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Identifying and Characterizing Cognitive Factors Significant to Practicing and Learning Meteorology

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IDENTIFYING AND CHARACTERIZING COGNITIVE FACTORS SIGNIFICANT TO PRACTICING AND LEARNING METEOROLOGY

by

Peggy M. McNeal

A dissertation submitted to the Graduate College in partial fulfillment of the requirements for the degree of Doctor of Philosophy
Mallinson Institute for Science Education
Western Michigan University
December 2017

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IDENTIFYING AND CHARACTERIZING COGNITIVE FACTORS SIGNIFICANT TO PRACTICING AND LEARNING METEOROLOGY

Peggy M. McNeal, Ph.D.
Western Michigan University, 2017

To see the world as a meteorologist, one must understand and interpret atmospheric processes through representations depicted on two-dimensional weather charts and maps that encode large amounts of spatial and numerical data. This is a cognitively demanding and spatially challenging task, especially for students with burgeoning levels of meteorology knowledge, who lack the expertise of practiced meteorologists that read such charts and maps with ease. With little prior work informing meteorology and meteorology education through a cognitive science lens, this study surveys the literature and follows models of discipline-based education and cognitive science research to identify the discrete intelligence factors contributing to the successful completion of a series of meteorology tasks. The overall purpose of the study is to identify malleable and stable intelligence factors that predict performance on the meteorology task series and characterize them for the purpose of designing instructional interventions and scaffolding student learning in undergraduate meteorology courses. Framed by Cattell-Horn-Carroll theory, and using a mixed-methods, embedded correlational design informed by exploratory research, this study follows a three-phase progression of inquiry that is described in three independent manuscripts. The first manuscript reports survey research that identifies the spatial thinking skills that student and professional meteorologists (N = 93) report using in their work. By identifying mental animation, disembedding and perspective taking as spatial skills likely influential in meteorology, this initial study effectively taps into the knowledge and wisdom of practitioners, and lays the groundwork for further investigation. The second manuscript describes a quantitative investigation that expands beyond the spatial thinking skills identified in the first study, to include other intelligence factors, including working memory, domain knowledge and expertise. In sum, five discrete intelligence abilities are measured among
meteorologists (N= 81) representing a range of expertise to determine their effect on performance on the meteorology task series. Ultimately, domain knowledge and disembedding emerge as significant predictors of meteorology skill, thus highlighting the importance of meteorology content coupled with good pattern identification ability as critical to success. The third manuscript describes a qualitative study using verbal data resulting from the think-aloud processes of a subset of meteorologists and meteorology students who participated in the prior study. This manuscript describes an in-depth analysis of three of these participants (n = 3) who exemplify low, medium and high disembedding skills. Evidence of the use of disembedding while working through the meteorology task series is quantified and characterized on a continuum representing low to high disembedding skills. This characterization exhibits the use of rule-based reasoning to augment disembedding, and highlights the aforementioned significance of knowledge and pattern identification when completing meteorology tasks. Overall study results are discussed in the context of meteorology education along with evidence-based potential directions for meteorology instruction.
ACKNOWLEDGMENTS

I extend heartfelt gratitude to Heather Petcovic, who guided me on this journey with the utmost competence, skill, and grace. I hope to someday “pay forward” all of the wisdom and support that she generously shared with me. My thankfulness extends to the rest of my committee, Nicole LaDue, Todd Ellis, and David Rudge, who were wonderful mentors and guides; each made contributions that were unique and immensely valuable. My husband, Jim McNeal, offered endless support and love; I could not have done this without him. Thank you always.

Peggy M. McNeal
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INTRODUCTION

The bulk of the atmosphere is a ten-mile thick “ocean” of air with overturning layers that move in different and constantly changing directions. The motions of this three-dimensional, largely invisible fluid are represented on two-dimensional weather maps that encode a large amount of numerical data. From these maps and data, meteorologists are able to see patterns, envision atmospheric movement and forecast upcoming weather. The broad question explored in this study is “How do they do it?”

My experiences teaching an undergraduate atmospheric science course include watching students struggle with problems that ask them to make sense of real-time, three-dimensional atmospheric processes from charts, maps and numerical data. They too likely ask, “How do they do it?”

This study grew from these experiences and motivated a desire to improve meteorology education broadly including university courses and operational meteorology training pipelines. The study seeks to understand the cognitive underpinnings of what it takes to succeed in meteorology in order to inform instruction and scaffold learning from a cognitive science informed pedagogy. It stands at the intersection of discipline-based education research, cognitive science and meteorology.

With little prior work informing the cognitive aspects of meteorology and meteorology education, this study relied heavily on models of similar research in other science, technology, engineering and math (STEM) disciplines, such as physics and geology. The study is framed by a review of the rich literature addressing cognition, discipline-based education research and meteorological reasoning. Human intelligence theory serves a lens through which to review the investigation.

Three separate manuscripts describe the development and results of the overall study. They are:

1. Using Practitioner Wisdom to Investigate the Foundations of Spatial Thinking in Meteorology
2. Identifying Aspects of Cognition Significant to the Training of Undergraduate Meteorology Students

3. Characterizing the Disembedding Skills of Undergraduate Meteorology Students

This collection of manuscripts represents a progression of inquiry conducted in three phases. The first phase of the study considered the spatial foundations of meteorological thinking and sought to identify those spatial thinking skills that practitioners in the field—operational meteorologists—report as important to their work. Thus informed, the next phase of research expanded beyond spatial thinking to include additional intelligence factors important in solving meteorological tasks. Two types of spatial thinking, along with visuospatial working memory, domain knowledge, and expertise were measured in student and professional meteorologists. These factors were compared to performance on a meteorology task typical of that assigned in undergraduate meteorology courses to analyze effects and test hypotheses. A final phase characterized one specific spatial skill—disembedding—among undergraduate meteorology students who demonstrated varying levels of ability with this particular skill. The purpose of the final phase was to portray student interaction with disembedding skills and inform meteorology education. Collectively, this sequence is intended to bring together practitioner wisdom, empirically based evidence, and observations of students to provide a basis for improving instruction and learning in the meteorology classroom, as well as to peer into the black box and begin to answer, “How do they do it?”

THEORETICAL FRAMEWORK

The overall study uses a theoretical framework that serves as a lens for understanding the discrete factors of intelligence that individuals exhibit when they undertake meteorology tasks typical in undergraduate meteorology courses. According to McGrew (2009), the Cattell-Horn-Carroll theory of cognitive abilities\(^1\) (or CHC theory) is a working taxonomy of intelligence factors used as a theoretical framework from which to test hypotheses regarding various aspects of human cognition. CHC theory is a result of the melding of two consensus psychometric-based

---

\(^1\) The word “abilities” refers to discrete factors that together describe the structure of human intelligence. This is to be consistent with the language used by McGrew (2009) and not meant to be a characterization of an individual’s capability or potential to perform.
models for understanding the structure of human intelligence—Cattell and Horn's Fluid and Crystallized Intelligence theory (see Horn & Blankston, 2005; Horn & Noll, 1997) and Carroll’s Three-Stratum models. CHC theory is psychometric in nature and rests on a large body of research accumulated over decades in thousands of empirical investigations. The two components of the theory were each developed using measurement and factor analysis of the underlying structures of “intelligence” (Keith & Reynolds, 2010). The theory is the basis for continued development of individually administered intelligence tests such as the Wechsler Adult Intelligence Scale (WAIS), the Woodcock–Johnson Tests of Cognitive Abilities, and the Stanford–Binet Intelligence Scales (Keith & Reynolds, 2010), and it is widely regarded as the most influential theory in the study of human intelligence (McGrew, 2009).

The integration of Carroll’s and Cattell–Horn's models under a single CHC theory produced a list of sixteen broad abilities of general intelligence (G). Within each of the sixteen broad abilities, additional narrow abilities are identified. The sixteen broad abilities are:

- Gf Fluid reasoning
- Ge Comprehension-knowledge
- Gsm Short term memory
- Gv Visual processing
- Ga Auditory processing
- Glr Long term storage and retrieval
- Gs Cognitive processing speed
- Gi Decision and reaction speed
- Grw Reading and writing
- Gq Qualitative knowledge
- Gkn General (domain specific knowledge)
- Gh Tactile abilities
- Gk Kinesthetic abilities
- Go Olfactory abilities
- Gp Psychomotor abilities
- Gps Psychomotor speed
This study investigates five narrow abilities that are components of three of the sixteen broad abilities: short term memory (G_{sm}), visual processing (G_{v}), and general, domain specific knowledge (G_{kn}). The specific narrow abilities include working memory (a component of short term memory), spatial visualization and flexibility of closure (components of visual processing), and expertise and domain knowledge (components of general, domain specific knowledge).

However, more important than the theory’s function as a nomenclature is its theoretical underpinning of the selected abilities. For example, Cattell and Horn's Theory of Fluid and Crystallized Intelligence (Cattell, 1963; Horn & Cattell, 1967; Horn & Cattell, 1966, 1978; Horn, 1982) suggests that working memory relies on fluid reasoning. Fluid reasoning is a highly significant influence on general intelligence; it is fluid in the sense that it serves multiple scenarios and situations. Most important, fluid reasoning is independent of abilities associated with previously acquired knowledge and is an inherited aspect of general intelligence that does not change throughout one’s lifetime (Hambrick & Meinz, 2011). Thus, a theoretical distinction exists between working memory and the other abilities targeted for investigation; working memory is unlikely to change in individuals.

As one might expect, expertise and domain knowledge, fall on the opposite end of the spectrum, clearly reflecting specialized knowledge that is developed through intensive systematic practice and training. The maintenance of this knowledge occurs through regular practice and motivated effort. Cattell and Horn (Cattell, 1963; Horn & Cattell, 1966, 1967, 1978; Horn, 1982) use the term, crystallized intelligence (G_{c}) when referring to the ability to use learned knowledge and experience.

Spatial relations and flexibility of closure, both components of visual processing, may be trainable aspects of cognition (Newcombe & Shipley, 2015). A large body of research shows that spatial skills are malleable and that even a small amount of instruction and coaching can improve spatial reasoning (Uttal et al., 2012).

Thus, by using CHC theory as a lens for understanding discrete intelligence abilities used with meteorological tasks, this study explicitly recognizes some abilities as malleable and others as stable components of general intelligence. In the context of meteorology education, this means that some aspects of meteorology engage trainable abilities, whereas others may require abilities that for some students are limiting. These students may benefit from instructional scaffolds. Before such scaffolds and improvements to pedagogy are developed, however, it is important to
determine which abilities are important to meteorology and their overall effect on successfully completing meteorological tasks.

**REVIEW OF THE LITERATURE**

The literature review examines selected literature describing empirical studies that address the five intelligence abilities in the context of meteorology, cognitive science, and discipline-based education research. Table 1-1 serves to introduce and categorize the reviewed literature. We begin with a review of what the literature reveals in the context of each intelligence ability, followed by a summary, and identification of areas soliciting further investigation.

