correct response which in turn, activated the 'Next' button at the bottom right of their computer screen enabling them to continue the study's spatial training. Time spent on each information panel was recorded. The third section of the website (Mission Performance) was accessible when all three training levels were completed.

Mission performance.

The third section of the website was designed to collect participant visual search task performance data. An information panel familiarized participants with the purpose and screen layout of the mission performance section (Figure 3.25). The information panel also contained a 'Main Menu' and 'Next' button, allowing participants to delay their attempt at the set of visual search tasks and return to the main menu or to activate the sequence of tasks, respectively. Participants were asked to complete the visual search tasks, which simulating uninhabited aerospace vehicles (UAVs) surveillance missions. Figure 3.26 shows standard computer display during an infrared visual search task set.

Figure 3.24: A Display Panel from the Basic Spatial Training Module

Figure 3.25: The Mission Performance Instructions Webpage

Mission debrief.

Participants could access the final phase of the study (Mission Debrief) once their Mission Performance phase of the study was completed. This Mission Debrief of the website was designed to provide participants with graphical information on their spatial test, training, and task performance results relative to all other participants who completed the study. Participant and group results were provided in three separate sections, with each section displaying the percentage of items completed, percentage of correct responses, average overall completion time, and average completion time among correct responses. Figure 3.27 shows an example of the Mission Debrief display.

Figure 3.26: Visual Search Task under Infrared Condition

Exiting the website.

Participants were encouraged to logoff the site, as required using the Logoff button provided on the site's main menu. Logging off the game returned participants to the site's main page. The website was designed to bookmark the participant's progress during the study. The bookmarking function was meant to ensure participants would be returned to the last test, training module, or to review their study results when they logged back on to the game.

Figure 3.27: Example of a Mission Debrief Display

Chapter 4: Statistical Analysis

Overview of the Analyses

The first phase of the study involved determining the normality and distribution of scores using descriptive statistics for the demographic (i.e., gender, level of education attained, and academic discipline), spatial test and training, and visual search task data. Reliability analyses were then conducted on spatial test and visual search item response data. The goal of these analyses was to ensure that each individual test and visual search measure was a reliable index of the construct it was designed to measure. Univariate analysis was then conducted on spatial test and visual search task scores with each demographic variable to determine if there were relations between these variables (i.e., gender, level of education attained, and academic discipline) and the other measures. These steps were necessary prior to conducting confirmatory factor analysis and structural regression modelling in this study. Descriptive, univariate analyses, and linear regression were done using SPSS version 25 whereas Mplus version 8 was used for confirmatory factor analyses.

The actual data analyses are described in Chapter 5. In this chapter I explain the criteria for reliability and for model fit that I used in the analyses. I focus on statistical criteria that assess the normality and reliability of the data. I describe the goodness of fit statistics I used to evaluate each measurement and structural model of spatial skills and visual search, with further details available in Appendix A. A general discussion of structural equation modelling is provided, along with an explanation of model specification and identification. Next, I explain the process of testing the four-factor

model using confirmatory factor analysis. Finally, I present my plan to test visual search on the four-factor model of spatial reasoning across gender. I discuss my contingency to predict visual search performance by spatial reasoning type and gender. Thus, the purpose of this chapter is to clarify the statistical methods and criteria I used separately from the actual analyses.

Statistical Criteria

This chapter presents a brief discussion of the statistical criteria used to evaluate the data analyzed in this study. I discuss measures of statistical significance commonly used to evaluate variables as indicators of psychological constructs, along with available measures of goodness of fit and the standard estimate of regression used in structural equation modelling to infer population parameters from sample statistics.

Reliability.

The reliability of a measurement is one of the most important requirements for any scale or test. It is a critical requirement in structural equation modelling (Kline, 2015; Schermelleh-Engel, Moosbrugger, & Müller, 2003). The Cronbach's Alpha coefficient is one of the most widely used criteria for assessing scale and test items (Cronbach, 1951; Steiner, 2003). Cronbach's alpha score evaluates the extent to which a measurement produces consistent results (Cronbach, 1951). Cronbach's Alpha is a standard measure of internal consistency, sometimes describe as a measure of how well test items 'stick together' (McNeish, 2017).

Alpha coefficients greater than 0.9 are considered excellent, those greater than 0.8 are considered good, and those greater than 0.7 are considered acceptable (Tavakol &

Dennick, 2011). It is generally accepted that a Cronbach's alpha greater than 0.70 indicates that a latent variable has adequate internal consistency among its indicators in the form of individual test items and unidimensionality among those indicators of that latent variable or single factor (Kline, 2015; Santos, 1999). A minimum Cronbach's alpha of .70 was therefore used to establish the internal consistency of spatial skills and visual search task performance in this study.

Many researchers over the past 40 years have drawn a distinction between unidimensionality and internal consistency (Cortina, 1993; Crutzen & Peters, 2017; Green, Lissitz, & Mulaik, 1977; Schmitt, 1996). Schmitt (1996) defined unidimensionality as the degree to which a set of items measure the same latent variable or factor and defined internal consistency as the interrelatedness among that set of items. For Green et al. (1977), internal consistency was necessary for unidimensionality but internal consistency was not sufficient to demonstrate unidimensionality on its own. There may be high internal consistency among a set of items that measure different latent variables.

Evidence of high internal consistency and unidimensionality are both important in structural equation modelling. In this study, spatial test item and visual search task results represent the indicators of four spatial latent variables namely, spatial visualization, mental rotation, spatial perception, spatial orientation, and visual search. The distinction between unidimensionality and internal consistency of test or task items is important. In this study, I demonstrate that the interrelationships between the items within each spatial test and the tasks designed to measure visual search are internally consistent to a

minimum of .70 and that together, they point to or indicate a single construct. Otherwise, confidence in each spatial test and the set of visual search task as instruments designed to measure these latent constructs will be low and contribute to poor fit between implied models and the observed data collected in this study.

For that reason, the basis of structural equation modelling depends on the internal consistency and the unidimensionality of each indicator of the latent constructs. I relied on the Cronbach's alpha obtained by reliability analyses of each spatial test and the visual search task set to evaluate internal consistency in this study. Unidimensionality was assumed based on past performance of the measures used in this study. Standard (regression) estimates of the latent spatial and visual search constructs represented internal consistency of the factors contained in the study's structural equation models. Standard estimates as a statistical criteria are discussed later in this chapter. Goodness of model fit was assessed once data normality and measurement reliability had been confirmed.

Goodness of fit statistics.

Goodness of fit tests are used to determine whether or not an implied model fits an observed dataset well enough to be retained (Kline, 2015; Schermelleh-Engel et al., 2003). Model fit statistics indicate whether the implied model should be retained or rejected; they do not indicate the significance of any specific coefficients in the model. Model fit evaluation in structural equation modelling can be more complex as compared to other statistical analysis where variables are assumed to be measured (at least theoretically) 'error-free', as in univariate or multivariate analysis of variance, for

instance. No single test of significance in structural equation modelling exists to indicate the consistency or goodness of fit between an implied model and the observed data.

Rather, statisticians continue to develop different indices of goodness of fit that have various uses (Kline, 2015; Jackson, Gillaspay Jr, & Purc-Stephenson, 2009; Schermelleh-Engel et al., 2003).

The chi-square test is the significance test commonly used to determine the fit between an implied model and observed data (Schermelleh-Engel et al., 2003). Other goodness of fit measures are descriptive in nature, and can be grouped into three main classes: measures of overall model fit; measures based on model comparisons; and measures of model parsimony. The chi-square test should not be used solely to evaluate model fit (Jackson et al., 2009; Schermelleh-Engel et al., 2003) because it is sensitive when sample size is small (i.e., $n < 100$) and therefore is prone to violate the multivariate assumption of normality (Curran, West, & Finch, 1996).

Researchers advocate different combinations of goodness of fit indexes for model evaluation. For example, Kline (2015) recommended chi-square, Comparative Fit Index (CFI), and Standardized Root Mean Square Residual (SRMR). Four measures are recommended in the literature: Chi-square, Root Mean Square Error of Approximation (RMSEA), the Tucker-Lewis index (TLI) and CFI. Jackson et al. (2009) recommended the chi-square and its associated p value, RMSEA and its associated confidence interval, SRMR, and CFI. Many studies report the RMSEA, CFI, and TLI since these fit indices are sensitive to model misspecifications and do not depend on sample size as strongly as the chi-square (Fan, Thompson, & Wang, 1999; Hu & Bentler, 1998; Rigdon, 1996).

After considering these recommendations, the following goodness of fit indexes and their cut-off values were selected for this study: The chi-square and its associated p value; Root Mean Square Error of Approximation (RMSEA) and its associated confidence interval; Tucker-Lewis Index (TLI); Comparative Fit Index (CFI); Standardized Root Mean Square Residual (SRMR); and the Weight Root Mean Square Residual (WRMR). The goodness of fit indexes used in this study are described further in Appendix A.

Structural Equation Modeling.

Structural equation modelling is a form of causal modelling designed to fit observed data to a theoretically-driven model. SEM includes a suite of causal models including the two used in the present study, confirmatory factor analysis and structural regression modelling. Structural equation modelling allows researchers to assess the relationships between unobservable or 'latent' constructs using samples to estimate population parameters (Kline, 2015). Theoretically, there are two general types of structural equation models: A measurement model that examines the relationship between at least three observed variables representing indicators of a latent variable, and a structural model that assesses the relationships between latent variables.

In a given analysis, the measurement model identifies the reliability of a latent variable based on its indicators or observed variables. The implied measurement model is derived from theory based on past research that identifies internally consistent measures that point to or indicate a unidimensional construct (Fan et al., 2009). Subsequently, the structural regression model reveals the association between latent variables to predict or explain a particular outcome (Schermelleh-Engel et al., 2003). In this study,

measurement models were produced for the spatial typology and for visual search. A structural regression model was used to regress visual search on the resulting spatial typology. The relations between indicators and latent constructs within the measurement models and between latent constructs in structural regression models were estimated with independent regression equations that were standardized. Standardized regression estimates served as the primary statistical criteria for evaluating the association between latent variables and their indicators in measurement and structural models in this study.

Standardized (regression) estimates.

The standardized regression estimate is a primary statistic in structural equation modelling. It estimates the association between an indicator and its latent construct or between latent constructs. Standardized regression estimates were considered along with selected fit statistics to evaluate the goodness of fit between implied models and observed data. Mplus confirmatory factor analysis and structural regression model output provided a standard estimate and an associated standard error for each model parameter. The standard estimate divided by the standard error was used to determine the probability of the *z*-score occurring by chance as represented by its *p*-value. Using this formula, the *p*-value was significant when the *z*-score was ± 1.96 or greater. Even when a *z*-score is significant, Costello and Osborne (2005) indicated that standardized regression estimates alone should be greater than 0.30 to be considered meaningful in confirmatory factor analysis. Standard regression estimates in relation to their standard errors determines whether such meaningfulness is statistically significant. Categorizing standard estimates into the following three groups is generally accepted: Given statistical significance, more

meaningful factor loadings begin at a range from 0.30 to 0.39; more meaningful loadings range from 0.40 to 0.49, with loadings greater than 0.49 considered very meaningful (Costello & Osborne, 2005; DiStefano, Zhu, & Mîndrilă, 2009).