**Expertise (G_{kn})**

The insight gained in the Chi, Feltovich and Glaser (1981) study of expert problem solving resulted from revealing the differences in how novices and experts approach physics problems. The authors’ description of novices focusing on literal problem features versus the categorization by deeper physical principles was echoed in additional literature reviewed. Joslyn & Jones (2008), Smallman & Hegarty (2007), and Trafton et al. (2000) all conducted studies with U.S. Navy forecasters and came to the same conclusion: expert forecasters delay consulting computer models until after their own appraisal of atmospheric conditions, whereas novice forecasters pursue readily available model data and augment it to a smaller degree with their own skill. This robust finding has implications for education research and the training of meteorologists who integrate available resources with their own expertise.

Sohn and Doane (2003) investigated the working memory and long-term working memory of pilots as they engaged with different cockpit displays. They found that expert pilots performed better at memory tests based on the displays and suggest that the expert pilots’ extensive experience with meaningful cockpit instrument values supports a mental “library” that is accessed when these pilots are presented with realistic cockpit configurations. This is akin to Chase and Simon’s (1973) assertion that expert chess players hold a “library” of chess positions
in long term memory. It is a premise that is open to investigation with expert meteorologists as well.

Table 1-1 Literature included in the review

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Investigated intelligence abilities:
1. Expertise (Gkn)
2. Working memory (Gsm)
3. Visual processing (Gv)
4. Domain knowledge (Gkn)

A striking incongruity of the included expertise studies is the liberal use of the term expert, ranging anywhere from Trafton et al.’s characterization of all participants (U.S. Navy forecasters) as experts, to Pliske, Crandall and Klein (2004), who considered none of their participants (U.S. Air Force forecasters) to be experts. This is problematic to the body of research and limits cross-study comparisons. As part of their work, Pliske, Crandall and Klein (2004) generated novice to expert categories and provide a structure for identifying expertise in weather forecasting. Hoffman (1998) is another source of expertise categorization for weather forecasting not included in this review.

**Working Memory (Gsm)**

The reviewed literature suggests that working memory interacts with other intelligence
abilities in complex ways. Sohn and Doane (2003) found that working memory capacity had a diminishing role for pilots engaged in cockpit display memory tests as their skill and expertise increase. However, Meinz and Hambrick (2010) were unable to show the same effect with pianists’ sight-reading abilities, suggesting that working memory remained influential even among expert pianists. Additional research, especially in different domains, will serve to tease out the complexities of working memory and its interplay with other intelligence abilities.

The literature also recognizes that the ability to offload information to reduce working memory is an important consideration for complex task performance, and important in education as well; it is one way to scaffold limitations with this particular intelligence factor. In their research with mental models of described scenes, Bryant, Tversky and Franklin (1992) conclude that individuals can reduce working memory demands by simply taking an internal viewpoint that relies on the body for a frame of reference. The Alles and Riggs (2011) study of student geoscientists illustrates how students can use gesture and three-dimensional models to reduce working memory demands when interacting with block diagrams representing geologic units. Hegarty’s 1992 work with mechanical systems (gears and pulleys) suggests that during mental animation, working memory better accommodates inferences in the direction of causality. These examples point to a need to research, identify and teach effective ways to reduce working memory demands without compromising complex task completion.

The literature also suggests that when task completion exceeds the limits of working memory capacity, individuals will use whatever strategies they can to offload information. The Joslyn and Jones (2008) study illustrated that even forecasters with higher levels of expertise revert to novice practices in order to manage working memory load when it becomes overwhelmed. Especially in the case of meteorology, where human expertise is crucial to interpretation of computer models, it is imperative to investigate and understand techniques to scaffold working memory in ways that promote accuracy and excellence in meteorology and meteorology education.

**Domain Knowledge (G\textsubscript{dk})**

Bearing in mind that researchers often assimilate measures of domain knowledge into representations of expertise, many of the findings on expertise, described above, apply here.
Notably, Pliske, Crandall and Klein (2004) used knowledge audits with forecasters as a method for soliciting information about meteorology knowledge, which they embedded into expertise categories. Only one paper (Hambrick et al., 2012) described an explicit measure of domain knowledge and used this measure during analysis; the Sohn and Doane (2003) paper included an analysis of domain knowledge based on presumptive assessments from levels of pilot expertise.

Hambrick et al. (2012) used a geology concept inventory to measure geologic knowledge and found that knowledge strongly predicted bedrock mapping accuracy, thus participants with high knowledge levels were more successful with the bedrock mapping task. Participants with lower knowledge levels were either less successful or presumably relied on spatial skills to achieve higher levels of success. Sohn and Doane’s (2003) work with pilots aligns with this finding. Sohn and Doane (2003) theorize that working memory capacity is a function of the amount of knowledge in long-term memory and how well that knowledge is accessed. Thus, like Hambrick et al. (2012), they suggest that performance improves with increased domain knowledge and the ability to access it. This suggests that increased levels of domain knowledge (G_{dom}) can compensate for limitations in other intelligence abilities and stimulates research questions regarding the effect of early, targeted, domain-specific education on problem solving success.

Other papers included in the review describe domain knowledge as an important factor contextualizing and informing schema development and the formation of mental models. Trafton et al. (2000) describe formation of mental spatial models among weather forecasters that are initially knowledge free, invoked, and populated with specific knowledge to represent different weather scenarios. Chi, Feltovich and Glaser (1981) similarly suggest that domain knowledge activates appropriate schema relevant to solving particular physics problems. Thus, how meteorology knowledge stimulates the formation of meteorology schema and mental models, especially during learning, is also an area ripe for research.

**Visual Processing (G_v)**

Ten of the fourteen papers included in this review refer to some aspect of spatial thinking, suggesting that visual processing is an important component for approaching many types of problems. The Bryant, Tversky and Franklin (1992) study provides a broad overview of how
individuals use spatial frameworks based on body axes to navigate through problem spaces. Liben, Kastens and Christensen (2011) continued with this theme and found that undergraduate students were severely lacking in navigation and orientation skills. Sohn and Doane (2003) include measures of spatial working memory in their study of complex aviation tasks, also recognizing that spatial thinking is an important component of navigation and working with maps. This is of particular interest in meteorology education, which depends significantly on deriving and interacting with information on maps.

The Alles and Riggs (2011) work nicely demonstrates the use of gestures and models to augment spatial information processing while interacting with geologic units. Hegarty (1992), like Alles and Riggs (2011) developed a process model for describing how people cognitively interpret mechanical systems from a spatial perspective. Generalizing observable cognitive processes into models makes thinking “visible” and helps scientists and researchers to compare and contrast between different tasks and domains; we see this again in the idealized models for weather forecasting described by Joslyn and Jones (2008), Pliske, Crandall and Kline (2004), and Trafton et al. (2000).

The literature also yields practical applications for solving tasks within different spatial contexts. Using origami, Tenbrink and Taylor (2015) suggest scaffolding students’ work with inherently spatial tasks through verbalization of mental processes. Smallman and Hegarty (2007) note that novice meteorologists, especially of low spatial ability, may need additional training on using complex, spatial weather displays.

However, among the plethora of spatial thinking research applied in various domains, there exist some discrepancies. The Hambrick et al. (2012) study proposes that an interaction between knowledge and spatial ability moderates geology task performance such that individuals with higher levels of domain knowledge are able to circumvent limited spatial skills. However, Ackerman (1992) demonstrated that a correlation between spatial skills and air traffic performance did not attenuate over time that included practice. Although some research documents the malleability of spatial skills (Uttal et al., 2012), it is not difficult to locate literature that claims the opposite, including Salthouse (1996) and Miyake et al. (2001). It is possible that some types of spatial thinking are malleable and others are not. There is much to keep researchers busy into the future.
Summary of the Literature Review

There are many questions left unanswered. This is particularly the case in meteorology, a field that could potentially shed light on other complex task scenarios in a variety of domains. Among the research gaps that invite investigation, there is an overall lack of research on specific intelligence abilities important to solving meteorology tasks. In particular, disembedding/flexibility of closure, or the ability to perceive patterns and configurations among a distracting background (a skill presumably important to interpreting busy weather maps) has no research basis in a meteorology context. The results of the Joslyn and Jones (2008) study necessitate a critical look at the role of working memory capacity in meteorology. If meteorological tasks draw heavily on working memory, an aspect of cognition that is stable, it is important to identify and understand the implications, especially for meteorology education. Among the existing literature, no study has yet characterized the interplay between specific intelligence abilities used when solving meteorological tasks, nor characterized students’ use of these abilities. This motivates the research addressed in this study and the questions contained therein.

OVERALL PURPOSE OF THE STUDY

There is evidence to suggest that cognitive abilities such as those associated with spatial thinking are necessary for success in meteorology and may be trainable. There is also evidence suggesting that stable intelligence abilities limit some individuals’ ability to perform complex tasks, such as those required in a meteorology undergraduate meteorology courses. Implications for meteorology education include introducing interventions to improve malleable abilities in students lacking requisite skills and developing strategies to scaffold the learning of struggling students. However, before effective pedagogies can be developed, it is necessary to identify and understand the discrete intelligence abilities that contribute to success in meteorology, and characterize how they are exhibited among meteorology students.

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2 Students undergoing a meteorology course of study are required to fulfill a sequence of math requirements usually through differential equations. These courses can present obstacles to undergraduate meteorology students as well. This study focuses on cognitive abilities important to success in meteorology content courses specifically.
RESEARCH DESIGN

The overall study uses an embedded correlational design (Creswell & Plano-Clark, 2007) informed by exploratory research that is overviewed in Figure 1-1. Here, the qualitative data provides a supportive, secondary role based primarily on the quantitative data. Such a design is used when the quantitative data is not sufficient to adequately address the overall study purpose; different questions need to be addressed and these questions require different types of data. In our case, we sought to include qualitative data to further examine howidentified intelligence abilities are characterized in undergraduate meteorology students. The embedded qualitative investigation serves to contextualize the quantitative results, giving perspective and further meaning overall.

The overall study includes an exploratory quantitative phase, followed by a central quantitative phase with an embedded qualitative phase. Three phases were necessary in order to:
1. Identify spatial thinking skills important in meteorology and worthy of investigation; 2. Determine the effect of identified intelligence abilities on meteorological tasks typical encountered in undergraduate meteorology classrooms; and 3. Characterize abilities significantly influencing performance for the purposes of designing instructional interventions and scaffolding student learning in undergraduate meteorology classrooms. Methods particular to each phase are outlined in the individual manuscripts.

The exploratory phase consists of data collected from practitioners—students and professional meteorologists—using a survey to identify spatial thinking skills important to completing meteorology tasks. This data is analyzed using descriptive statistics that address the main research question, along with Pearson’s correlations and chi-squared tests to address validity of the survey, and determine differences in responses from student and professional meteorologists, respectively.

The findings from the first phase inform the central phase of research, specifically, the selection of psychometric tests to measure the particular spatial skills identified in the first phase. Data collected from meteorologists representing a range of expertise are analyzed primarily using hierarchical linear regression to estimate the predictor variables’ effect on a series of meteorology tasks, and to test interactions proposed by relevant hypotheses. These findings, in turn, inform the embedded qualitative phase by focusing on the variables identified as significant
in the model resulting from the regression analysis. The embedded phase collects think-aloud data from a subset of participants as they complete the series of meteorology tasks. This data is qualitatively analyzed using a priori and emergent coding to characterize student use of identified skills. Final integration of the embedded phase with the statistical results further addresses the overall study purpose, and provides synthesized outcomes for discussion, conclusions, and future work.

**Figure 1-1** An overview of the mixed-methods, embedded correlational design
USING PRACTITIONER WISDOM TO INVESTIGATE THE FOUNDATIONS OF SPATIAL THINKING IN METEOROLOGY

Peggy McNeal, Todd Ellis, and Heather Petcovic

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ABSTRACT

Recent work has highlighted the critical role of spatial thinking in the geosciences, including in such tasks as map reading, interpreting geologic structures, crystallography, and geologic mapping. Like geology, meteorology is highly spatial, involving identifying, interpreting, and mentally manipulating three-dimensional spatial forms. It also entails seeing patterns in complex information displays and processing geographically distributed data. In this study, we seek to identify which specific spatial thinking skills practicing meteorologists and meteorology students report using with meteorological charts, maps and images. A key feature of this exploratory study is gathering practitioner wisdom through an unstructured task to collect authentically intuitive responses in order to establish “what we know.” Using a survey with nine charts, maps, and images from a 2015 significant weather event, we asked student and professional meteorologists (N = 93) to identify which spatial thinking skills they think they would use with each chart, map, and image. Results suggest that mental animation, disembedding and perspective taking are important spatial skills for meteorologists. Analyses of the response patterns suggest that students and professionals perceive their use of specific spatial thinking skills differently; particularly, when analyzing a surface analysis plot, professionals report using mental animation and disembedding at higher rates than students. These results will inform further investigation into spatial thinking during weather forecasting and may inform training of student meteorologists.
INTRODUCTION

Spatial data and representations are at the core of multiple geoscience disciplines including geology, oceanography and meteorology. A large body of research in the geosciences has primarily focused efforts on the role of spatial thinking in geologic tasks such as map reading, interpreting geologic structures, crystallography, and geologic mapping. The highly spatial nature of disciplines such as oceanography and meteorology can also benefit greatly from insights about spatial thinking as applied to the daily practices of geologists and geology students.

To illustrate, Liben and Titus (2012) share a vignette depicting a day in the life of a structural geologist doing fieldwork in southern Utah. Of the many tasks that the geologist accomplishes, the first is to study a topographic map to plan a traverse for the day. Analyzing this action through a cognitive science lens, Liben and Titus (2012) recognize this initial action as spatially demanding. It “requires reading a topographic map, which itself requires an understanding of scale, orientation, and viewing angle and extracting three-dimensional meaning from a two-dimensional graphic representation” (p.57). Newcombe (2015) relates student use of topographic maps to the following research findings:

- “Novice map readers” struggle to understand how information on a 2D map informs the reader about a 3D space (Liben & Titus, 2012).
- “Novice map readers” struggle with visualizing the 3D terrain the map depicts (Rapp et al., 2007).
- “Novice map readers” have difficulty finding meaningful contour patterns in maps due to their focus on printed elevation information rather than the contour patterns used by experienced map readers (Chang et al., 1985).

As instructors of an introductory atmospheric science course for preservice teachers at a mid-sized Midwestern university, the first and second authors recognize these “novice map readers” among students who struggle to visualize and make sense of atmospheric motion from weather analysis maps with contour lines depicting upper-atmospheric and surface pressure patterns. We intuitively know that like geology, meteorology is highly spatial, and requires making sense of fluid flows and overturning air masses. We also recognize that geology and meteorology are inherently different, thus, identifying what spatial thinking skills are useful to
meteorologists is an important first step. Could established research and pedagogy in spatial thinking as applied to geology guide our efforts and enhance our understanding of spatial thinking in meteorology? This question, along with the potential research that it could stimulate, was the initial motivation for our study.

BACKGROUND

Previous Work at the Intersection of Meteorology and Cognitive Science

Research interest in how meteorologists think has focused on the nature of meteorology expertise (Pliske et al., 2004), forecaster knowledge (Hoffman et al., 2006) and skill (Roebber & Bosart, 1996), making inferences from visual displays (Hegarty et al., 2010), and the formation and use of mental models (Trafton et al., 2000). Military research organizations fund much of the research, which involves military personnel as research subjects. In addition to seeking to understand and improve forecaster ability, the research effort contributes to understanding the human factors of workstation design (Hoffman, 1991), investigating decision making (Joslyn & Jones, 2008), improving the timing of weather watches and warnings (Wilson et al., 2016) and developing expert weather forecasting systems (Collopy et al., 2001). The spatial nature of meteorology is largely unexplored and applications of research from cognitive science in meteorology education are sparse.

The Foundations of Spatial Thinking in the Geosciences

Spatial thinking has received significant attention in the geoscience education research (GER) literature since 2002, when twenty geoscience educators, cognitive scientists, and discipline-based education researchers (DBERs) met as part of the Wingspread Conference series in a workshop called “Bringing Research on Learning to the Geosciences.” The momentum from this meeting prompted ongoing forums for discussion, research and professional development in GER, including a plenary session at the 2002 Geological Society of America (GSA) Annual Meeting that resulted in the 2006 GSA Special Paper 413: *Earth and Mind: How Geoscientists Think and Learn About the Earth* (Kastens & Manduca, 2012).
Included was Kastens and Ishikawa (2006), which represents an “early step” (p. 53) in what the authors’ hoped would be (and has been) an ongoing dialog between geoscience and cognitive science. The authors identify and describe ten geoscientist’s tasks that require spatial thinking from the perspective of the practicing geoscientist as well as the geoscience learner with insights and lines of inquiry from cognitive science literature that map pertinent connections. Two features of this work relate directly to our study. First, the paper provided a basis for further research and a strong foundation from which the geoscience education research community moved forward. Subsequent studies detail the development of a process model for visual penetrative ability using geologic block diagrams (Alles & Riggs, 2011), investigate how students navigate and interpret 3-D structures (Ishikawa & Kastens, 2005; Liben et al., 2011), explore how spatial thinking influences bedrock mapping skills (Hambrick et al. 2012), and develop the use of sketching to elicit knowledge of geologic processes (Jee et al., 2014). Second, by identifying and describing some of the geoscientists’ tasks, the paper approached geoscience thinking from the perspectives of the practicing geoscientist as well as the geoscience learner. We similarly propose to use the wealth of practitioner wisdom to identify key spatial thinking skills in meteorology.

Using Prior Research to Frame the Spatial Nature of Meteorology

In addition to spatial thinking literature produced by the GER community, we looked broadly to frame our initial conceptions of the spatial nature of meteorology. Carroll (1993) refers to spatial visualization as processes of apprehending, encoding, and mentally manipulating three-dimensional spatial forms such as what we imagine meteorologists do when they visualize three-dimensional atmospheric, dynamic fluid processes. Hegarty (2014) describes spatial relations thinking as the ability to mentally transform objects. Such mental transformation and animation may be analogous to what meteorologists do when predicting the motion of fronts and rotations of cyclones. Linn and Peterson (1985) identify spatial perception as the ability to interpret an object relative to its frame of reference or surroundings, a critical skill both in cartography and navigation as well as meteorology; meteorologists must be able to situate geographically distributed data and see patterns in complex information displays. Attempting to unify multiple characterizations of spatial thinking and provide a top-down typology, Newcombe

Cognitive scientists working with geoscientists (e.g., Shipley et al., 2013) have broadly identified the types of spatial thinking used by geoscientists and examined how novices and experts employ spatial thinking in practice (see Kali & Orion 1996; Kastens & Ishikawa 2006; Liben, Kastens & Christensen 2011; Hambrick et al. 2012; Ormand et al. 2014). These studies provide a theoretical foundation upon which to ground our work, specifically the identification of particular spatial thinking skills that contribute to the interpretation of dynamic atmospheric processes and their transformations. Manduca and Kastens (2012) describe six spatial thinking skills defined at the intersection of cognitive science and geoscience research. These six spatial thinking skills are:

- **Object location memory:** Remembering the spatial location of previously seen objects or phenomenon
- **Perspective taking:** Envisioning how something would appear from different vantage points
- **Mental rotation:** Rotating mental representations of two-dimensional and three-dimensional objects
- **Disembedding:** Observing and recognizing patterns and isolating the important aspects from distracting, nonessential ones
- **Mental animation:** Developing a plausible scenario of a sequence of events based on static information
- **Visual penetrative ability:** Envisioning the three-dimensional geometry of structures inside a volume using mostly two-dimensional clues from the edge of a volume

We applied this categorization to our initial work based on broad similarities in processes used in geoscience and meteorology (e.g., understanding contour lines on topographic maps is analogous to understanding isobars on weather maps).
Informing Meteorology Education

Our overarching purpose is to understand how practicing meteorologists perceive the atmosphere spatially in order to identify ways to effectively assist meteorology students. Such discipline-based applications of pertinent spatial thinking skills are already being used in other science, technology, engineering, and math (STEM) education domains. As one example, Sorby and Baartmans (2000) recognize that visualization of engineering problems is an essential ingredient for student understanding in early engineering courses. Thus, they developed a pre-graphics course for freshman engineering majors who demonstrate weak spatial visualization ability on standard spatial thinking tests. The course, together with development of a multimedia software and workbook, “Developing Spatial Thinking” (Sorby, 2011) has had a positive impact on developing student spatial skills, improving student grades in follow-on engineering courses and improving retention rates (Sorby, 2007).

Similarly, Ormand et al. (in press) have developed curricular materials for mineralogy, structural geology, and sedimentology and stratigraphy courses that support student understanding of spatially challenging concepts (Ormand et al., in press). Supported by a large body of research, the team identified 3D visualization and penetrative thinking as critical to success in these courses and developed a Spatial Thinking Workbook with exercises to develop these skills. They use strategies identified by cognitive science researchers, such as gesture, predictive sketching, analogy, and alignment to promote 3D visualization and penetrative thinking in the context of the courses. Pre- to post-test gains show that using the curricular materials provided in the Spatial Thinking Workbook strengthen students’ ability to solve geological problems with spatial components (Ormand et al., in press).