Statistical analysis are based on three broad principles in the practice of structural equation modelling. The first principle known as *model identification* occurs when what is known about a model by way of measured variables of latent constructs is at least as much as what is unknown naturally by the parameters to be estimated. The second principle is *model specification*: measurement and structural model development based on theory is used to further clarify indicators of latent constructs and between latent constructs. The third principle working within these bounds of model identification and specification leads to *model parsimony* to achieve the simplest solution in model fit as constrained by current theory, research, and data collected. I discuss these three principles and their application to the statistical criteria used in this study below.

Model identification.

Identification is an important concern in structural equation modelling because the methodology gives users the freedom to specify models that are not identified. Structural equation modelling techniques provide flexibility to determine the goodness of fit of a number of different model configurations as long as the variances and covariances of measured variables outnumber a model's parameters. A parameter represents a value of interest within a model such as a regression coefficient between factor loadings or the regression coefficient between an indicator such as a spatial test score and its factor like a particular spatial type. For instance, the standard estimate is a specific parameter value. A

data point is a variable with observed scores, like a variable containing the item or overall scores on a spatial test or a mean score based on the set of visual search tasks. A model is *just identified* when a specific parameter value uniquely identifies the model and no other equivalent formulation can be given by a different parameter value. When this occurs, only one model is implied for evaluation of its goodness of fit with observed data. Such *just identified* models yield perfect fit statistics, with no alternative models available for comparison.

Under-identification occurs when model parameters outnumber the variances and covariances of measured variables. It is not possible to evaluate goodness of fit of under-identified models with the data collected on measured variables. If there are fewer data points than the number of estimated parameters, the resulting model is "unidentified", since there are too few reference points to account for all the variance in the model.

Optimally, the number of variances and covariances of measured variables exceeds the number of model parameters, which yields *over-identification* and thus allows multiple models for evaluation. The positive degrees of freedom implied by over-identification means any given model configuration may not fit well relative to another configuration. Goodness of fit amounts to meaningful evidence in the condition of over-identification such that the model is a reasonable representation of how spatial types and visual search tasks are organized in separate measurement models and how spatial types explain visual search task performance in a structural regression model.

Model specification.

To evaluate the theory of spatial typology, I developed hypotheses concerning the relationship between spatial skills and visual search and gathered data on these constructs by selecting measurement instruments of spatial skills and designing a set of visual search tasks to confirm the typology's four spatial types. My hypotheses based on current theory and research are presented in Chapter 2 (Literature Review). I applied structural equation modelling in the form of confirmatory factor analysis and structural regression modelling to test these hypotheses using data gathered from participants who completed the spatial tests and visual search tasks. By specifying separate measurement models of spatial types implied by the typology proposed by Chatterjee (2008) and applied by Uttal et al. (2013) to spatial tests, I determined the goodness of fit of the overall four-factor model and the underlying dimensions implied by each dichotomy of the object features and motion dimensions. In the same way, the theory-driven development of a visual search task set was evaluated for goodness of fit. The goodness of fit of these measurement models by significant demographic factors identified in the sample were also specified and evaluated.

I planned to evaluate a set of structural models by regressing visual search performance on to spatial types according to the theoretical framework of the typology. However, such modelling proved too complex for the observed data collected in this study. Subsequently, I tested models of visual search on spatial reasoning and gender using linear regression. Spatial types that were significant in predicting visual search were multiplied by the dummy code of each gender to produce interaction terms. A

subsequent model of visual search on these interaction terms was tested, with line graphs to depict how the visual search, spatial reasoning of men and women interacted based on data collected in this study.

Parsimony.

Kline (2015) stresses the principle of parsimony in structural equation modeling such that theoretical processes and structural relations between parameters that are simpler should be considered over those that are more complex. The simplest measurement model is assumed to be a single-factor model, where at least three psychological measures are used to indicate a latent construct. In this study, the single-factor spatial ability model and the single-factor visual search model may be the simplest theoretically and structurally, according to the goodness of fit with observed data. If the measure's normality and reliability and the model's fit statistics indicate goodness of fit, then further analysis is not required.

However, alternative models may be assessed for goodness of fit and compared with the fit statistics of the single-factor model, given the condition of over-identification achieved in this study. Alternative models include (a) a single-factor model, (b) models that combine the four factors (i.e., intrinsic, extrinsic, static, and dynamic) into two-factor models, and (c) the four-factor spatial model. Alternative visual search models include separate static and dynamic models and the three visual sensory types of normal vision, infrared, and night vision. I used structural regression models to combine the most parsimonious of these models to address the theoretical process and structural relations between parameters of spatial skills and visual search. Statistical criteria discussed in this

chapter were used to evaluate these models and the utility of the spatial typology proposed by Chatterjee (2008) and applied by Uttal et al. (2013) to indicate four types of spatial reasoning.

Chapter 5: Results

In this chapter, I first present descriptive analyses of each of the spatial tasks, grouped by the hypothesized spatial process that each was chosen to represent. Each section includes a discussion of task characteristics (e.g., means, distribution of scores, reliability), gender differences, and correlations among tests. The purpose of the dissertation was to test the typology's structure and determine if the spatial types defined thereby applied to visual search. To that end, it was essential to establish the association between the measures of each spatial type and visual search. I present findings that items within each spatial test are correlated with one another to show that together they indicate a measure of a specific construct. I also show that the tests selected to indicate a specific spatial type are correlated with each other, thereby measuring the same construct. I also demonstrate the same association between visual search tasks as measures of that construct. The correlations between visual search and the spatial measures of each spatial type are also shown in each correlation table. Second, I present the confirmatory factor analyses that test the proposed four-factor model. Third, I present descriptive analyses of the visual search task and the confirmatory factor analysis of the task structure. Fourth, I present the complete structural equation model that assesses the relations between the spatial typology and visual search performance. Structural regression models are then presented to compare the goodness of fit of single spatial factors with various combination between them by gender to predict visual search.

Descriptive Analyses of Spatial Ability Tests

Spatial Visualization.

Performance on each of the spatial visualization measures is shown in Table 5.1 and correlations among the tests of spatial visualization are shown in Table 5.2. Three tasks were selected to capture spatial visualization: Measure of the Ability to Form Spatial Imagery, Card Rotation, Figure Completion, and Hidden Figures.

Measure of the ability to form spatial imagery.

Participants received -1 or +1 for each incorrect or correct match of among the four alternative to the target figure depicted in each test item. Cronbach's alpha was .34 ($n = 304$) based on 22 items. Analysis showed that removing items 1, 3, 12, 15, 16, 18, 20, and 21 based on their low inter-item correlations increased the reliability of the mean test score, significantly. Cronbach's alpha was .80 ($n = 304$) based on the remaining 14 test items. Mean test scores ranged from -1.71 to 0.79 out of a possible range from -2 to +2. Mean test scores indicated participants correctly identified one of the two alternates to the target figure at most or did not identify either alternate. Mean test scores were normally distributed. Kurtosis was significant for by male (-2.57) and female (-3.26) participants. Gender differences by mean test scores were not significant. Mean time to complete the Measure of Ability to Form Spatial Imagery was three minutes, 55 seconds. Completion time was significant by gender ($F(1, 302) = 38.91, p = .000$).

Card rotation.

Participants received +1 for each correct determination that an item was rotated and -1 for each incorrect determination when the figure was 'flipped', thus, it was

Table 5.1: Descriptive Statistics for Accuracy for the Spatial Visualization Measures

Test	Gender	N	Range	Mean	SE	Min	Max	Skewness		Kurtosis	
								Statistic	SE	Statistic	SE
Measure of Ability to Form Spatial Imagery	M	109	2.36	-0.61	0.06	-1.71	0.64	0.03	0.23	-1.18**	0.46
	F	195	2.43	-0.60	0.04	-1.64	0.80	-0.06	0.17	-1.14**	0.35
	Total	304	2.50	-0.60	0.04	-1.71	0.80	-0.03	0.14	-1.16	0.28
Card Rotation	M	109	5.43	1.97	0.16	-1.14	4.29	-0.25	0.23	-1.60	0.46
	F	195	6.36	1.71	0.11	-2.14	4.21	-0.01	0.17	-1.35	0.35
	Total	304	6.23	1.81	0.09	-2.14	4.29	-0.09	0.14	-1.46	0.28
Figure Completion	M	109	0.71	0.47	0.02	0.10	0.81	-0.02	0.23	-1.28	0.46
	F	195	0.75	0.46	0.01	0.10	0.85	0.02	0.17	-1.07	0.35
	Total	304	0.75	0.46	0.01	0.10	0.85	0.00	0.14	-1.14	0.28
Hidden Figures	M	109	0.93	0.44	0.02	0.07	1.00	0.57*	0.23	-0.03	0.46
	F	195	0.93	0.45	0.01	0.00	0.93	0.32	0.17	-0.08	0.35
	Total	304	1.00	0.44	0.01	0.00	1.00	0.41*	0.14	-0.06	0.28

*Correlation is significant at the 0.05 level (2-tailed).

**Correlation is significant at the 0.01 level (2-tailed).

possible to receive a negative score. Mean scores were positive, however, indicating that participants were generally able to avoid selecting the mirror-image foils, and the distribution of scores was normal. Cronbach's alpha was .95 ($n = 304$) based on the 14 items of the Card Rotation Test. The difference in mean test score achieved by males and females was not significant. Performance was not skewed and there was no indication of kurtosis for mean test score. Cronbach's alpha was .93 ($n = 271$) based on the 21 item response times. Mean test completion time was three minute, 51 seconds. Completion time did not differ significantly by gender.

Figure completion test.

Participants earned one point for each of the 22 items they solved correctly. Item 21 of the Figure Completion Test was removed from further analysis as it yielded a zero variance; all participant scores were recorded as correct due to a programming error. Cronbach's alpha was .74 ($n = 271$) for the remaining 21 items. Mean test scores were positive, with no indication of kurtosis. The descriptive statistics for Figure Completion items are displayed in Table 5.2. Mean test scores did not differ significantly by gender. Participants took 14.43 seconds on average to complete each item on the Figure Completion Test. Cronbach's alpha was .93 ($n = 271$) based on the 21 item response times. Participants required four minute, 58 seconds on average to completion the test. Mean item completion time was 15.89 seconds. No significant gender differences were found by completion time.

Hidden figures test.

Participants studied each test item to discover one of five possible figures hidden within a diagram. One point was awarded for each correct answer provided. Cronbach's alpha was .70 ($n = 200$) based on the test's 15 items. There was no difference in performance by gender. Mean scores were positive. However, sample test scores were not normally distributed, with a significant positive skew, $z = +2.99$ caused by infrequently higher mean scores by some participants. Three male were identified as outliers. There was no significant gender difference on mean test score. Cronbach's alpha was .93 ($n = 271$) on 21 time items. Mean test completion time was three minute, 22 seconds. Mean

item completion time was 13.65 seconds. No significant difference in test completion time was found by gender.

Summary and correlations.

For the three measures of spatial visualization, test scores were reliable. Two of the four test samples had normal distributions. The scores of all three measures also showed considerable range across individuals. There were no significant differences between males and females for any of the measures. As shown in Table 5.2, the three measures of spatial visualization were significantly correlated, and all three were correlated with performance on the visual search task (mean percentage correct). The analysis indicated that mean test scores were reliable indicators of spatial visualization. Mean test completion time was also reliable and no differences were found by gender.