These successes exemplify the potential for enhancement of current meteorology education and training. Working collaboratively, we can potentially develop parallel instructional activities or transfer some of the strategies used in other STEM domains.

Locating the Study

The GER community has recently proposed a conceptual model to organize the strength of evidence of generalizable claims generated by geoscience education research (St. John &
McNeal, 2017). Organized as a pyramid with five levels, the base level includes practitioner wisdom and expert opinion, reflecting the recognition “that practitioners are not separate from this process; their expert opinions have value, they are an important part of the knowledge base” (p. 10). Our research approach deliberately taps into this wisdom. We reasoned that, in our case, practitioners of meteorology (both student and professional) could provide an interface for connecting the essential skills that they use in meteorology with our efforts in meteorology education research.

Thus, we attempted to elicit genuine, intuitive responses that reflected meteorologists’ perceptions of their own spatial thinking to capture the authentic skill of the practitioner. By locating our research at the base of the GER community-claims pyramid, we hope to provide a starting point for further research and a strong foundation from which we can elevate confidence in claims about how meteorologists think spatially.

RESEARCH QUESTIONS

Our research questions were:
1. Which, among the six spatial thinking skills identified by Manduca and Kastens (2012) do meteorologists report that they use most frequently when interpreting common meteorological charts, maps, and images related to a severe weather event?
2. What, if any, differences exist in the identification of key spatial skills between meteorology students and professional meteorologists?

The study was exploratory in nature and designed to inform future investigations into how meteorologists use spatial thinking when working with meteorological charts, maps and images.

METHODS

Our research used a cross-sectional design that included professional and student meteorologists. We administered a survey that asked participants to identify which spatial thinking skills they perceive they use with nine different weather maps, charts and images. We conducted a quantitative analysis of the data to determine which spatial thinking skills were most
highly reported and looked for differences in responses between students and professionals using chi-squared tests.

**Instrumentation**

We designed a survey to present a plausible weather scenario using charts, maps and images typically encountered by a practicing meteorologist (Figures 2-1 through 2-9). The survey asked participants to identify the spatial thinking skills they would use when working with each chart, map or image. By limiting the guidance given to participants, we purposefully left interpretation of the images up to each participant, and instead, sought to reveal the instinctive spatial strategies that they would use when first encountering each image.

The weather scenario involved a significant mid-latitude cyclone event that occurred in the central United States on 18 November 2015. We selected a mid-latitude cyclone event for the opportunity it presents to potentially use multiple forms of spatial thinking. These storms are characterized by vertical and horizontal air motion. They turn in a counter-clockwise direction while traveling in a generally easterly direction. Meteorologists analyze mid-latitude cyclones on a synoptic scale (a horizontal distance of 1000 km or greater) thus, storm movement relative to an observer’s location is important. They use multiple charts that represent several layers of the atmosphere at different pressures (heights) to analyze storm development. The charts are typically superimposed with a large amount of numerical data from which meteorologists search for patterns.

The set of nine charts, maps and images included a visible satellite image (Figure 2-1), a water vapor satellite image (Figure 2-2), a base reflectivity radar image (Figure 2-3), a base velocity radar image (Figure 2-4), a surface temperature map (Figure 2-5), a surface analysis plot (Figure 2-6), a 500 mb chart (Figure 2-7), a traditional four-panel plot of the 6-hour North American Model (NAM) forecast model, representing conditions predicted at 1800 UTC at 500 mb, 250 mb, 850 mb, and 700 mb (Figure 2-8), and a constructed four-panel plot of the 12, 24, 36, and 48-hour forecasts of the 1800 UTC forecast run of the Global Forecasting System (GFS) model depicting how the storm was predicted to evolve (Figure 2-9).
Figure 2-1 Visible satellite image from GOES-East, NOAA Office of Satellite and Product Operations

Figure 2-2 Water vapor satellite image from GOES-East, NOAA Office of Satellite and Product Operations
Figure 2-3 Base reflectivity image from the KIND (Indianapolis, IN) radar. Source: National Center for Atmospheric Research Applications Laboratory (http://weather.rap.ucar.edu/radar/)

Figure 2-4 Base velocity radar image from the KIND (Indianapolis, IN) radar. Source: National Center for Atmospheric Research Applications Laboratory (http://weather.rap.ucar.edu/radar/)
Figure 2-5 Surface temperature map from Plymouth State Weather Center (http://vortex.plymouth.edu)

Figure 2-6 Surface analysis plot from Plymouth State Weather Center (http://vortex.plymouth.edu)
Figure 2-7 500 mb chart from Plymouth State Weather Center (http://vortex.plymouth.edu)

Figure 2-8 North American Model (NAM) 4 panel plot: (top left) 500 hPa heights, winds and absolute vorticity; (top right) 250 hPa heights, winds and wind speed; (bottom left) 850 hPa heights, winds and temperature; (bottom right) 700 hPa relative humidity, sea level pressure and 100-500 mb thickness. Source: Precipitation Systems Research Group at Colorado State University (http://schumacher.atmos.colostate.edu). Used with permission.
To familiarize participants with the six spatial thinking skills described above, we provided written descriptions and illustrations of each spatial skill (an example for visual penetrative ability is provided in Figure 2-10). We did not assess participants’ spatial thinking ability; rather, we used publically available examples from spatial thinking tests to introduce participants to the spatial thinking skills. Participants read each description and viewed the illustrations before viewing the nine meteorological charts, maps and images, and were able to refer to the descriptions and illustrations of spatial thinking skills as they progressed through the untimed survey questions. Participants were asked to consider their thought processes as they interpreted the images, looked for patterns, noticed trends, mentally noted features, ascertained the situation, and imagined a forecast. The survey asked participants to respond “yes” or “no” to indicate whether they used each spatial thinking skill while observing and interpreting each of the nine images (Figure 2-11).

Before we administered the survey to our study population, we pilot tested the survey with meteorology colleagues (not part of the study) and incorporated their feedback into the final survey design. Participant responses between comparable images (e.g., the two satellite images and the two surface plots) significantly correlated (using the Pearson correlation coefficient; p < .05) with each other 83% of the time, providing construct validity of the survey.
Participants and Data Collection

We deliberately recruited participants representing a broad range of meteorology expertise, including academic and professional meteorologists and meteorology students. The minimum criterion to participate was enrollment in or completion of a college course in meteorology. We administered the survey to 98 individuals. After eliminating results from participants with incomplete surveys, we analyzed 54 data points for 93 participant surveys. Ultimately, our study population included 25 undergraduate meteorology students, 12 graduate students of meteorology and 56 professional meteorologists (Table 2-11). Although we collected demographic data that gave us information about expertise, we refer to the participants as students and professionals rather than novices and experts. In meteorology and forecasting, these labels are used discriminatively, and proficiency scales are preferred (Hoffman et al., 2017) because years of experience do not always correspond to expertise, and factors such as formal training, on-the-job training, and opportunities for feedback exert a strong influence (Pliske et al., 2004). We did not collect data on proficiency and as such avoid novice-expert categorization.

In the first phase of data collection, we administered a paper version of the survey at the 2016 Annual Meeting of the American Meteorological Society (AMS). We recruited 43 participants from among attendees at the AMS meeting. This initial sample was composed of 86% undergraduate and graduate student meteorologists.

In order to increase our study population and recruit participants representing the professional end of the spectrum, we conducted a second data collection phase with an identical online survey hosted by selectsurvey.net and solicited interest through professional networks and the email list maintained by the National Weather Association. Fifty-five participants completed the online survey. We combined participants from both phases to create one study population, justified by our use of uniform recruiting criteria and identical surveys with each phase.
Visual penetrative ability refers to the ability to visualize the cross section of the interior of an object as it is sliced at different locations and at different angles. Example: How would the new surface of this object appear if sliced as indicated?

Figure 2-10 Sample spatial thinking skill description used in the survey. Image from Titus and Horsman, 2009 (http://www.nagt-jge.org/doi/pdf/10.5408/1.3559671?code=gete-site)

Figure 2-11 Screen capture from a section of the online version of the survey
Our study population was 22.6% female, which is within the range reported by multiple studies of female participation in atmospheric science (see Hartten & LeMone, 2010; Avallone et al., 2013; MacPhee & Canetto, 2015). The study population included participants from 29 states, Guam, Ethiopia, New Zealand and Canada. Average age was 33.5 years with a range of 20 to 65 years.

Table 2-1 Descriptive statistics for the study population, N = 93

<table>
<thead>
<tr>
<th>Demographic</th>
<th>% of total responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td></td>
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<tr>
<td>Male</td>
<td>77.4</td>
</tr>
<tr>
<td>Female</td>
<td>22.6</td>
</tr>
<tr>
<td>Race/Ethnicity</td>
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<tr>
<td>Caucasian/White</td>
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<tr>
<td>Latino/Hispanic</td>
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<td>Asian</td>
<td>1.0</td>
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<tr>
<td>Current status</td>
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</tr>
<tr>
<td>Undergraduate/Post-secondary</td>
<td>26.9</td>
</tr>
<tr>
<td>Graduate/Postgraduate</td>
<td>12.9</td>
</tr>
<tr>
<td>Professional/Retired</td>
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<td>Primary professional experience, if any (70 responses)</td>
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</tr>
<tr>
<td>College/University</td>
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</tr>
<tr>
<td>Government</td>
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</tr>
<tr>
<td>Industry</td>
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</tr>
<tr>
<td>Ever taught a college level meteorology course</td>
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<tr>
<td>Yes</td>
<td>26.9</td>
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<tr>
<td>No</td>
<td>73.1</td>
</tr>
<tr>
<td>Ever participated in WxChallenge or other forecast contest</td>
<td></td>
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<tr>
<td>Yes</td>
<td>63.4</td>
</tr>
<tr>
<td>No</td>
<td>36.6</td>
</tr>
</tbody>
</table>

Data Analysis

Upon completion of the survey, participants responded to a short list of demographic questions. The survey included inquiries into status, professional focus and years in the profession. Although we broadly interpret results in terms of student and professional differences, we split our participants into three groups for the purpose of the statistical analysis: undergraduate students, graduate students and professional meteorologists. We used IBM’s
Statistical Package for the Social Sciences (SPSS) Version 24 to tabulate the data (Research Question 1), calculate Pearson’s correlations (to establish construct validity of the survey), and seek significant differences among levels of expertise using chi-squared tests (Research Question 2). For all tests, a p value of <.05 was considered significant.

**RESULTS**

Which Spatial Thinking Skills Do Meteorologist Report Using Most Frequently?

The meteorologists in our sample reported using mental animation (74.6%), disembedding (72.4%) and perspective taking (71.6%) most frequently when working with the provided images (Table 2-2). Our participants almost unanimously reported using mental animation (93.9%) when interpreting the visible satellite image depicting a mid-latitude cyclone. Mental animation was also highly reported with the 4 panel plots (NAM=86.7%, GFS=89.8%), water vapor imagery (88.8%), 500 mb chart, and base velocity radar (both 80.6%). Our participants reported using mental animation with lower frequencies on the two surface charts. Participants consistently reported high use of disembedding with all images, with the highest reported use in the four panel plots (NAM=84.7%, GFS=78.6%). The highest use of perspective taking was reported when interpreting the surface analysis plot (80.6%) and both radar images (79.6% for each).

Three spatial thinking skills were not identified as highly used in interpreting the imagery. Participants’ average reported use of object location memory across all images was 53.4%. Less than half of our participants reported using mental rotation with all of the images except the NAM 4 panel plot (51.0%) and the average reported use of visual penetrative ability was also less than half (47.8%).

What Differences Exist in the Identification of Spatial Skills Between Meteorology Students and Professional Meteorologists?

Among the three highly reported spatial thinking skills, we used Pearson’s chi-squared tests to test the null hypothesis that there is no difference between student and professional responses. We rejected the null hypothesis in four instances where we found significant
differences between undergraduate student, graduate student, and professional groups (Table 2-3). The strongest group independence (p < .001) occurred with participant responses to, “Did you use mental animation with the base reflectivity radar?” Here, undergraduates overwhelmingly responded “yes” (88.0%). Graduate students also responded affirmatively at a high rate (75.0%). However, less than half of the professional meteorologist reported using mental animation for base reflectivity radar data (42.8%).

The opposite pattern was observed when participants were asked “Did you use mental animation with the surface analysis plot?” The majority (70.2%) of undergraduate and graduate students reported that they do not use mental animation when working with a surface analysis plot, however 38 out of 56 professional meteorologists reported that they do (67.9%).

When asked, “Did you use perspective taking with the visual satellite imagery?” the graduate students were atypical and the only group with the majority responding “no”. Finally, when participants responded to “Did you use disembedding with the surface analysis plot?” the undergraduate and graduate students had lower levels of affirmative responses (56.8% overall). However, the professional meteorologists responded, “yes” at a rate of 82.1%.

DISCUSSION

Mental Animation

Hegarty (1992), who has studied mental animation extensively, describes mental animation as “the process of inferring motion, the type of knowledge that allows people to infer motion, and the characteristics of human information processing that constrain the inference process” (p. 1084). Although her work describes mental animation in the context of mechanical systems (see Hegarty, 1992; Hegarty, 2004; Hegarty, 2010), her findings are germane to our investigation. In particular, Hegarty’s findings can guide our interpretation of participants’ high reporting rate of mental animation when interpreting visible satellite imagery. Hegarty (1992, 2010) proposes that spatial thinking does not happen in isolation; analytic thinking, specifically
Table 2-2 Percent of participants who replied “yes” for each spatial thinking skill on each image, averaged across all images. N = 93

<table>
<thead>
<tr>
<th>Spatial Thinking Skill</th>
<th>Visual Satellite Imagery</th>
<th>Base Reflectivity Radar</th>
<th>Base Velocity Radar</th>
<th>Surface Temperature Map</th>
<th>Surface Analysis Plot</th>
<th>500 mb Chart</th>
<th>Water Vapor Imagery</th>
<th>NAM Model 4 Panel Plot</th>
<th>GFS Model 4 Panel Plot</th>
<th>Average (mean) across all images</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mental Animation</td>
<td>93.9</td>
<td>58.2</td>
<td>80.6</td>
<td>40.8</td>
<td>52.0</td>
<td>80.6</td>
<td>88.8</td>
<td>86.7</td>
<td>89.8</td>
<td>74.6</td>
</tr>
<tr>
<td>Disembedding</td>
<td>67.3</td>
<td>59.2</td>
<td>70.4</td>
<td>76.5</td>
<td>70.4</td>
<td>74.5</td>
<td>70.4</td>
<td>84.7</td>
<td>78.6</td>
<td>72.4</td>
</tr>
<tr>
<td>Perspective Taking</td>
<td>63.3</td>
<td>79.6</td>
<td>79.6</td>
<td>61.2</td>
<td>80.6</td>
<td>62.2</td>
<td>67.3</td>
<td>78.6</td>
<td>72.4</td>
<td>71.6</td>
</tr>
<tr>
<td>Object Location Memory</td>
<td>33.7</td>
<td>42.9</td>
<td>42.9</td>
<td>58.2</td>
<td>60.2</td>
<td>44.9</td>
<td>39.8</td>
<td>78.6</td>
<td>79.6</td>
<td>53.4</td>
</tr>
<tr>
<td>Visual Penetrative Ability</td>
<td>48.0</td>
<td>40.8</td>
<td>40.8</td>
<td>34.7</td>
<td>18.4</td>
<td>65.3</td>
<td>63.3</td>
<td>70.4</td>
<td>49.0</td>
<td>47.8</td>
</tr>
<tr>
<td>Mental Rotation</td>
<td>37.8</td>
<td>36.7</td>
<td>35.7</td>
<td>27.6</td>
<td>32.7</td>
<td>43.9</td>
<td>35.7</td>
<td>51.0</td>
<td>37.8</td>
<td>37.7</td>
</tr>
</tbody>
</table>

Table 2-3 Significant differences between undergraduates, graduate students, professionals (numbers represent individuals, N = 93)

<table>
<thead>
<tr>
<th>Question</th>
<th>Response</th>
<th>Undergraduate</th>
<th>Graduate</th>
<th>Professional</th>
<th>Independence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Did you use perspective taking with the visual satellite imagery?</td>
<td>Yes</td>
<td>15</td>
<td>3</td>
<td>39</td>
<td>X2(2, N=93)* = 8.3, p=.016</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>10</td>
<td>9</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>Did you use mental animation with the base reflectivity radar?</td>
<td>Yes</td>
<td>22</td>
<td>9</td>
<td>24</td>
<td>X2(2, N=93)** = 16.0, p&lt;.001</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>3</td>
<td>3</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>Did you use mental animation with the surface analysis plot?</td>
<td>Yes</td>
<td>8</td>
<td>3</td>
<td>38</td>
<td>X2(2, N=93)** = 13.1, p=.001</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>17</td>
<td>9</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Did you use disembedding with the surface analysis plot?</td>
<td>Yes</td>
<td>15</td>
<td>6</td>
<td>46</td>
<td>X2(2, N=93)* = 7.5, p=.023</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>10</td>
<td>6</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

* Correlation is significant at the 0.05 level  
** Correlation is significant at the 0.01 level
task decomposition and rule-based reasoning, inform mental animation processes. Her research, which collected eye tracking and think-aloud data, suggests that people infer the motion of complex systems by decomposing the task into a sequence of relatively simple interactions. This may also be true with diagnosing complex weather systems. It is possible that meteorologists decompose tasks contributing to overall storm motion, such as rotation, wind direction and the advance and occlusion of fronts, to determine the overall path of a storm.

Schwartz and Black (1996) similarly found that while solving problems requiring mental simulation of the motion of individual gears, individuals quickly discovered rules (any two interlocking gears move in opposite directions), which they relied upon to greatly simplify mental processing. We suggest that meteorologists may also augment mental animation with rule-based reasoning and prior experiences that place storm rotation and progression in context and guide predicted motion.

The perceived high use of mental animation with the GFS 4 panel plot, the NAM 4 panel plot, water vapor imagery, 500 mb chart and base velocity radar are also reasonable given the context. Because the GFS 4 panel plot contains consecutive temporal snapshots of forecasts, linking them together requires simulation of the omitted time. Meteorologists use the NAM 4 panel plot, water vapor imagery, and 500 mb charts like visible imagery, to visualize flow at each level. Thus, we propose that these types of images may elicit mental animation for the same reasons as the visible satellite imagery. The need for mental animation with the base velocity radar image is also reasonable, as the data provided explicitly measures atmospheric motion, and often requires deduction of two-dimensional flows from only one motion vector component.

As an overall average, our participants did not highly report using mental animation with either surface charts or the base reflectivity radar. However, of the two surface charts, the surface analysis plot exhibited significant differences between students and professionals. We will discuss these differences in a later section.

**Disembedding**

Disembedding, (related to flexibility of closure and field independence) (Ekstrom et al., 1976), is a distinctly different spatial thinking skill as compared to mental animation because it focuses on static rather than dynamic relationships (Newcombe & Shipley, 2015). Carroll (1993)
describes disembedding type skills as the ability to identify a stimulus or part of a stimulus that is either embedded in or obscured by visual noise. Newcombe and Shipley (2015) discuss disembedding in the context of “isolating and attending to one aspect of a complex display or scene” (p. 10).

As previously described, the majority of participants in our sample perceived using this skill on all of the images we provided, most frequently with the 4 panel plots. When interpreting images saturated with data, it is logical that individuals report use of disembedding. For example, with the interpretation of surface analysis plots, one seeks to identify fronts, wind direction, cloud coverage and pressure tendencies amid multiple data points encoded in each station model.

**Perspective Taking**

Piaget’s Mountain Task (cf. Borke, 1975), which asks children to take a perspective other than their own, illustrates perspective taking well. While sitting at a table in front of an asymmetric diorama, children describe how the scene would appear to a person sitting across from them (usually represented by a doll). There is a clear application for this type of perspective taking with radar, which may explain our participants’ high reporting with both radar images; how an observer interprets the image in relation to their location and the radar source requires an understanding of perspective. Additionally, interpretation of radial velocities and their relationship to the two-dimensional wind requires changing one’s perspective to facilitate correct interpretation. With the surface chart also, construing factors such as wind direction obliges one to orient directional relationships seen on a screen or paper to an authentic context in three-dimensional space.

Perspective taking and the ability to orient oneself to the external framework of the surrounding environment is a skill that for many adults is readily apparent. However, Liben, Kastens and Christensen (2011) found in a study of 125 college students, that many lacked awareness of their immediate surroundings to such a degree that when recording information on a map of their location, they did not attempt to align the map nor did they make links between map symbols and environmental referents such as roads and buildings. Because weather forecasting relies on working with weather maps, limitations in map reading, orientation and perspective taking will obviously create additional challenges. This has implications not only for
the training of student meteorologists, but also for the way that we communicate weather information to the public.

**Mental Rotation, Visual Penetrative Ability and Object Location Memory**

Perhaps as interesting as those spatial thinking skills that participants perceived as highly used, were those that were not. When averaged across all images, less than half of our participants reported using mental rotation and visual penetrative ability. They also did not report highly using object location memory. This is interesting in the context of the literature. Multiple studies (Trafton et al., 2000; Pliske et al., 2004; Trafton, 2004) describe forecasters creating mental models of the atmosphere that represent how spatial and temporal components integrate cause and effect relationships. Trafton et al. (2000) propose that during forecasting, weather forecasters create qualitative mental models that are spatial in nature and perspective free. These mental models allow for many different perspectives (e.g., either synoptic or mesoscale) and time scales that relate interactions between physical properties such as wind speed and pressure at different heights. This suggests an elaborate mental visualization of three-dimensional fluid motion.