Table 5.2: Correlations among Measures of Spatial Visualization (n = 304)

Indicator	Mean Percent Score Correct					Mean Completion Time				
	1	2	3	4	5	1	2	3	4	5
1. MASMI	1					1				
2. Card Rotation	-.55**	1				.06	1			
3. Figure Completion	-.53**	.60**	1			.08	.51**	1		
4. Hidden Figures	-.47**	.37**	.41**	1		.01	.27**	.35**	1	
5. Visual Search	-.37**	.47**	.44**	.29**	1	.00	.41**	.42**	.24**	1
α	0.80	0.95	0.70	0.69	0.66	-	-	0.93	0.93	0.67

**Correlation is significant at the 0.01 level (2-tailed).

Spatial Perception.

Performance on each of the spatial perception measures is shown in Table 5.3 and correlations among the tests of spatial perception are shown in Table 5.4. Four tasks were selected to capture spatial perception: Crossbar Horizontal, Crossbar Vertical, Water Level, and Plumb Line.

Crossbar horizontal test.

In this test, participants studied a target figure depicting the starting position of a horizontal red bar fixed to stationary vertical blue bar. One point was provided when one of four alternate figures showing the correct resting position of the blue bar was selected. Cronbach's alpha was .94 ($n = 303$) based on 17 items. Participants achieved scores within the full range of mean correct responses. The mean scores were positive, indicating participants correctly identified the resting position of the horizontal bar on slightly more than half of test items. Crossbar Horizontal Test scores had a significant positive skew, $z = +2.43$ caused by some participants achieving higher mean scores than most participants. No significant kurtosis was found, however. However, there was no significant difference in mean test score by gender. Cronbach's alpha was .86 ($n = 303$) on the 16 time items. Mean time to complete the Plumb Line Test was one minute, ten seconds. Participants required 4.40 seconds on average to complete each item on the Plumb Line Test. Test completion time did not differ significantly by gender.

Table 5.3:

Descriptive Statistics for Mean Correct Response for the Spatial Perception Measure

Test	Gender	N	Range	Mean	SE	Min	Max	Skewness		Kurtosis	
								Statistic	SE	Statistic	SE
Crossbar Horizontal	Male	109	1.00	0.54	0.04	0.00	1.00	0.21	0.23	-1.75	0.46
	Female	195	1.00	0.51	0.03	0.00	1.00	0.40*	0.17	-1.50	0.35
	Total	304	1.00	0.52	0.02	0.00	1.00	0.34	0.14	-1.59	0.28
Crossbar Vertical	Male	109	1.00	0.56	0.04	0.00	1.00	-0.08	0.23	-1.69	0.46
	Female	195	1.00	0.46	0.02	0.00	1.00	0.39*	0.17	-1.25	0.35
	Total	304	1.00	0.50	0.02	0.00	1.00	0.23	0.14	-1.48	0.28
Water Level	Male	109	1.00	0.70	0.03	0.00	1.00	-0.68*	0.23	-0.73	0.46
	Female	195	1.00	0.53	0.02	0.00	1.00	0.00	0.17	-1.11	0.35
	Total	304	1.00	0.59	0.02	0.00	1.00	0.22	0.14	-1.16	0.28
Plumb Line	Male	109	1.00	0.66	0.03	0.00	1.00	-0.57*	0.23	-0.85	0.46
	Female	195	1.00	0.55	0.02	0.00	1.00	-0.07	0.17	-1.19	0.35
	Total	304	1.00	0.59	0.02	0.00	1.00	-0.24	0.14	-1.17	0.28

* Correlation is significant at the 0.05 level (2-tailed).

Table 5.4:

Pearson Correlations between Indicators of Spatial Perception (n = 304)

Test	Mean Percent Correct					Mean Completion Time				
	1	2	3	4	5	1	2	3	4	5
1. Crossbar Horizontal	1					1				
2. Crossbar Vertical	.49**	1				.34**	1			
3. Water Level	.43**	.28**	1			.61**	.30**	1		
4. Plumb Line	.43**	.34**	.53**	1		.64**	.38**	.54**	1	
5. Visual Search	.31**	.14*	.30**	.32**	1	.23**	.17**	.14*	.20**	1
α	0.94	0.94	0.76	0.76	0.66	0.88	0.83	0.75	0.67	0.67

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

Crossbar vertical test.

In contrast to the Crossbar Horizontal Test, participants studied a target figure depicting the starting position of a vertical red bar fixed to a stationary horizontal blue bar in each item. One point was provided for selecting one of four alternate figures showing the correct resting position of the red bar. Cronbach's alpha was .94 ($n = 302$) based on 16 test items. Participants achieved the full range of scores on the Crossbar Vertical Test. Mean scores were positive but was .50 but were not normally distributed due to infrequent high mean scores by some participants. No significant kurtosis was revealed. Mean test scores achieved by males was significantly higher than those achieved by females ($F(1, 302) = 4.97, p = .03$). Cronbach's alpha was .79 ($n = 302$) on 16 item response times. Mean time to complete the Crossbar Horizontal Test was one minute, 30 seconds ($SD = 53.39$ seconds). Participants took 6.66 seconds on average to complete each item on the Crossbar Vertical Test. Mean test completion time was not significantly different by gender.

Water level test.

Participants received one point for correctly identifying a figure showing the resting position of a liquid in a tipped cup. Cronbach's alpha was .76 ($n = 304$) on the six test items. The sample achieved the full range of mean scores. Mean test score were positive, indicating participants often correctly selected the correct test item. Test scores were not normally distributed, with a significant negative skew, $z = -2.96$ caused by some participants achieving lower than average scores on this test. Heavy tails were not found, indicating no outliers in the distribution of mean scores. Gender differences by mean

scores were significant; males achieved higher mean scores than females ($F(1, 302) = 19.83, p = .000$). Cronbach's alpha was .73 ($n = 303$) based on the 14 time items. The mean time to complete the Crossbar Horizontal Test was 27.74 seconds ($SD = 17.62$ seconds). Participants took 5.55 seconds on average to complete each item on the Water Level Test. The time taken to complete the test was not significantly by gender.

Plumb line test.

Participants received one point for identifying the correct resting positive of a plumb line in each test item. Cronbach's alpha was .76 ($n = 304$) based on six items. Participant mean scores ranged across the full distribution. The mean test score was positive. Sample test scores were not normally distributed; a negative skew, $z = -2.48$ indicated some mean test scores were lower than those achieved by most participants. No significant kurtosis was revealed. Gender differences by mean scores were significant, with males achieved higher mean scores than females ($F(1, 302) = 7.80, p = .006$). Cronbach's alpha was .65 ($n = 303$) on the five time items. Mean test completion time was 28.35 seconds and the mean item completion time was 5.55 seconds. Males and female participants did not differ significantly by mean test completion time.

Summary and correlations.

Mean test scores were reliable for the four measures of spatial perception. Sample of test scores were not normally distributed but not to the extent that heavy tails and the presence of outliers were an issue. Mean scores showed considerable range across individuals. There were no significant differences between males and females on the Crossbar Horizontal Test. Significant differences were found on mean scores achieved by

Table 5.5: Descriptive Statistics for Accuracy for the Mental Rotation Measures

Test	Gender	N	Range	Mean	SE	Min	Max	Skewness		Kurtosis	
								Statistic	SE	Statistic	SE
Mental Rotation	M	109	2.13	0.32	0.05	-0.54	1.58	0.78**	0.23	-0.05	0.46
	F	195	2.33	0.20	0.04	-0.71	1.63	1.11**	0.17	0.82**	0.35
	Total	304	2.33	0.24	0.03	-0.71	1.63	0.97	0.14	0.40	0.28
Rotated Blocks	M	109	0.75	0.33	0.02	0.00	0.75	0.34	0.23	-0.84	0.46
	F	195	0.86	0.27	0.01	0.00	0.86	0.60**	0.17	-0.11	0.35
	Total	304	0.86	0.29	0.01	0.00	0.86	0.51	0.14	-0.44	0.28
Revised Spatial Visualization	M	109	0.93	0.46	0.02	0.07	1.00	0.33	0.23	-1.00**	0.46
	F	195	0.97	0.40	0.01	0.03	1.00	0.55*	0.17	-0.16	0.35
	Total	304	0.97	0.42	0.01	0.03	1.00	0.52	0.14	-0.48	0.28

*Correlation is significant at the 0.05 level (2-tailed).

**Correlation is significant at the 0.01 level (2-tailed).

gender for the other three spatial perception measures, favouring males. Time to complete the four measures of spatial perception were also reliable. However, no significant differences were found between males and female on test completion time. As shown in Table 5.3, the three measures of spatial perception were significantly correlated. All four measures were correlated with visual search task performance (mean percentage correct). Mean test scores were reliable indicators of spatial perception.

Mental Rotation.

Performance on each of the mental rotation measures is shown in Table 5.5 and correlations among the tests of mental rotation are shown in Table 5.6. Four tasks were selected to capture mental rotation: The Measure of Ability to Form Spatial Imagery; Mental Rotation Test; Rotated Blocks Test; and the Revised (Purdue) Spatial Visualization Test.

Mental rotation test.

As with the Measures of Ability to Form Spatial Imagery, participants received -1 or +1 for each incorrect or correct match of two of the four alternatives to the target figure depicted in each test item. Cronbach's alpha was .82 ($n = 304$) based on 22 items. Mean test scores ranged from -0.71 to 1.63. Test scores were not normally distributed; the positive skew of +3.39 for male and +6.53 for female participants indicated that most mean scores were low, with some participants correctly identifying one or both alternative figures on each test item more often than most other participants. A heavy positive tail was revealed among female participants, revealing 30 outliers. Mean test scores did not differ by gender males and females were not significantly different. Mean

test completion time was three minutes, 59 seconds. Completion time was significant by gender ($F(1, 302) = 38.91, p = .000$).

Table 5.6: Correlations among Measures of Spatial Visualization (n = 304)

Indicator	Mean Percent Score Correct					Mean Completion Time				
	1	2	3	4	5	1	2	3	4	5
1. MASMI	1					1				
2. Card Rotation	-.55**	1				.06	1			
3. Figure Completion	-.53**	.60**	1			.08	.51**	1		
4. Hidden Figures	-.47**	.37**	.41**	1		.01	.27**	.35**	1	
5. Visual Search	-.37**	.47**	.44**	.29**	1	.00	.41**	.42**	.24**	1
α	0.80	0.95	0.70	0.69	0.66	-	-	0.93	0.93	0.67

**Correlation is significant at the 0.01 level (2-tailed).

Rotated blocks test.

Participants received one point for correctly selecting an alternate depicting the item target figure in a different rotation. Cronbach's alpha was .62 ($n = 289$) based on 14 items. Mean test scores used the full range of the distribution. Mean Rotated Blocks Test scores were not normally distributed due to a positive skew of +3.53 among female participants. One female outlier was found. Men scored higher than women, $F(1, 302) = 5.98, p = .02$, favouring males. Cronbach's alpha was .89 ($n = 288$) on 13 time items. Test completion mean time was two minutes and 11 seconds. Mean item completion time was 10.14 seconds. No significant differences were found between males and females by mean completion time.

Revised Purdue spatial visualization test.

One point was awarded for each correct item match depicting a target and alternate figure before and after rotation. Item 26 yielded zero variance due to a programming error and was removed from the test dataset. Cronbach's alpha was .84 ($n = 217$) based on 29 items. Mean test scores ranged from three to 100 percent. Mean test score were not normally distributed due to a positive skew of +3.24 among female participants mean test scores. Four female outliers were identified. Mean test scores achieved by male participants were significantly different compared to mean test scores achieved by female participants, $F(1, 302) = 5.91, p = .02$. Cronbach's alpha was .91 ($n = 304$) based on 28 time items. Mean completion time was six minutes and 28 seconds. Participants required 13.87 seconds on average to complete test items. Mean completion time was not significantly different by gender.

Summary and correlations.

The four measures of mental rotation were reliable. However, the sample of test scores were not normally distributed. Mean Mental Rotation Test scores achieved by male and female participants were positively skewed. Mean scores on Rotated Blocks and the Revised (Purdue) Spatial Visualization Test were positively skewed for female participants. All four measures revealed gender differences by mean test score, favouring males. Mean completion time did not differ significantly by gender. Table 5.6 showed the four mental rotation measures were significantly correlated. All four measures were correlated with visual search task performance (mean percentage correct).

Spatial Orientation.

Table 5.7 displays performance on each of the spatial orientation measures. Correlations among the tests of spatial orientation are shown in Table 5.8. Three tasks were selected to capture spatial orientation: Guay's Visualization of Viewpoint; the Map Perspective-Taking Test; and the Perspective-Taking and Spatial Orientation Test.

Guay's visualization of viewpoints.

Participants received one point for identifying the correct viewing position of a three-dimensional object. Cronbach's alpha was .88 ($n = 298$) on 23 items. Mean test scores ranged from zero to 95.70 percent. Mean test scores were not normally distributed due to a positive skew of +6.06 among female participants. Six female outliers were found. A significant negative skew (-2.20) was found among male mean test scores, indicating the mean deviation by degree of some males was much lower compared to other participants. Mean test scores achieved by males and female participants were

significantly different ($F(1, 302) = 8.25, p = .004$). Mean male scores were significantly higher than female mean scores. Cronbach's alpha was .82 ($n = 293$) on 22 time items. Mean completion time was three minutes and 50 seconds. Participants required 10.49 seconds on average to complete each item. Mean completion time did not differ by gender.

Map perspective taking test.

The mean difference between the correct and the participant's stated radial degree based on two landmarks from a third reference as stated in each test item determined the mean deviations by degree on this test. Cronbach's alpha was .675 ($n = 304$) based on the 12 items. Mean deviations by degrees ranged from 12.17 to 194.37 degrees and were normally distributed. Mean deviations by degree did not differ significantly by gender. Cronbach's alpha was .90 ($n = 304$) based on 11 time completion items. Mean completion time was two minutes and 55 seconds. Participants took 15.96 seconds on average to complete each item. Mean completion time did not differ by gender.

Perspective taking spatial orientation test.

Mean deviation between the correct and a participant's stated radial degree based on two objects within an array from an alternative viewpoint determined the mean deviations by degree on each test item. Cronbach's alpha was .87 ($n = 304$) based on the 12 items. Mean test scores ranged from 6.60 to 194.37 deviations by degree. Mean deviations by degrees were normally distributed. However, significant kurtosis was revealed among some male (-2.24) and female (-3.09) participants. Some participants achieved much better test scores compared to the sample as indicated by their

significantly lower mean deviation by degree on test items. No outliers were revealed in the data. Gender differences by mean deviations by degree were significant ($F(1, 302) = 9.47, p = .002$); the mean deviations achieved by male participants were significantly less than those achieved by females.

Table 5.7:

Descriptive Statistics for Accuracy for the Spatial Orientation Measures

Test	Gender	N	Range	Mean	SE	Min	Max	Skewness		Kurtosis	
								Statistic	SE	Statistic	SE
Guay's Visualization of Viewpoints	M	109	0.96	0.40	0.03	0.00	0.96	0.58	0.23	-1.01**	0.46
	F	195	0.96	0.32	0.02	0.00	0.96	1.03**	0.17	0.36	0.35
	Total	304	0.96	0.35	0.01	0.00	0.96	0.87	0.14	-0.28	0.28
Map Perspective- Taking	M	109	171.11	91.87	3.61	12.17	183.28	0.38	0.23	0.04	0.46
	F	195	180.64	98.84	2.85	13.73	194.37	0.01	0.17	-0.66	0.35
	Total	304	182.20	96.34	2.25	12.17	194.37	0.14	0.14	-0.50	0.28
Perspective- Taking Spatial Orientation	M	110	177.80	75.21	4.98	6.60	184.40	0.33	0.23	-1.03**	0.46
	F	198	186.92	93.12	3.70	7.45	194.37	-0.04	0.17	-1.08**	0.35
	Total	308	187.77	86.72	3.00	6.60	194.37	0.08	0.14	-1.12	0.28

**Correlation is significant at the 0.01 level (2-tailed).

Summary and correlations.

Analysis of data showed that the three measures of spatial orientation were reliable. The sample of female Guay's Visualization of Viewpoint test scores were not normally distributed; some female participants achieved much higher test scores compared to other participants. The male distribution of scores revealed significant kurtosis but no outliers were found. However, test scores collected on the Map Perspective-Taking Test were normally distributed, with no significant kurtosis. The Perspective-Taking and Spatial Orientation Test were normally distributed. However, male and female test scores revealed significant kurtosis. Gender differences were found on mean Visualization of Viewpoint scores and mean deviations by degree on Perspective-Taking and Spatial Orientation test items were significant, favouring males. Table 5.3 showed the three spatial orientation measures were significantly correlated. All three measures were correlated with visual search task performance (mean percentage correct). Scores achieved on Guay's Visualization of Viewpoint and the Revised (Purdue) Perspective-Taking and Spatial Visualization Test by males were significantly different than those achieved by female participants. Gender differences on Map Perspective-Taking test scores were not significant. Test item completion time was reliable for all three measures of spatial orientation.

Table 5.8:
Pearson Correlations between Indicators of Spatial Orientation (n = 304)

Test	Mean Correct Response				Mean Response Time			
	1	2	3	4	1	2	3	4
1. Visualization of Viewpoints		1				1		
2. Map Perspective Taking	-.38*		1		0.47		1	
3. Perspective Taking Spatial Orientation	-.49*	.52*		1	.46*	.61*		1
4. Visual Search	.48*	-.32*	-.34*		.30*	.33*	.23*	1
α	0.88	0.71	0.87	0.66	0.92	0.91	0.93	0.67

* Correlation is significant at the 0.05 level (2-tailed).

Visual Search.

Participants received one point for correctly matching one of four vehicle choices as the target vehicle based on the driver's viewpoint and aerial visual input provided from a series of loitering drones in each visual search task. Data collected on tasks 3 and 10 yielded zero variance due to a programming error and were removed from further analysis. Cronbach's alpha was 0.48 ($n = 304$) based on the remaining eight visual search tasks. Pallant (2016) notes that Cronbach's alpha should be greater than 0.5 if a scale has less than ten items. Cronbach's alpha was 0.56 ($n = 304$) when task 4 was removed due to low inter-item correlations with the remaining tasks. Mean task scores were positive and normally distributed. Kurtosis was significant +2.43, indicating heavy tails in the overall distribution of mean task scores. However, no outliers on visual task performance were revealed. Gender differences by mean visual task scores were significant, $F(1, 302) = 12.99, p < .001$, favouring men. Cronbach's alpha was .56 ($n = 304$) on the seven items. Mean completion time was three minutes and 39 seconds. Participants required 36.61 seconds on average to complete each task. Mean time completion on the remaining seven visual search task items was not significantly different by gender.

Section summary.

Measures selected for this study were reliable and within the range reported for the original versions of the spatial tests. Some of the measures were positively skewed and some showed relatively high kurtosis, no outliers were found. Studies that administered the original versions of the spatial tests reported normally distributed

samples. In both versions, gender differences were significant on all measures of each spatial type except for those measuring spatial visualization. Males had higher scores than women on tests of mental rotation, spatial perception, and spatial orientation. Thus, in the further analyses, models were tested with gender as a predictor.

Test time limits are set for each of those selected for this study; participant or group test completion times are not reported in the literature. Mean completion time variables were reliable for the spatial measures and the visual search items used in this study. However, it was difficult to compute the mean completion time for Card Rotation; Measure of Ability to Form Spatial Imagery; and Mental Rotation Test because for these tests, participants chose any two of the four alternatives as the correct answers. Some participants did not choose two alternatives as a match with the target figure. Cells designed to store the timestamp when such figures were selected remained blank, further complicating the calculation of mean completion time. Such technical difficulties may be part and parcel of the consequences when using online methods to collect study data. However, reaction time in response to test and task items may be delayed for a number of reason related to the dependency on a host of information technology and communication systems integrated in three separate operating systems, three individual internet browsers, and a diversity of internet providers used to capture each reaction time as participants completed the study's requirements. For these reasons, no further analysis was conducted on mean completion time data.

Confirmatory Factor Analysis of Spatial Types and Visual Search

Measures selected to indicate the four spatial types contained in the typology were found to be reliable and correlated with one another and with the set of visual search tasks. Significant differences between mean test and task scores achieved by male and female participants were also found. These findings support the analysis of a measurement model containing these measures as indicators of the four spatial types.

Spatial visualization.

The implied measurement model of spatial visualization fit the observed data, $\chi^2(2, N = 304) = 8.11, p = .02$. CFI was 0.98 and TLI was 0.95. RMSEA (*Estimate* = 0.10 [90% CI 0.04-0.19, $p < .05$] = 0.09). Variance explained by the four indicators were significant. The measurement model of spatial visualization is presented in Figure 5.1.

Figure 5.1: Factor Structure of Spatial Visualization

Note: sv - Spatial Visualization; masmi - Measure of Ability to Form Spatial Imagery; art - Card Rotation Test; fc - Figure Completion Test; hf - Hidden Figures Test.

Spatial perception.

The implied measurement model of spatial perception fit the observed data, χ^2 (2, $N = 304$) = 10.31, $p = .01$. CFI was 0.97 and TLI was 0.90. RMSEA (*Estimate* = 0.12 [90% CI 0.05-0.20, $p < .05$] = 0.04). Variance explained by the four indicators of spatial perception were significant. The measurement model of spatial perception is presented in Figure 5.2.

Figure 5.2: Factor Structure of Spatial Perception

Note: sp - Spatial Perception; cbh - Crossbar Horizontal; cbv - Crossbar Vertical; hrs - Water Level Test; vert - Test of Inclines.

The measurement models for mental rotation (Figure 5.3) and spatial orientation (Figure 5.4) were *just-identified*. Fit statistics do not provide meaningful information when a model is just-identified. Since there are just as many free parameters as observations in a just-identified model, there are no parameters to estimate and the model is assumed to perfectly fit the observed data. The model can perfectly reproduce the

observed data and therefore does not test any particular hypothesis. Adding a fourth indicator as per the measurement model of spatial visualization and spatial perception would result in an over-identified model capable of estimating the model's fit with the observed data. Three indicators is the minimum recommended by Kline (2015).

Maintaining only essential test administration also reduce the possibility of test fatigue experienced by participants and the potential of participants selecting out of the study.

Figure 5.3: Factor Structure of Mental Rotation

Note: mr - Mental Rotation; mrt - Mental Rotation Test; rpsvt - Revised Purdue Spatial Visualization Test; rb - Rotated Blocks Test.

Figure 5.4: Factor Structure of Spatial Orientation

Note: so - Spatial Orientation; gvv - Guay's Visualizaton of Viewpoint; mpt - Map Perspective-Taking Test; ptsot - Perspective-Taking Spatial Orientation Test.

Four-factor model fit.