Yet, subsequent work by Joslyn and Jones (2008), who studied Navy forecasters producing Terminal Aerodrome Forecasts (TAFs) in a busy naval forecasting office, indicates that these forecasters did not produce the type of mental models suggested by prior research. Instead, these forecasters (mostly novices) relied mainly on computer models and products, streamlined processes and rules of thumb. This may be an artifact of lack of expertise. However, we suggest that our results reporting lower perceived use of mental rotation and visual penetrative ability (both involving three-dimensional representation) potentially align with Joslyn and Jones’ (2008) results.

**Differences in Student and Professional Meteorologists’ Reported Use of Spatial Thinking Skills**

Among the three highly reported spatial thinking skills, we found significant differences between the three groups in four areas (Table 2-3). The data collected in this study do not allow
Chi, Feltovich and Glaser (1981) provided a basis for a well-established finding in expert-novice problem solving research. Their paper describes how expert physicists represent routine physics problems according to underlying principles, whereas novice physics students base representations on literal features. Many subsequent studies of expertise in other domains replicated their findings of deep versus shallow representation, including Lowe (1988, 1993) who investigated weather map interpretation by meteorologists and non-meteorologists.

Similarly, de Groot (1966, 1978, 1996) laid groundwork for expert-novice problem solving research among chess players, which was later corroborated by the work of Chase and Simon (1973) and Ericsson (2006). This body of work suggests that an expert chess player’s advantage comes from a huge mental library of chess positions held in long-term memory, rather than major differences in cognitive processes and abilities.

In our study, when we asked, “Did you use mental animation with the surface analysis plot?” the number of affirmative responses increased with experience. Professional meteorologists responded, “yes” at a rate of 67.8% whereas less than half of the undergraduate and graduate students responded affirmatively. Considering the literature and drawing a parallel to studies with chess, we suggest that the additional insight of the professional meteorologist may result from exposure to multiple weather scenarios that form the basis for prediction of future motion through mental animation. We hypothesize that by referring to a mental library of weather scenarios, meteorologists with higher expertise can anticipate motion from static “snapshots in time” while those with less experience interpret the plot for what it is—a mere description of recent conditions.

When participants responded to “Did you use disembedding with the surface analysis plot?” the undergraduate and graduate students also had lower levels of affirmative responses (60.0% and 50.0%, respectively). However, the professional meteorologists responded, “yes” at a substantial rate of 82.1%. We consider that these results corroborate classic expert-novice findings by suggesting that student meteorologists make superficial interpretations of surface analysis plots without attempting to disentangle deeply embedded, underlying representations, such as a professional meteorologist may attempt to do as implied by the higher rate of reported disembedding.
We find the dwindling reported use of mental animation with the base reflectivity radar with increasing experience intriguing. What many of the student meteorologists are mentally animating is ambiguous. Anecdotal conversations with university meteorology faculty suggest that this may be due to a lack of familiarity with different radar products and confusion over product types.

When asked, “Did you use perspective taking with the visual satellite imagery?” the graduate students were anomalous and the only group with the majority answering, “no” (75.0%). However, the small number of participants in this group may be the cause of this anomaly.

**LIMITATIONS AND FUTURE WORK**

When considering these results, two limitations should be acknowledged. The first limitation addresses the question of how well our participants understood the nature of each spatial skill from the written and pictorial representations. There is the possibility that the representations did not provide enough information for some participants. Participants were invited to leave comments in the final section of the survey; none of the comments indicated difficulty with interpreting the spatial skill descriptions or representations.

Second, confirming equivalence between our two sample groups would serve to further justify their combination into one study population and erase any concern regarding paper versus online administration of the survey. However, because our student population was contained entirely within the first sample that took the survey on paper, demonstrating equivalence between the groups was not possible, as this (student) factor made the two groups inherently different.

Having identified mental animation, disembedding and perspective taking as spatial thinking skills that may figure highly in interpretation of meteorological charts, maps, and images, we plan to use these findings in future work that explicitly tests participant aptitude with these skills in an attempt to characterize the effect of varying ability on weather forecasting performance. This is a next step toward our goal of developing spatial thinking training similar to that developed in other education domains. We also anticipate that it will serve to strengthen evidence and generate claims that are increasingly generalizable to larger populations, thereby advancing this work to higher levels in the GER Strength of Evidence Pyramid.
Other interesting questions were generated by this study as well. For example, we wonder if the greater reported use of disembedding by professionals distinguishes disembedding as a “gatekeeper skill”. Do meteorologists who easily see patterns, i.e., are “good disembedders”, persist in meteorology because it comes naturally or do these aptitudes develop with training and experience? If findings from research in other domains are any indication, the former relationship is likely dominant. A longitudinal study that tracked data from 400,000 participants over fifty years found that spatial thinking ability assessed during adolescence was a salient psychological attribute among those participants who subsequently went on to work in science, technology, engineering and mathematics (STEM) occupations (Wai et al., 2009).

We are interested in exploring the degree that task decomposition and rule-based reasoning accompany instances of mental animation while forecasting as described in the literature (Hegarty, 1992, 2010; Schwartz & Black, 1996). We also wonder about meteorologists’ creation of three-dimensional mental models of the atmosphere within the context of spatial thinking. We hypothesize that this may often represent an idealized notion of forecasting rather than actual practice, especially in light of the limited amount of time often allotted to generating forecasts in an operational setting. We plan to investigate this notion through qualitative analysis of think-aloud data in future work. Finally, we are curious about the effect of gender differences. Some tests of spatial ability show differences in results by gender, particularly, tests of mental rotation (Newcombe & Stieff, 2012). The number of females was too low in our study to investigate differences by gender; however, this is another area that we intend to investigate in future work.

CONCLUSION

Based on our results, we identified mental animation, disembedding and perspective taking as spatial thinking skills that may figure highly in interpretation of meteorological charts, maps, and images. The identification of mental animation by our participants may indicate that task decomposition and rule-based reasoning accompany mental animation processes. Our participants did not report a high use of spatial thinking skills associated with three-dimensional visualization, indicating that for them, their spatial thinking may be directed more at
understanding weather products and models through processes such as disembedding, rather than the elucidation of their own mental models.

We also identified differences in how student and professional meteorologists report using spatial thinking. We found that perceived use of mental animation with the surface analysis chart increased with increasing meteorology experience; this may be due to the professionals’ ability to recall similar weather scenarios from a large experiential library and project a future scenario. With the same chart, we also found that participants’ reported use of disembedding increased with experience, suggesting that many students are not attempting to disembed patterns and may focus more on the chart’s literal features.

When the idea for this study began, we felt somewhat at a loss as to where to begin, however, we successfully worked with practitioners who ultimately “steered us in the right direction.” Surprisingly, our participants expressed some benefit as well—some anecdotally commented that the enhanced awareness they gained through this exercise in metacognition might mediate their daily tasks. Overall, this study certainly created more questions than it asked, but by doing so, it provides grounding for exploring additional lines of research well into the future.

ACKNOWLEDGMENTS

The Department of Geography at Western Michigan University funded this research, for which we are grateful. In addition to our participants, we would like to thank Nicole LaDue and Karen McNeal for feedback and review. We also wish to thank Janice Bunting, Executive Director of the National Weather Association, for her assistance in recruiting participants for this study.
IDENTIFYING ASPECTS OF COGNITION SIGNIFICANT TO THE TRAINING OF UNDERGRADUATE METEOROLOGY STUDENTS

Peggy McNeal, Heather Petcovic, Nicole LaDue, and Todd Ellis

Manuscript in preparation for submission to Cognitive Research: Principles and Implications
In this study, we investigate the role of cognitive skills important to solving typical meteorology problems in undergraduate meteorology courses. We administer two spatial thinking tests, a visuospatial working memory test, a concept inventory and an expertise survey to 81 participants, including student through professional meteorologists. We compare these results to performance on a series of meteorology tasks. Analysis of the data suggests that meteorology knowledge along with disembedding skill (the ability to observe and recognize patterns among nonessential information) positively predicts performance with meteorological tasks. Data relating knowledge level to disembedding skill indicate that disembedding is an important predictor of meteorology success at both low and high levels of meteorology knowledge. Thus, our results suggest that instructional sequences providing frequent and sustained opportunities for pattern recognition with multiple weather scenarios may optimally support meteorology training.
INTRODUCTION

As in many science, technology, engineering and math (STEM) undergraduate courses, students in meteorology courses often struggle with complex scientific problems. In particular, meteorology students are asked to make sense of real-time, three-dimensional atmospheric processes from charts, maps and numerical data that depict upper-atmospheric and surface weather conditions. Presumably, this involves multiple aspects of cognition, such as spatial thinking and working memory, as well as domain knowledge and expertise. In an effort to improve student learning in undergraduate meteorology courses, this study investigated aspects of cognition important to successful completion of the types of meteorology tasks typically provided to undergraduate students in meteorology courses.

In other undergraduate STEM disciplines, cognitive science research has been combined with discipline based education research (DBER) to improve teaching and support student learning. Henderson, Mestre and Slakey (2015) advocate for collaborative efforts between cognitive science and DBER, noting that 1) both are concerned with developing knowledge about complex human reasoning; 2) their perspectives are not mutually exclusive; and 3) together they can be used to improve instructional practices. They provide an example resting on established cognitive science research that documents the different ways novices and experts categorize and approach physics problems (e.g., Chi, Feltovich, & Glaser, 1981). The research demonstrates that whereas novices group problems according to surface features of a problem’s scenario, experts tend to rely on the applicability of underlying principles and concepts. As a result, novices tend to hunt for equations containing the variables that they are given in a problem, unlike experts who first consider a problem’s major principles and concepts before applying appropriate equations as dictated by these concepts.

Dufresne, Gerace, Hardiman, and Mestre, (1992) applied this robust finding in a study that investigated the problem solving abilities of novice problem solvers after constraining them to qualitative strategies designed to mimic the problem solving behaviors of experts. The novices were required to perform a qualitative analysis of individual problems based on principles, concepts, and procedures before they were allowed to compute quantitative answers. When compared to a control group, the novices were significantly better both in ability to categorize
problems according to physics principles and in ability to solve physics problems. Thus, the
authors claim that it is the organization and use of knowledge, and not the knowledge itself that
plays a pivotal role in physics problem solving. Their paper describes implications for instruction
and includes suggested activities that are not part of traditional coursework. This example, and
others like it, has immediate and transferrable applicability to meteorology education.