The implied four-factor model of spatial types fit the observed data, $\chi^2 (71, N = 304) = 143.91, p < .001$. CFI was .96 and TLI was .95. RMSEA (*Estimate* = 0.06 [90% CI 0.05-0.07, $p < .05$] = 0.15). SRMR was 0.04. The ratio of χ^2/df was 2.03. Taken together, these fit statistics indicate adequate model fit. Model fit should not depend solely on the chi-square statistic, particularly when the sample size is relatively small (e.g., $n \leq 200$). Jackson (2003) also recommended the $N:q$ ratio of parameters to sample size should ideal be at least 10:1 or greater. The present model's $N:q$ ratio was 6:1 further emphasizing the importance of evaluating the model's fit on more than one single fit statistic. Estimates of the indicators for the four spatial factors and between the four

factors were significant. Estimated intercepts for each of the indicators were significant, as were variances for each of the four spatial factors and the residual variances estimated for their indicators. The estimated variance explained by each of the indicators in the model were also significant.

Table 5.9 provides the fit statistics for the one-, two-, and four-factor models of spatial reasoning. Fit statistics for these models show better measures of overall model fit, comparative model fit, and model parsimony by the four-factor model relative to the one- and two-factor models of spatial reasoning. The measures of model parsimony (i.e., Akaike Information Criterion (AIC); Bayesian Information Criterion (BIC), and Adjusted BIC) were lower for the four-factor model compared to other models displayed in Table 5.10. Measures of model comparison (i.e., CFI and TLI) were higher and overall model fit (i.e., χ^2 , χ^2/df , and SRMR) were lower for the four-factor model relative to the one and two-factor models. The pattern of fit statistics for the four-factor model was within acceptable criteria according to Schermelleh-Engel et al. (2003). Satorra–Bentler scaled comparisons between the single-factor and intrinsic-extrinsic model ($t(1) = 26.87, p < .01$), single-factor and static-dynamic model ($t(1) = 24.88, p < .01$), single-factor and four-factor-model ($t(6) = 79.62, p < .01$), intrinsic-extrinsic and four-factor model ($t(5) = 47.38, p < .01$), and static-dynamic and four-factor models ($t(5) = 71.40, p < .01$) were significant. Figure 5.5 displays the four-factor structure of spatial reasoning.

Table 5.9:
Fit Statistics by Model of Spatial Reasoning

Model	Spatial Types	Adjusted					RMSEA							
		AIC	BIC	BIC	χ^2	p	df	χ^2/df	Estimate	CI	p<=.05	CFI	TLI	SRMR
One-Factor	Spatial Reasoning	7213.31	7358.87	7235.67	247.00	0.00	77	3.21	0.09	0.07-0.10	0.00	0.9	0.86	0.06
Two-Factor	Static-Dynamic	7209.04	7368.3	7291.93	240.73	0.00	76	3.17	0.09	0.07-0.10	0.00	0.91	0.89	0.05
Two-Factor	Intrinsic-Extrinsic	7169.78	7329.04	7192.67	201.46	0.00	76	2.65	0.07	0.06-0.09	0.00	0.93	0.91	0.05
Four-Factor	Spatial Visualization, Mental Rotation, Spatial Perception, Spatial Orientation	7122.22	7300	7147.77	143.91	0.00	71	2.03	0.06	0.05-0.07	0.15	0.96	0.95	0.04

Figure 5.5:

Factor Structure of the Four-Factor Model of Spatial Reasoning

Note: SV - Spatial Visualization; MASMI - Measure of Ability to Form Spatial Mental Imagery; CRT - Card Rotation Test; FC- Figure Completion Test; HF - Hidden Figures Test.

MR - Mental Rotation; RB - Rotated Blocks Test; RPSVT - Revised Purdue Spatial Visualization Test; MRT - Mental Rotation Test.

SP - Spatial Perception; Vert - Plumb Line Test; Hrzt - Test of Inclines; CBH - Crossbar Horizontal Test; CBV - Crossbar Vertical Test.

SO - Spatial Orientation; PTSOT - Perspective-Taking Spatial Orientation Test; MPT - Map Perspective-Taking Test; GVV - Guay's Visualization of Viewpoint Test.

Overall model fit and gender.

Two other measurement models were also tested, given the gender differences in spatial reasoning revealed during univariate analyses. An overall measurement model consisting of the four spatial factors fit the observed data by participant gender, χ^2 (162, $N = 304$) = 246.43, $p < .000$. The male contribution to chi-square was 136.62 and the female contribution was 109.81. CFI was .95 and TLI was .95. RMSEA (*Estimate* = 0.06 [90% CI 0.04-0.07, $p < .05$] = 0.16). SRMR was .06. Model fit was assessed as adequate, given these fit statistics. Measurement model parameters did not differ by gender. The model produced the same indicator loadings and indicator intercepts for men as for women. Thus, the model fit the observed data collected from men and women in this study.

Estimates of the indicators for the four spatial factors and between the four factors were significant for men. Estimated means of the four spatial latent variables were significant for men as well. Estimated intercepts for each of the indicators were significant, as were residual variances estimated for each of the indicators of the four spatial factors for men. The estimated variance explained by each of the indicators contained in the men's model of spatial reasoning were also significant. Figures 5.6 displays the men's model of spatial reasoning.

Figure 5.6:

Factor Structure of the Four-Factor Model of Spatial Reasoning for Men

Note: SV - Spatial Visualization; MASMI - Measure of Ability to Form Spatial Mental Imagery; CRT - Card Rotation Test; FC - Figure Completion Test; HF - Hidden Figures Test.

MR - Mental Rotation; RB - Rotated Blocks Test; RPSVT - Revised Purdue Spatial Visualization Test; MRT - Mental Rotation Test.

SP - Spatial Perception; Vert - Plumb Line Test; Hrzt - Test of Inclines; CBH - Crossbar Horizontal Test; CBV - Crossbar Vertical Test.

SO - Spatial Orientation; PTSOT - Perspective-Taking Spatial Orientation Test; MPT - Map Perspective-Taking Test; GVV - Guay's Visualization of Viewpoint Test.

Estimates of the indicators for the four spatial factors and between the four factors were significant for women. Estimated means of the spatial latent variables were significant for women except for spatial visualization ($Estimate = 0.08$, $SE = 0.14$, $p = 0.58$). Estimated intercepts for each of the indicators were significant, as were residual variances estimated for each of the indicators of the four spatial factors for women. The estimated variance explained by each of the indicators contained in the women's model of spatial reasoning were also significant. Figure 5.7 displays the women's model of spatial reasoning.

Figure 5.7:

Factor Structure of the Four-Factor Model of Spatial Reasoning for Women

Note: SV - Spatial Visualization; MASMI - Measure of Ability to Form Spatial Mental Imagery; CRT - Card Rotation Test; FC - Figure Completion Test; HF - Hidden Figures Test.
MR - Mental Rotation; RB - Rotated Blocks Test; RPSVT - Revised Purdue Spatial Visualization Test; MRT - Mental Rotation Test.
SP - Spatial Perception; Vert - Plumb Line Test; Hrzt - Test of Inclines; CBH - Crossbar Horizontal Test; CBV - Crossbar Vertical Test.
SO - Spatial Orientation; PTSOT - Perspective-Taking Spatial Orientation Test; MPT - Map Perspective-Taking Test; GVV - Guay's Visualization of Viewpoint Test.

Figure 5.8: Factor Structure of Easy and Difficult Search

Note: e - Easy Visual Search; d - Difficult Visual Search; m - task.

Visual search.

A two-factor model of static and dynamic visual search did not converge.

Exploratory factor analysis showed a two-factor model would fit the observed data. One factor labelled, 'Easy', consisted of tasks 2, 5, and 9, with mean correct scores of .72 ($SD = .45$), .55 ($SD = .50$), and .72 ($SD = .45$), respectively. The second factor labelled, 'Difficult', consisted of tasks 6 through 8, with mean correct scores of .44 ($SD = .50$), .36 ($SD = .48$), .37 ($SD = .48$), respectively. A two-factor model of overall visual search consisting of an easy and a difficult search factor demonstrated goodness of fit, $\chi^2(8, N = 300) = 4.12, p = .85$. CFI was 1.00 and TLI was 1.03. RMSEA ($Estimate = 0.00$ [90% CI 0.00-0.04, $p < .05$] = 0.98). SRMR was .04. No modifications were required to fit the model with the observed data. The standard estimate between the easy and difficult factor

($Estimate = 0.53$, $SE = .10$, $p < .00$) was significant. Variance explained by the six tasks shown in Figure 5.8 were significant.

Figure 5.9: Proportion Correct by Visual Search Type by Gender

The descriptive statistics for the two visual search factors by gender are provided in Table 5.10. Mean scores reflect the proportion of correct responses on each visual search type by gender. Tasks 2, 5, and 7 were presented in infrared, while tasks 6, 8, and 9 were presented in normal ambient colours. All tasks presented visual information in five windows, with a main view in the centre of the participant's computer screen bounded on each side by an upper and lower window. Visual information in each window appeared to be rotating in a clockwise fashion throughout the task. Targets and distractors were stationary in tasks 2 and 5, while the targets and most distractors in the remaining tasks were in motion, travelling around on the city's streets. That is, two of the three easy

visual search tasks presented stationary targets and distractors, while all three difficult visual search tasks presented targets and most distractors in motion. Figure 5.9 displays the proportion of correct responses for each visual search type by gender.

Table 5.10: Descriptive Statistics of Visual Search (N = 304)

Factor	Mean	SD	Min	Max	Skewness		Kurtosis	
					Statistic	SE	Statistic	SE
Easy (Tasks 2, 5, 9)	0.67	0.32	0.00	1.00	0.58**	0.14	-0.70*	0.28
Difficult (Tasks 6, 7, 8)	0.39	0.36	0.00	1.00	-0.40*	0.14	-1.16**	0.28

* $p < .05$; ** $p < .01$

Section summary.

Confirmatory factor analysis showed that an overall implied measurement model of spatial types fit the observed data collected in this study and that the model parameters were the same for men and women. Thus, the patterns of relations among the measures collected in this study were consistent with the four-factor model proposed by Uttal et al. (2013). In the next section, the four spatial factors were regressed on visual search.

Structural Regression Modeling.

The structural regression model of visual search with the four factor model of spatial visualization, mental rotation, spatial perception, and spatial orientation did not converge, likely due to multiple unmeasured relations between visual search performance and the 14 spatial tasks and the relatively small sample size for a model this complex. Thus, multiple regression was used to explore the relations between the four spatial measures, gender, and visual search performance.

Table 5.11:

Correlations between Visual Search, Spatial Types, and Gender (n = 304)

	1	2	3	4	5	6	7
1. Easy Visual Search	1						
2. Difficult Visual Search	.30**	1					
3. Spatial Visualization	.31**	.49**	1				
4. Spatial Perception	.27**	.26**	.52**	1			
5. Mental Rotation	.36**	.45**	.77**	.56**	1		
6. Spatial Orientation	-.30**	-.41**	-.61**	-.52**	-.67**	1	
7. Gender	-.16**	-.15**	-.03	-.20**	-.15**	.18**	1

** Correlation is significant at the 0.01 level (2-tailed).

Multiple regression results.

The factor scores for easy and difficult visual search was used as dependent measures in a multiple regression. The independent variables included factor scores from the model of spatial abilities and gender. Table 5.10 displays the correlations among the two visual search types, gender, and the four spatial types. The correlations were

significant. Similar correlations were revealed between the two intrinsic spatial factors and the two visual search factors. The correlation between mental rotation and spatial visualization was particularly high, indicating shared variance with visual search. A higher correlation was revealed between mental rotation and easy visual search than between spatial visualization and easy visual search. Conversely, the correlation between spatial visualization and difficult visual search was higher than the correlation between mental rotation and difficult visual search.

Table 5.12:

Summary Statistics for a Regression Model of Easy Visual Search (n = 304)

Model	B	SE	Beta	t	p
1 (Constant)	0.37	0.083		12.77	0.00
Spatial Visualization	0.26	0.03	0.08	0.92	0.36
Spatial Perception	0.18	0.02	0.06	0.82	0.41
Mental Rotation	0.62	0.03	0.20	2.08	0.04
Spatial Orientation	-0.03	0.02	-0.08	-1.04	0.30
gender	-0.66	0.04	-0.10	-1.77	0.08

* $p < .05$

Gender and the four spatial factors were entered in the main analysis.

Subsequently, I tested each interaction between gender and spatial ability as potential predictors of easy and difficult visual search. As shown in Table 5.11, the model of easy visual search that included the five main effects was significant, $F(5, 298) = 10.41, p < .000$, adjusted $R^2 = .13$. The only unique predictor of easy visual search was mental rotation. As displayed in Table 5.13, the model of difficult visual search that included the

five main effect was also significant, $F(5, 298) = 23.01, p < .000$, adjusted $R^2 = .28$.

Gender, spatial visualization, and spatial orientation were significant unique predictors of difficult visual search.

Table 5.13:

Summary Statistics for a Regression Model of Difficult Visual Search ($n = 304$)

Model	B	SE	Beta	t	p
1 (Constant)	0.16	0.08		1.85	0.07
Spatial Visualization	0.38	0.08	0.38	4.65	0.00
Spatial Perception	-0.09	0.06	-0.09	-1.51	0.13
Mental Rotation	0.11	0.09	0.11	1.22	0.22
Spatial Orientation	-0.15	0.07	-0.15	-2.11	0.04
gender	-0.24	0.11	-0.12	-2.28	0.02

* $p < .05$

Men achieved higher mean visual search scores than women. None of the interactions between gender and the spatial factors were significant. Thus, differences in spatial ability as measured by the four-factor model did not fully account for gender differences in visual search.

Chapter 6: Discussion

Spatial ability has been studied since the early years of the last century, as described in detail in Chapter 2 of this thesis. Many tests and tasks have been developed that are commonly used to measure spatial reasoning. A succession of factor analyses have identified two or three latent spatial factors that have come to be known as spatial visualization, spatial perception, and mental rotation. A fourth spatial factor - spatial orientation - has also been studied extensively over the past twenty years. Only in the past ten years has a framework been proposed to explain how spatial reasoning is structured. Testing the proposed framework is important to confirm the theory, dimensionality, and to specify models predicted by spatial reasoning.

Recently, a general framework of spatial thought and language was proposed by Chatterjee (2008) and extended to include spatial tasks by Uttal et al. (2013). Classifying spatial reasoning according to general type organized thinking about space in a logical manner. The literature on spatial reasoning as a cognitive process focused on object recognition and manipulation also extends back to the early years of spatial research (e.g., Brown & Stephenson, 1933; Guilford & Lacey, 1947; Kelley, 1928). Chatterjee (2008) proposed that people organized their reasoning about space by two dimensions involved in recognizing and manipulating objects, specifically, the location of object features (i.e., intrinsic or extrinsic to the object) and object motion (i.e., static or dynamic). Chatterjee's (2008) framework as a typology of spatial tasks remains theoretical; only one article testing its dimensions has been published to date (Mix et al., 2018). However, object recognition is the central process in two of the most important, competing theories of

visual search namely, feature integration (Gelade & Treisman, 1980) and guided search (Wolfe, 1994; 2017). The theory of guided search includes a specific set of intrinsic object features that are used to compare and contrast a set of objects and determine a target's presence or absence, and thus is closely tied to Chatterjee's theory of object recognition.

In this dissertation, I designed a study to test the 2 x 2 typology proposed by Uttal et al. (2013). Each spatial type was assessed with three or four different measures that were chosen based on Uttal et al.'s categorization of tasks. Participants were recruited through an online system. A total of 304 people completed enough of the study to be included in the analyses. In general, the measures were reliable and normally distributed, with only a few exceptions. The data were therefore used in a confirmatory factor analysis to test the four-factor model of spatial reasoning. As predicted, the proposed four-factor model of spatial reasoning fit the observed data. Measures of overall model fit, comparative model fit, and model parsimony showed that the four-factor model of spatial reasoning was superior to the one- and two-factor implied models based on the study's observed data. The pattern of relations between indicators of spatial reasoning and the four factors was the same for men and women, even though men performed better than women on most of the spatial measures.

Participants also completed a visual search task that was designed to be similar to a military or para-military aerial surveillance task. Exploratory factor analysis revealed a two-factor model of easy and difficult rather than static and dynamic visual search, as originally designed. Men achieved higher mean scores than women on visual search. A

structural model that included the four spatial factors and visual search was tested but did not converge, presumably because there were multiple unmeasured relations between visual search and spatial reasoning that were not included in the model.

To determine which, if any, of the four spatial factors predicted visual search performance, visual search scores were regressed on the four spatial factors and gender. Mental rotation (i.e., intrinsic dynamic skills) predicted easy visual search. Spatial visualization (i.e., intrinsic static skills), spatial orientation (i.e., extrinsic dynamic skills), and gender predicted difficult visual search performance. Men achieved higher visual search scores than women, even after controlling for the four spatial ability measures. However, there were no interactions between gender and any of the four spatial factors, suggesting that the patterns of individual differences among participants on spatial visualization and spatial orientation were similar for men and women.

Why were spatial visualization and spatial orientation related to difficult visual search performance? Spatial visualization presumably predicted visual search because it required participants to recognize a vehicle as the target among other vehicles which were distractors – thus, participants had to pay attention to the target's intrinsic features to choose the correct answer. For example, intrinsic features such as colour and shape could be used to recognize a police car as the target in contrast to a dump truck, a pick-up truck, a red or blue car, or an ambulance. Thus, an individual's skill at processing intrinsic but static features of objects, as measured by the spatial visualization factor, was related to difficult visual search. Notably, however, mental rotation was also correlated with visual search; the high co-linearity between mental rotation and spatial visualization suggests

the two measures were accounting for the same variance in visual search. Mental rotation operationalized as the manner of motion of intrinsic object features predicted easy visual search. Higher mental rotation skill was related to higher performance on easy visual search.

Furthermore, it is likely that participants used their ability to process the extrinsic features of dynamic (moving) objects to track the pathways of target vehicles and decide among the four possible choices in each difficult visual search task, resulting in the correlation between the spatial orientation factor and difficult visual search. Participants needed to track the moment-by-moment location of vehicles in the visual search task relative to landmarks such as buildings, parks, and other vehicles passed. Participants needed to evaluate which of the four vehicle choices matched the driver's perspective. They may have evaluated the potential views one at a time in a serial decision process, however, the current study did not assess the specific processes used in the visual search task. Spatial perception may also have also been involved in visual search, however, individual differences in this factor did not uniquely predict visual search performance independently of spatial visualization and spatial orientation. For example, spatial perception may have been involved when participants had to determine the target vehicle's location to recognize the target vehicle among the other three distractor vehicles.

The four-factor model fit was adequate, given the data collected in this study. Based on chi-square alone model fit could be assessed as poor but the chi-square test for model evaluation is highly sensitive to sample size. Significant differences between

observed data and an implied model are found when sample size is large even though these differences are very small. As a rule of thumb, sample size over 200 are required to test structural equation models. Even with such samples, the significance of the chi-square statistic must be considered with other fit statistics to determine goodness of fit. Jackson's (2003) $n:q$ rule provides further guidance for evaluating fit as a ratio of free parameters to sample size to indicate appropriate statistical power. Generally a ratio of 10:1 is considered adequate to test structural equation models. The ratio of free parameters to sample size was $48/304 = 6.33$ for the four-factor model of spatial reasoning. The ratio of free parameters to sample size was $76/304 = 0.25$ for the model including gender. Still, other fit statistics commonly used and selected to evaluate goodness of fit in this study showed the four-factor model fit the observed data. Overall, therefore, this study suggests that the four-factor model proposed by Uttal et al. (2013) is a reasonable characterization of spatial abilities. Nevertheless, further studies based on samples that meet the minimum $n:p$ ratio would be useful in instilling greater confidence in the overall model.

Object recognition seems to be intuitive in visual search. The most complex visual search trials are framed as spatial configurations, with less complex searches involving either two or a single intrinsic feature. Therein lies a common nexus between spatial reasoning and visual search: These trials typically involve objects whose features are stationary during visual search trials conducted in laboratory studies. To reiterate, object features are intrinsic when they are innate to the feature; they are extrinsic when those features are in relation to another object in some way. The recognition of a target

due to its relations with other objects and their distinct features exemplifies how spatial reasoning and visual search are associated in this study.

Gender differences in spatial reasoning were significant in this study. An intersectional approach has identified moderators that further define whether gender differences are genetic or experiential. An extensive review of gender differences by Hyde (2014) noted the interaction between gender and ethnicity provided an advantage for white males on math performance. However, the effect size was trivial among other ethnicity groups. Hyde (2014) also reported a moderate effect size on mental rotation favouring men, regardless of ethnicity. The interaction of gender and ethnicity on other spatial types has not been reported in the literature.

Gender differences in spatial reasoning do not appear to be genetic. Hyde (2014) pointed out that only the sex chromosome distinguishes men from women. Rather, the difference between men and women in spatial reasoning is likely due to experience. Men tend to be interested in things, while women tend to be interested in people. The diversity of interest leads to distinct differences in experience, which may account for the moderate to large effect sizes favouring the interests of men in STEM disciplines and occupations. Men report higher self-confidence and lower anxiety in math, which translate into larger effect sizes than actual performance by gender (Hyde, 2014). Alternatively, women's share of research positions significantly predicted smaller math self-concept and math self-efficacy. Attitudinal differences moderate the experience of men and women in important tasks such as math achievement and pursuit of STEM disciplines and occupations where spatial reasoning is essential.

The effect of practice also indicates how spatial reasoning is influenced by experience. Studies report boys practice twice as much as girls in video gaming, gaining greater experience in three-dimensional spatial skills to substantiate the large effect size by gender in mental rotation. Uttal et al. (2013) showed that experience in the form of spatial training can eliminate gender differences in spatial reasoning. Spatial reasoning is malleable and can be improved, regardless of gender.

Future work

Although many studies cite the theory proposed by Chatterjee (2008) and operationalized by Uttal et al. (2013), only one published study has tested the typology to date (Mix et al., 2018). Mix et al. were not able to test the four-factor model with grade 6 students; for kindergarten and grade 3 students, either one or two factor models were the best fit for the data. Many more studies that directly test the typology are required to demonstrate the validity of the framework for understanding individual differences in spatial abilities. Such studies will demonstrate the validity and utility of the typology if they employ a variety of measures as indicators of the four spatial types. The tests chosen in the present study were aligned as closely as possible to those indicated in Uttal et al. However, other measures may be as good, or better, indicators of the spatial abilities defined in the 2 x 2 model.

The 2 x 2 typology captures important dimensions of object processing. In future, using the 2 x 2 typology to predict measures of navigation and way finding may support the development of assessment techniques, as well training and selection systems for air traffic controllers, harbour pilots, officers of the watch on ships, and submariners. The

typology may also serve to identify which spatial types predict math ability in children. Training may also be developed to assist children who show low ability in particular spatial types that predict math ability so that such spatial training can eliminate barriers to later interest and success in academics that demand higher spatial reasoning such as science, technology, engineering, and math and associated STEM careers.