In the case of spatial thinking, multiple large-scale data sets (e.g., Wai et al., 2009) have
documented a correlation between spatial thinking and persistence and attainment in STEM
learning, prompting researchers such as Uttal and Cohen (2012) to suggest that spatial thinking
may be an early filter in undergraduate STEM courses. Informed by these studies, along with a
meta-analysis demonstrating the malleability of spatial skills (Uttal et al., 2013), efforts to train
students in spatial thinking in conjunction with learning domain specific content have
accelerated. Sorby and Baartmans (2000), recognized that visualization of engineering problems
is an essential ingredient for student understanding in early engineering courses, and developed a
pre-graphics course for freshman engineering majors who demonstrate weak spatial visualization
ability on standard spatial thinking tests. Similarly, Ormand et al. (in press) have developed
curricular materials for mineralogy, structural geology, and sedimentology and stratigraphy
courses that support student understanding of spatially challenging concepts. In both cases, post-
treatment evaluations of learning gains demonstrate positive effects.

Working memory has also been the subject of research in STEM education. In addition to
measuring the effect of working memory on STEM learning, this research addresses structuring
learning to accommodate for differences and promoting student success (Jaeger et al., 2017). As
one example, Danili & Reed (2004) identified working memory as a factor affecting students’
understanding of chemistry concepts and subsequent performance on exams. They redesigned
curricular materials to reduce working memory load by presenting material stepwise,
consolidating content into meaningful units, referencing previous knowledge and organizing
material to reduce the need for note-taking, thus allowing greater focus on new concepts.
Experiments between treatment and control groups demonstrated a significant difference in the
average improvement of the experimental group.

In meteorology education, there has been little work at the intersection of cognitive
science and DBER. Thus, the overarching purpose of this study was to inform meteorology
education by characterizing the relative importance and interplay of particular intelligence
factors, domain knowledge and expertise in the context of typical problems assigned to students in undergraduate meteorology courses. More specifically, our purpose was to provide direction for enhanced pedagogy. We pursued evidence for including spatial training in undergraduate meteorology courses, along with evidence that working memory capacity may regulate student performance. We also sought confirmation for sustaining current practices, including maximizing content delivery and opportunity for repetitive training with authentic weather scenarios.

**BACKGROUND**

To characterize aspects of cognition of interest to this study, we referred to Cattell-Horn-Carroll (CHC) theory (McGrew, 2009). CHC theory is a working taxonomy of intelligence factors used as a theoretical framework from which to test hypotheses regarding various aspects of human cognition. It results from the merging of two consensus psychometric-based models for understanding the structure of human intelligence— Cattell and Horn's Fluid and Crystallized Intelligence theory (see Horn & Blankston, 2005 and Horn & Noll, 1997) and Carroll’s Three-Stratum models. The theory also forms the basis for continued development of individually administered intelligence tests.

Specifically, we were interested in investigating expertise, malleable aspects of cognition that are improvable with training, stable components of intelligence, and acquired knowledge resulting directly from education. We additionally sought to understand the interplay of these factors in the context of meteorology by testing hypotheses found in cognitive science literature. Such understanding could lead not only to improvements in instructional materials, but inform pedagogy specifically regarding the role of each factor and its relative importance in advancing meteorology skill. We next describe each factor considered in the study in the context of CHC theory, along with justification for inclusion, and relevant hypotheses.

**Spatial Thinking Ability**

CHC theory includes spatial thinking within the broad intelligence category, visual processing ($G_v$), which is defined as “the ability to generate, store, retrieve, and transform visual
images and sensations” (McGrew, 2009, p. 5). Accounting for spatial thinking factors, however, is complex; several are recognized and how they are classified and measured vary considerably (Uttal et al., 2013). Thus, we additionally refer to Newcombe and Shipley (2015), who provide a typology of spatial skills framed by linguistic, cognitive, and neuroscience research. Their categories are:

1. Intrinsic-Static: coding the spatial features of objects, including their size and the arrangement of their parts.
2. Intrinsic-Dynamic: transforming the spatial codings of objects, including rotation, cross-sectioning, folding, plastic deformations.
3. Extrinsic-Static: coding the spatial location of objects relative to other objects or to a reference.
4. Extrinsic-Dynamic: transforming the inter-relations of objects as one or more of them moves, including the viewer.

We investigated two spatial thinking skills, mental rotation—part of spatial relations in CHC theory, but also broadly associated with spatial visualization—and disembedding, or what CHC theory (and others) refers to as flexibility of closure. Withstanding the confusing nomenclature, mental rotation is included in Newcombe and Shipley’s (2015) intrinsic-dynamic category, and disembedding in the intrinsic-static group.

**Mental Rotation**

Mental rotation involves rotating mental representations of two-dimensional and three-dimensional objects (Manduca & Kastens, 2012). We chose to investigate mental rotation due to its association with spatial visualization, a skill deemed important to meteorologists who must understand atmospheric dynamics and the motions of three-dimensional, largely invisible fluids. Additionally, mental rotation is one spatial skill for which the cognitive processes underpinning improvement are better understood (Uttal et al., 2013). Research has established that mental rotation training increases response time (Kali & Park, 1992) as well as improves initial encoding of the figure to be rotated (Wright et al., 2008). Especially of interest, however, is work
by Just and Carpenter (1985) that shows that not all individuals who excel at mental rotation do so through visualization. Comparing specific aspects of a figure, followed by checking whether corresponding elements match after rotation works as well. Thus, using pattern recognition and learning rules are methods that can potentially lead to improvement with mental rotation. Hegarty and Waller (2005) suggest that mental rotation may be partially dependent on working memory (discussed in a later section) because the figure, along with its features must be held in memory in order to be rotated. Thus, because individual, stable differences are associated with working memory, mental rotation may be an intelligence factor that is trainable, but within the confines of an individual’s working memory capacity.

**Disembedding**

Disembedding consists of observing and recognizing patterns, and isolating important aspects from distracting, nonessential ones (Manduca & Kastens, 2012). Our choice to investigate disembedding resulted from a prior investigation that sought to identify which spatial thinking skills meteorologists report using in their work (Chapter 2; McNeal et al., in review). Our results suggested disembedding as worthy of investigation; 72% of the meteorologists in our sample (N = 93) reported using disembedding while interacting with nine meteorological charts and images. Furthermore, we found a significant difference in how student and professional meteorologists reported their use of disembedding. Student meteorologists reported using disembedding with a surface analysis plot at a much lower rate when compared to professional meteorologists. Referencing classic expert-novice findings (e.g., Chi, Feltovich & Glaser, 1981), we hypothesized that student meteorologists make superficial interpretations of surface analysis plots without attempting to disentangle deeply embedded, underlying patterns, such as a professional meteorologist may attempt to do.

A meta-analysis (Uttal et al., 2012) of studies purporting to train a variety of spatial skills showed that intrinsic-static spatial skills such as disembedding do not demonstrate the same degree of malleability as other types of spatial skills. Average effect size (Hedges’ g) over multiple intrinsic-static training scenarios was 0.32 (compared to 0.69 for extrinsic-static training). Uttal et al. (2012) propose that intrinsic-static type skills, such as those measuring disembedding, respond less to training because implicit in the skill is finding an unidentified
form; the trainer does not divulge what form to look for. Whether the limiting factor affects the training or the learning is ambiguous; however, considering the small effect size (Cohen, 1988), we hesitate to characterize disembedding as a robustly trainable spatial thinking skill.

**Working Memory**

Working memory is the ability to maintain task-relevant information in a highly active state. It is an inherited aspect of intelligence (Kremen et al., 2007; Polderman et al., 2006) that is considered constant throughout one’s life (Unsworth, Heitz, Schrock, & Engle, 2005). Hambrick and Engle (2002) describe working memory as one of several “hardware aspects of the cognitive system—factors that are thought to reflect general, and relatively stable, characteristics of the individual” (p. 341).

CHC Theory categorizes working memory as part of overall short-term memory ($G_{sm}$), however to conflate the two would be a mistake. Whereas short-term memory does not involve intervening processing, working memory does and therefore specifically describes the ability to process and hold information simultaneously (Wiley et al., 2014). Kyllonen and Dennis (1996) found an almost perfect correlation between working memory and fluid reasoning\(^3\) ($G_f$), thus it is often used to approximate $G_f$ (Hambrick & Engle, 2002). We investigated working memory capacity due to its important role in STEM learning (Jaeger et al., 2017), as a cognitive component recognized as influential to forecasting (Joslyn & Jones, 2008) and as a proxy for fluid reasoning ($G_f$) (Kyllonen & Dennis 1996).

**Domain Knowledge and Expertise**

Domain knowledge results from an accumulation of school and lifetime experiences that can be measured through concept inventories and tests of the factual knowledge required for understanding a field. Expertise serves to increase skill acquisition and together, domain knowledge and expertise contribute to general, domain specific knowledge, $G_{kn}$ in CHC theory.

\(^3\) McGrew (2009) defines fluid reasoning as deliberate and controlled mental operations used to solve novel problems.
Expertise studies have a history tracing back to De Groot’s (1965) work with expert chess players. Chase and Simon (1973) continued this line of research, notably using verbal protocol analysis. Through studies of chess players, typists and pianists, Ericsson (2014) and Ericsson and Smith (1991) captured superior performance of domain experts and determined that: 1) extensive experience is necessary to attain superior expert performance; 2) only some types of domain related experience are shown to lead to improvement of performance; and 3) many thousands of hours of specific types of practice and training have been found to be necessary for reaching the highest levels of performance. A theoretical framework described by Ericsson, Krampe and Tesch-Römer (1993) suggests ten years of deliberate practice necessary to attain expert-level performance and is the basis of the 10,000-hours/10 years practice rule commonly used to define expertise.

**Relevant Hypotheses**

Two hypotheses described in the literature guided the design of our study. Hambrick and Meinz (2011) refer to the first as the circumvention-of-limits hypothesis. The hypothesis predicts that domain knowledge moderates the impact of other intelligence factors on domain relevant performance. As an example, a study conducted by Hambrick et al. (2012) worked with geologists as they engaged in a bedrock-mapping task. Participants completed a suite of cognitive tests that measured visuospatial ability along with domain knowledge and working memory. When compared to performance on the bedrock-mapping task, Hambrick et al. (2012) found that visuospatial ability affected performance on the task at low, but not high levels of domain knowledge. This demonstrated that novice geologists were able to “circumvent” limitations in knowledge and perform well on the task if they possessed high visuospatial abilities.

Other studies demonstrate this as well, from Chase and Simon’s 1973 study of chess expertise to studies of air traffic control operations (Ackerman, 1992). These cases confirm that performance level increases as domain knowledge grows, even for individuals who score lower on tests of other intelligence abilities.