Replication and generalizability.

Kline (2015) emphasized the importance of replicating structural equation models. It is important to replicate the results of the present research in similar conditions (e.g., online studies) and in more traditional studies. Such replications would address the generalizability of the model. Similarly, it is important to extend this research to other samples that assess individual differences in groups other than undergraduate students. My original goal for this study was to examine the spatial reasoning requirements and visual search performance of military personnel. Similar findings with a group of military personnel would indicate these models generalize beyond the current sample characteristics. The findings on spatial reasoning in this study and those relating the importance of our common perception system in visual search suggest that the four-factor model will generalize across samples. In this study, only target-present tasks were conducted without time constraints. The study's visual search tasks may have been further complicated if target-absent tasks were also conducted.

Further, the generalizability of visual search in relation to spatial types is an important question. The current results are plausible in that the visual search tasks used in this study involved the types of spatial information, in relation to the intrinsic features of

objects and the relations between those objects and other objects in the world, that were required in the visual search task. Feature detection and integration is essential in everyday searches. Moreover, any visual search is very likely guided by a specific set of features that distinguish the search item from all others in a defined space. The object proper, its manner of motion, stationary location, or position at any moment while in transit can be identified by features and motion. At rest or in motion, a target is likely to be recognized by its distinct features, indicating spatial visualization and spatial orientation are integral in visual search.

Further work is required to improve the reliability of some of the spatial measures and the visual search trials designed for this study. The technical difficulties encountered of conducting the study online should also be addressed before the study is replicated. Replications of this study by applying these improved measures of spatial reasoning and visual search to participants online may also show the models generalize across a diversity of samples as well.

It would be interesting to explore the relations between spatial abilities and performance of individuals who use visual search in their jobs: For example, exploring how radiologists, baggage handlers, pilots, and air traffic controllers reason about space to detect the presence and absence of targets among distractors (Yuan, Uttal, & Franconeri, 2016). The common human perception system relied on by undergraduates and specialists alike may result in similar patterns, however, each real-world task may involve different aspects of their spatial abilities. Gender differences in spatial reasoning should reduce to a matter of skill and should be addressed by providing women with

more practice. Spatial training could improve and therefore eliminate differences in spatial and visual search task performance between men and women (Uttal et al., 2013). More generally, any individual who initially demonstrates low spatial reasoning may show improved performance given research on spatial training techniques and methods (Law, Pellegrino, & Hunt, 1993; Reilly & Neumann, 2013; Stieff & Uttal, 2015).

In this study, measures selected based on the typology demonstrated that spatial reasoning was dependent on object features and motion. Two types of spatial reasoning about static and dynamic intrinsic object features predicted men's and women's visual search. The typology provided a different perspective on spatial reasoning compared to the broader, more holistic view of Newcombe and Shipley's (2015) *disembedding* factor. Measuring spatial visualization and mental rotation as variables that share a common dimension of intrinsic object features but were distinct from each other by an object's manner of motion distinguished these two spatial types. In a similar way, spatial orientation was distinguished from spatial perception by its unique contribution to predicting visual search by detecting the intrinsic and extrinsic features of a target and its distractors, as the target moved along its pathway. Motion was integral in discriminating between spatial types that predicted target recognition in this study.

Test and task difficulty and complexity.

This dissertation heeded past findings on the importance of task difficulty and complexity in identifying spatial factors and types of visual search. Mean scores suggested that participants found some tests and visual search tasks more difficult and complex relative to others. The exploratory factor analysis that was necessary to re-

specify visual search showed that visual search performance depended on whether tasks were easy or difficult rather than static or dynamic as originally designed. Past research findings that showed the cognitive process by which object manipulation and recognition depended on the degree of task complexity and difficulty. Zimmerman (1954) reported perceptual speed decreased as spatial test items became more difficulty and complex by manipulating the degree of rotation from zero of test figures, like those depicted in Guay's Visualization of Viewpoints, the Revised Purdue Spatial Visualization Test, the Perspective-Taking and Spatial Orientation Test, and the Map Perspective-Taking Test. Early research such as Zimmerman (1954) and Fleishman (1957) also showed that test and task complexity and difficulty predicted pilot training success. Future replications of this study that successfully capture the time required to complete spatial test items may support these earlier findings that relate perceptual speed to task complexity and further discriminate between spatial factors defined by the typology.

This study demonstrated visual search difficulty was predicted by separate spatial factors, regardless of gender. The visual search performance of women and men depended on their mental rotation, spatial visualization, and spatial orientation skills. As alluded to earlier, future studies examining the typology to predict visual search performance among military personnel may predict basic training outcomes of women and men employed in occupations that conduct such as Unmanned Aerospace Vehicle Operators, Sensor Operators, or Search and Rescue Technicians.

Neurological findings and spatial reasoning.

Studies that examined how the human brain processes visual input to recognize and manipulate objects lead to the framework of spatial thought and language (Chatterjee, 2008). Neurological studies show the ventral system processes visual information on object intrinsic features, while extrinsic object features are processed by the dorsal system's neuronal pathway (Chatterjee, 2008; Deubel, et al., 1998; Kroliczak et al., 2008)). Studies also reported that visual information on object motion was integrated via these same pathways to further distinguish the four types of spatial reasoning (Chatterjee, 2008; Farivar, 2009; Hickok & Poeppel, 2004; Rauschecker, 2012). Interestingly, neurological studies on spatial reasoning do not discriminate by gender; the function of these two neurological pathways are used in the same way by women and men to process object features.

Further research is required to further establish the typology as a classification of spatial reasoning, while advancing scientific research on spatial types. Detailed analyses and findings have been reported on the modalities of the brain that support object recognition. Science would benefit from neurological studies that clarify how the various areas of the brain work to recognize targets among distractors during visual search trials (Yuan, Uttal, & Franconeri, 2016). Such research may provide convergent validity to the findings reported in this study and further linking the typology, its dimensions, and four spatial types to the spectrum of perspectives on spatial thought, language, and task performance.

Visual Search

I referred to visual search as a type of perceptual task requiring attention involving an active scan of the visual environment for a target among distractors. Three common categories of visual search tasks were discussed in the context of two complementary theories linking the basic physiology of visual search to understand how individuals conduct searches. In this study, object features predicted visual search task performance as implied by both theories. The study could not address whether visual search involved a pre-attentional stage. The study could not determine whether a small set of intrinsic features guided the visual search of participants.

Theory and object recognition.

Feature integration and guided search theory were discussed in Chapter 2 to show visual search had a theoretical basis in object recognition similar to spatial reasoning and could serve as a criteria to evaluate the typology. Object recognition on the basis of object features was supported by the study's findings. Both spatial visualization and spatial orientation predicted visual search conducted by women and men in this study. Future studies may examine whether these two spatial types are activated as successive layers of cognitive maps used by participants are developed to conduct environmental scans of the search field during a pre-attentional phase. Such studies may also determine whether spatial types are involved in the formation of a more discreet set of intrinsic features to filter distractors and recognize the target during the attentional phase of visual search.

Target-absent trials.

Only target-present visual search trials were conducted in this study. The set was considered to be difficult and complex, given the sensory input available during each visual search task without removing the target from among the set of distractors. Target-absent trials could have been included by removing the target and adding another response item to the multiple choice set (e.g., “No Target” or “Target Absent”). The visual search literature supports the inclusion of target-absent trials as a criteria. It is difficult to determine whether target-absent trials would improve model fit between visual search, spatial visualization, spatial perception, mental rotation, and spatial orientation across gender. Further research of this study of the effect of target-absence on the model’s retained in this study is required.

Ease of search and set size.

The study did not find ease of search was a function of set size. Target movement determined ease of search in this study; a lower percentage of participants correctly identified the target in three trials where the target and distractors were in motion. The set of easy and difficult trials contained the same set of distractors, with one of the distractors serving as the target in each trial. The finding on set size and ease of search in this study is limited however by the fact that only three easy and three difficult visual search tasks were retained for testing. Again, the target was present in each of these tasks. Further study and testing is required to determine if target and distractor movement significantly effects the association between ease of search and set size.

Conjunctive search.

This study focused on conjunctive search trials. More than one intrinsic feature was likely used by participants to distinguish the target from distractors in the study's visual search tasks. Search trials were not designed to focus participant attention on the spatial arrangement of line segments as opposed to any single or conjunction of the target's and distractor's intrinsic features. Although the study's visual search tasks were online simulations, they were designed to activate the spatial reasoning likely used in real-world situations. Subsequent studies may compare the differences between men and women's spatial reasoning to resolve a similar set of visual search tasks where vehicles as targets and distractors must be distinguished from one another by a specific single intrinsic feature (e.g., colour or shape), conjunctions limited to colour and shape for instance, and spatial configurations where vehicles are depicted as simple-to-complex line drawings among common city infrastructure such as roads and buildings. Such future studies may support past findings that such conspicuous single features become more difficult to detect when bound with others or are implied by spatial configurations. Future research that study the effect of target and distractor motion on recognition and search performance by task type may also advance the science of visual search and its prediction by spatial reasoning types found in the typology (Wagner & Schnotz, 2017).

Simulating a real world task.

Given the findings in this study, questions may arise concerning the necessity of measuring spatial reasoning to predict a simulated real world task. Why not simply test research participants or candidates for training and employment with a work sample test such as the visual search tasks selected as a criteria set in this study? To do so would return to the fundamental question of measuring and identifying the latent factors activated while a simulated real world task is being performed. What occurs within the individual when a simulated visual search is being performed and does performance on simulated visual search predict actual visual search? How similar is the simulated and actual real world task? To address these questions at the very least, the variance explained of an actual real world task by a simulated real world task would need to be determined. It is likely that other unmeasured factors predict simulated and actual visual search tasks and that these other factors generalize across a variety of tasks, including visual search.

Simulations present a consistent task to each participant. Test conditions are much more difficult to control in real world tasks, particularly in the context of aerial surveillance. Even simulations that introduce possible real world conditions may not be consistent with those experienced during actual training or employment. Validation studies would be necessary to establish the utility of a simulated real world task as an assessment technique. Even so, the shared variance between simulated and actual real world tasks may be limited.

The importance of validation research becomes even more important as the risk and consequences associated with selecting candidates solely on their work sample test results increase. Organizations would need to carefully weigh the risk of selecting or hiring candidates to detect anomalies on x-rays, radars, and security scanners based on work sample results instead of longstanding valid predictors of training and job performance like those identified by Schmidt and Hunter (1998) such as general mental ability and consciousness, for instance. It would be likely that a simulated real world task is specific to certain aspects of one job within an occupation. Therefore, any simulated real world task is unlikely to generalize across many occupations and jobs. For instance, the simulated real world task in this study may predict only a narrow scope of the training and job tasks performed by search and rescue technicians, air navigators, or surveillance operators. Such a simulated real world task may not predict any training or job performance conducted by airport security scan operators or radiologists.

Even though the structural regression model of visual search on spatial reasoning did not converge in this study, the subsequent regression analyses showed that specific spatial types predicted specific types of visual search independent of gender. Higher measures of specific types of spatial reasoning predicted higher performance of specific types of visual search. Future studies may also determine that certain types of visual search conducted by training candidates and job incumbents are easier or more difficult than others and that specific types of spatial reasoning predict their visual search performance independent of gender. Such findings would confirm the literature on general cognitive ability and specific cognitive abilities such as spatial reasoning as consistent predictors of training and job performance.

Limitations

Many participants consented but did not complete any of the study's requirements. Participants completed the 14 tests of spatial reasoning in any order. The spatial tests ranged from easy to difficult. Participants may have encountered a difficult spatial test initially or early in the completion of these tests. They may have assumed the remaining tests were equally difficult to complete and therefore, abandoned the study's requirements. In the future, spatial tests may be grouped by difficulty, with each test group being administered from easy to difficult to mitigate the high attrition rate experienced in this study. Instructions to participants should also clearly indicate that spatial tests are grouped by relative ease or difficulty, while reiterating responses are anonymous and for research purposes only.

The high attrition rate experienced in this study may have also occurred due to the requirement for participants to download the game from the study's website to their personal computers. Participants may have been reluctant to fulfil this study requirement after consenting to participate, with reservations concerning the potential harm to their personal computers. The study's website was secure and participants did not provide any indication that downloading the study materials affected the function or performance of their personal computers.

In addition, this study had several limitations. The first limitation is that the participants were undergraduate students taking first-year courses in either cognitive science or psychology and thus the results cannot be generalized to other groups. The second limitation was that majority of participants in this study were female and were mostly enrolled in social science disciplines. Males and undergraduate STEM students were under-represented. A third limitation is that data collection was done online, and thus there was no control over whether participants were focused on the tasks, on the order in which they completed the tasks. The very high rate of non-completion reflects the lack of consequence of failing to complete the study. Thus, the findings should not be generalized to more traditional and well-controlled situations.

A fourth potential limitation is that the spatial tests selected to measure spatial reasoning in this study were originally in paper-and-pencil form and intended for group administration. Direct comparisons between the online and in-person test performance would be helpful in determining the validity of the current use of these measures.

A fifth limitation focused on the freedom to complete the study requirements at the participant's convenience. Participants received a small percentage of their course credit for completing the study's requirements. Some may have reconsidered the commitment and work required to complete 14 spatial tests, three levels of spatial training, and a set of ten visual search tasks in order to receive that course credit. Others may have rushed through the study to satisfy its requirements and receive their partial course credit. Further replication of this study will determine if the models in this study will be retained if participants were limited by the time to complete each spatial test and the set of visual search tasks, while under supervision. However, in practical terms, the current study was only possible in the online format. Online spatial testing and training and visual search tasks took participants in this study approximately an hour and 15 minutes to complete, asynchronously. Mass testing would have required groups to attend testing administrations at specific times and locations, requiring significant resources and coordination. The very low completion rate (20%) reflects the limitation of online testing.

It should be noted there was ecological validity in allowing participants to complete the study's requirements under these online conditions. The online method used in this current research showed that asynchronous test administration yields results that are interpretable. Modern technology implies testing participants online and at their convenience will continue as a acceptable and perhaps expected or preferred method of data collection into the future.

Conclusion

In the current research, I used an innovative method for testing models of spatial reasoning and visual search and collected online data from participants. The goal of the study was to test a framework of reasoning about space that integrated past research and theory. The framework identified four spatial types defined by crossing object features and motion. Object recognition and manipulation was long ago hypothesized as necessary and sufficient in spatial reasoning, as was object recognition by intrinsic features in visual search. The theoretical link between spatial reasoning and visual search by object features made the visual search a plausible criterion for testing the utility of a typology of spatial types.

The results of this study showed that reasoning about space on the basis of object features and motion captured variability among the 14 spatial ability measures. Consistent with previous research, women had lower scores than men, however, the pattern of relations among tests did not differ by gender. Visual search depends on particular types of spatial reasoning. People use spatial processes in many aspects of their daily lives, from complex tasks. The typology is a useful framework for determining the specific processes that characterize spatial reasoning, and how individual differences in those spatial processes are related to search performance.

Appendices

Appendix A - Fit Statistics

This annex presents fit statistics used to determine the goodness of fit of models tested in this dissertation. The fit statistics discussed in this annex are generally used in the current literature to evaluate the fit between an implied model and a sample of observed data. The descriptions below are meant as a basic guide.

Chi-square and its associated p value.

The chi-square goodness of fit is the most commonly used goodness of fit statistic. It is used to evaluate the appropriateness of an implied model, given a set of observed data. Chi-square tests the null hypothesis that the model's covariance matrix is equal to the population covariance matrix. It is a measure of 'badness of fit'; when the fit between the implied model and observed data is poor, the p -value is significant (i.e., the null hypothesis of no difference is rejected). When the chi-square value is small, the population covariance matrix and the model's implied covariance matrix are not significantly different from one another. A chi-square p value greater than 0.05 indicates the model is compatible with the population matrix. Otherwise, the implied model does not fit the observed data and should not be retained.

Caution must be applied when relying solely on the chi-square test for model evaluation as it is highly sensitive to sample size (Curran, West, & Finch, 1996). Researchers are more likely to find significant differences between the observed data and the implied model when the sample size is large even though these differences are very small (Jackson et al., 2009; Schermelleh-Engel et al., 2003). As a general rule, the

significance of the chi-square statistics can be disregarded when the sample size is over 200 and other fit statistics also indicate goodness of fit (Jackson et al., 2009).

Schermelleh-Engel et al. (2003) also recommend using the chi-square as a goodness of fit index by comparing the magnitude of the χ^2 with the number of degrees of freedom as an expected value of the sample distribution. Theoretically, a small ratio χ^2/df between 2 and 3 would signify an adequate-to-good model fit.

Root Mean Square Error of Approximation (RMSEA).

Root Mean Square Error of Approximation (RMSEA) is often cited by many scholars who use structural equation modeling as one of the best performing goodness of fit indexes when the implied model is evaluated against observed data (McDonald & Ho, 2002; Jackson et al., 2009; Marsh et al., 2005). However, testing the null hypothesis by comparing the exact match between the population variance and the variance implied by the specified model, is more likely to be rejected when the sample size is sufficiently large. The RMSEA allows researchers to test an approximation of the null hypothesis rather than the exact null hypothesis (Browne & Cudeck, 1993; Nevitt & Hancock, 2000). RMSEA is a measure of goodness of model fit that approximates the closeness of fit between the model and population, rather than the exact fit, which is often not practical especially when large samples are not available (Nevitt & Hancock, 2000). RMSEA is assessed by confidence interval (CI) and the statistic's probability of occurring with a less than 5% probability represented as a percentage on a scale of 0-100. For example, statistical output may be reported as RMSEA (*Estimate* = 0.029 [90% CI 0.000-0.049, $p < .05$] = 0.958), indicating that the approximate estimate is less than .05 and therefore

significant, with 95.8 percent confidence in the estimate's location within the interval range (i.e., between 0.000 and 0.049).

RMSEA is a measure of the discrepancy between the observed data and the population due to approximation of closeness of fit between the implied model and the population from which the observed data was obtained (Jackson et al., 2009; Schermelleh-Engel et al., 2003). A RMSEA cut-off value of 0.05 or lower is commonly reported as the conventional threshold indicating good model fit (Browne & Cudeck, 1993; Schumacker & Lomax, 2004). RMSEA values between 0.05 and 0.08 also are considered acceptable for model fit (Jackson et al., 2009; Schermelleh-Engel et al., 2003). Hu and Bentler (1999) recommended 0.06 as a cut-off value for RMSEA for good model fit.

The value of PCLOSE with RMSEA is also important, since PCLOSE tests the null hypothesis that the value of RMSEA is less than or equal to 0.05, which indicates a close fit model. The value of PCLOSE associated with RMSEA should be greater than 0.05 to ensure a close fit (Schermelleh-Engel et al., 2003).

Tucker-Lewis Index (TLI).

The Tucker-Lewis Index (TLI) is a goodness of fit index that compares the null model fit with the implied model fit when the degrees of freedom of both models are taken into account. TLI is less affected by sample size than other fit statistics like chi-square and RMSEA. Examination of the TLI is highly recommended during model evaluation (Hoe, 2008).

TLI values range from zero to one. TLI can sometimes be not normed, which may cause its value to leave the zero-to-one range, most typically above one. Normed and not normed TLI values close to one or greater than one respectively, indicate better fit.

Schermelleh-Engel et al. (2003) recommend TLI values at 0.97 or higher indicate good model fit, although 0.95 is considered acceptable by many researchers (Hu & Bentler, 1999; Jackson et al., 2009; Lomax & Schumacker, 2004). Hoe (2008) suggested that TLI values of 0.90 or greater provide an acceptable threshold value. A TLI value lower than 0.90 indicates model re-specification is required.

Comparative Fit Index (CFI).

The Comparative Fit Index (CFI) compares the null model fit with the implied model fit by assuming that the latent variables and the indicator variables are uncorrelated in the null model (Schermelleh-Engel et al., 2003). Jackson et al. (2009) indicated the value of CFI should be greater than 0.90 in order for the model to be retained. At 0.90, the CFI indicates that 90% of the covariation in the observed data are reproducible by the implied model. Schermelleh-Engel et al. (2003) recommended that a value of 0.97 indicated good model fit, although 0.95 signifying adequate model fit. Most researchers accept CFI values above 0.95 values as indicating good fit, with values between .90 and .95 also considered acceptable (Hu & Bentler, 1999; Jackson et al., 2009; Schreiber, Stage, King, Nora, & Barlow, 2006).

Standardized Root Mean Square Residual (SRMR).

SRMR is an absolute measure of fit measuring the standardized difference between the observed correlation and the predicted correlation of model fit. SRMR is

positively-biased, with bias increasing for small samples and for studies involving low degrees of freedom (Hooper, Coughlan, & Mullen, 2008). SRMR calculates the average standardized difference between the predicted and the observed model covariance by taking the standardized residuals into account. An SRMR value of zero indicates perfect fit. However, SRMR tends to be smaller as sample size and the number of model parameters increase Sugawara, 1996). An SRMR value less than 0.05 is widely accepted as a good fit and a value lower than 0.08 as adequate fit (Hu & Bentler, 1999; Jackson et al., 2009). Schermelleh-Engel et al. (2003) state that the SRMR value smaller than .10 can be interpreted as acceptable for model fit. MacCallum, Browne and Sugawara (1996) offered 0.01, 0.05, and 0.08 as benchmarks of excellent, good, and mediocre fit, respectively.

Weight Root Mean Square Residual (WRMR).

The WRMR uses a variance-weighted approach to model fit that is useful for models whose latent variables are measured by categorical indicators, on different scales, or have widely unequal variances (Muthen & Muthen, 2015). The WRMR is a residual-based fit index. A WRMR value represents goodness of fit that is (in part) based on (weighted) average differences between the sample variance or covariances and the model estimated values. Like chi-square, the WRMR is also a measure of badness of fit, with smaller values indicating better fit. Based on Yu and Muthén (2002), the Mplus manual suggests values below 0.90 for the WRMR provided evidence of a “good fitting” model when either categorical or continuous data is analyzed. Yu and Muthén (2002) recommended a slightly higher cut-off of 1.0. Cook, Kallen, and Amtmann (2009) report

the WRMR is highly appropriate for non-normally distributed data. However, the WRMR performed poorly in studies analyzing large sample sizes (Asparouhov & Muthén, 2018; DiStefano, Liu, Jiang, & Shi, 2018). Table A.1 provides the information about goodness of fit indexes selected for this study and their cut-off values for model evaluation, according to cited researchers.

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