These results seem to indicate that a main source of “power”, contributing to performance in complex tasks is domain knowledge, a view known as the knowledge-is-power hypothesis.
(Feigenbaum, 1989). This hypothesis predicts that domain knowledge is the primary determinant of success in complex tasks, with other intelligence factors taking a less important role. Ericsson, Krampe, & Tesch-Römer (1993) maintain that knowledge and skill abilities acquired through deliberate practice are more influential than recognized in the cognitive science field.

However, results of a 2010 study conducted by Meinz and Hambrick contrast with this claim. Their study worked with pianists representing a range of expertise and lifetime amounts of deliberate practice. Participants completed working memory tests and demonstrated ability to sight-read difficult piano pieces. The Meinz and Hambrick (2010) study found that both working memory and hours of deliberate practice positively predicted sight-reading performance. These results suggest that even high levels of deliberate practice may not be sufficient to overcome limitations generated by lower levels of working memory capacity.

RESEARCH QUESTION

There appears to be a complex interplay between different aspects of cognition, domain knowledge, and expertise. Accumulated domain knowledge is powerful, and offsets limitations in other intelligence abilities, but clearly not in every context or situation. Our research design included testing both the circumvention-of-limits hypothesis and the knowledge-is-power hypothesis to augment our research question: What effects do working memory, domain knowledge, mental rotation, disembedding, and expertise have on performance on a series meteorology tasks?

METHODS

Our research used a cross-sectional design that included professional and student meteorologists. We collected data from November 2016 through September 2017 at three universities, a National Weather Service Forecasting Office, a U.S. Navy Fleet Weather Center and a professional conference. An a priori power analysis indicated that a sample size of 68 was necessary for satisfactory power (probability of correctly rejecting a false null hypothesis greater than 0.8) to observe a medium effect in a regression analysis with two predictors. We administered a survey along with tests of mental rotation, disembedding, visuospatial working
memory, and meteorology knowledge, followed by a series of meteorology tasks. We conducted a quantitative analysis of the data to seek correlations and compare means before performing a regression analysis to investigate the effects of the targeted intelligence factors on meteorology task performance. We used IBM’s Statistical Package for the Social Sciences (SPSS) Version 24 for data analysis.

**Participants**

We sought a wide range of expertise, thus our participant recruiting targeted undergraduate and graduate meteorology students, university meteorology faculty, and military and civilian operational forecasters. Minimal qualification for participation was enrollment in or completion of a college-level meteorology course. To recruit participants, we used professional networks to identify gatekeepers at host institutions. The gatekeeper distributed an email directing individuals interested in participating in the research to contact the first author, who arranged for time and place to meet at the host institution. Upon meeting, individuals were briefed on the research and signed informed consent. Table 3-1 gives detailed information about our data sources.

Our sample included 81 participants who ranged in age from 19 to 64 years with an average age of 27.3 years (SD\(_{\text{age}}\) = 1.2). Our sample was 63% male. Descriptive statistics for participants are included in Table 3-2.

**Data Collection and Instrumentation**

Data collection occurred with participants individually, or in groups of up to five participants and took 1½ to 2 hours per individual. Participants completed the Educational Testing Service (ETS) Hidden Figures Test, the Vandenberg and Kuse Test of Mental Rotation, a Matrix Span Test of Visuospatial Working Memory, the Fundamentals in Meteorology Inventory (FMI), a Domain and Experience Questionnaire (DEQ) and a series of meteorology tasks. Each measure is described below. Participants first completed the three timed tests, then the FMI and DEQ, and finished with the series of meteorology tasks. On occasions when testing was conducted in groups, the working memory test, which was administered on a laptop, was
administered individually while others worked ahead, in turn. Participants were compensated with stipends of 20 or 50 dollars, due to restrictions on gifts that can be accepted by federal employees.

**Table 3-1** Data sources

<table>
<thead>
<tr>
<th>Institution type</th>
<th>Participants</th>
<th>Dates of data collection</th>
</tr>
</thead>
<tbody>
<tr>
<td>University 1</td>
<td>13 undergraduate students, 6 graduate students, 3 faculty</td>
<td>November 2016 and September 2017</td>
</tr>
<tr>
<td>University 2</td>
<td>9 undergraduate students, 4 graduate students, 1 faculty</td>
<td>April 2017</td>
</tr>
<tr>
<td>University 3</td>
<td>19 undergraduate students, 8 graduate students, 2 faculty</td>
<td>April 2017 and September 2017</td>
</tr>
<tr>
<td>National Weather Service Forecast Office</td>
<td>6 operational forecasters, 1 student intern</td>
<td>July 2017</td>
</tr>
<tr>
<td>U.S. Navy Fleet Weather Center</td>
<td>3 U.S. Navy aerographer’s mates, 2 civilian forecasters</td>
<td>July-August 2017</td>
</tr>
<tr>
<td>Conference attendees</td>
<td>3 faculty, 1 operational forecaster</td>
<td>July 2017</td>
</tr>
</tbody>
</table>

**Vandenberg and Kuse (1978) Mental Rotation Test**

We selected the Vandenberg and Kuse Mental Rotation Test to measure mental rotation due to its role in spatial visualization ($G_v$). It is a paper and pencil test that consists of symmetric and asymmetric figures of 3-D objects, drawn in a 2-D isometric format, rotated around a horizontal axis. The test requires subjects to select two rotated figures that have the same configuration as the first figure in a series (Vandenberg & Kuse, 1978). It consists of twenty-four
items administered in two sets of twelve with a three-minute time limit for each set. Each item was scored correct only if both correct configurations were selected, to eliminate correct guesses (Vandenbeurgh & Kuse, 1978). Historically, male scores on the Vandenbeurgh and Kuse Mental Rotation Test are higher than female scores (Linn & Peterson, 1985) capturing gender differences in mental rotation ability recognized in the literature (Newcombe and Stieff, 2012).

**Table 3-2** Descriptive statistics for participants in the study

<table>
<thead>
<tr>
<th>Experience</th>
<th>% of sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Have you completed military weather training?</td>
<td>8.7</td>
</tr>
<tr>
<td>Have you completed (or are enrolled in) college courses:</td>
<td></td>
</tr>
<tr>
<td>• Intro to Weather Analysis</td>
<td>91.4</td>
</tr>
<tr>
<td>• Synoptic Meteorology</td>
<td>67.9</td>
</tr>
<tr>
<td>• Dynamic Meteorology</td>
<td>82.7</td>
</tr>
<tr>
<td>• Mesoscale Meteorology</td>
<td>55.6</td>
</tr>
<tr>
<td>• Physical Meteorology</td>
<td>64.2</td>
</tr>
<tr>
<td>• Climatology</td>
<td>64.2</td>
</tr>
<tr>
<td>• Forecasting</td>
<td>67.9</td>
</tr>
<tr>
<td>• Broadcast Meteorology</td>
<td>11.1</td>
</tr>
<tr>
<td>Have you completed/are you working on:</td>
<td></td>
</tr>
<tr>
<td>• Internship in atmospheric science</td>
<td>58.0</td>
</tr>
<tr>
<td>• Original research in atmospheric science</td>
<td>45.7</td>
</tr>
<tr>
<td>What is your education level in atmospheric science/meteorology:</td>
<td></td>
</tr>
<tr>
<td>• Pursuing an M.A./M.S.</td>
<td>18.5</td>
</tr>
<tr>
<td>• Completed an M.A./M.S.</td>
<td>23.5</td>
</tr>
<tr>
<td>• Pursuing an Ph.D.</td>
<td>4.9</td>
</tr>
<tr>
<td>• Completed a Ph.D.</td>
<td>12.3</td>
</tr>
<tr>
<td>Have you worked professionally as a meteorologist?</td>
<td></td>
</tr>
<tr>
<td>• Less than 5 years</td>
<td>8.6</td>
</tr>
<tr>
<td>• 5-10 years</td>
<td>4.9</td>
</tr>
<tr>
<td>• More than 10 years</td>
<td>13.6</td>
</tr>
</tbody>
</table>
Educational Testing Service (1975) Hidden Figures Test

The ETS Hidden Figures Test measures ability with disembedding/flexibility of closure. It is a paper and pencil test that requires subjects to search in a perceptual field containing irrelevant or distracting material in order to find one or more given configurations (Ekstrom et al., 1976). The test asks subjects to decide which of five geometrical figures is embedded in a complex pattern. It consists of two similar sections. Each section contains sixteen questions and participants have twelve minutes to complete each section. We administered one section of the test to reduce overall test time and diminish test fatigue in participants. We followed scoring procedures described by Danili and Reid (2004); one point for a correct simple shape embedded in each complex pattern.

Matrix Span Test of Working Memory

Several complex-span tests are used to target different aspects of working memory, including visuospatial, verbal, and arithmetic. We measured working memory capacity ($G_{sm}$) with a matrix span working memory test to specifically target the visuospatial domain of working memory. The test was administered on a computer tablet and scored using partial-credit load scoring (Conway et al., 2005). The test requires subjects to store information in memory while engaging in an unrelated processing task. Specifically, subjects are presented with thirty-six items, each with an array of L’s, followed by a matrix with one cell filled. Subjects circle yes if an upside-down T is included in the array of L’s, and remember the location of the filled cells.

Fundamentals in Meteorology Inventory

To measure domain knowledge ($G_{kn}$), we administered the Fundamentals in Meteorology Inventory (FMI) (Davenport, Wohlwend & Kohler, 2015), an untimed, meteorology concept inventory. The FMI was designed to measure the conceptual understanding of fundamental meteorology concepts presented in most introductory courses. Thirty-five multiple choice questions span seven broad topics covered in meteorology courses: clouds and precipitation,
wind, fronts and air masses, temperature, stability, severe weather, and climate. We used the FMI as a measure of basic meteorology knowledge commensurate with that of an undergraduate, upper-level meteorology major (e.g., juniors and seniors) that aligns with the difficulty level of the proposed forecasting task. Other than the FMI, which is still in development, but has undergone initial evaluation and validation, a concept inventory in meteorology comparable to the FMI does not exist (Davenport, Wohlwend & Kohler, 2015).

**Domain and Experience Questionnaire (DEQ)**

To measure expertise and gather additional demographic data, we modified valid and reliable surveys from two prior studies (Baker et al., 2012; Petcovic, Ormand & Krantz, 2016) to make them applicable to weather forecasters, meteorologists and atmospheric scientists. We pilot tested the DEQ with a small group of meteorology students and faculty and weighted the scoring to favor operational and professional experience. The DEQ is provided in Appendix A.

**Meteorology Task Series**

To evaluate participants’ ability to solve novice level meteorology problems, such as those involved in forecasting scenarios, we developed a meteorology task series based on multiple versions of case study problems typically provided to undergraduate meteorology students. We collected requisite charts and plots from archived data maintained at the Plymouth State University Weather Center for the task series that involves a weather event from 2013. Starting with a plotted surface data map, the instructions ask the participant to mark the low-pressure center and draw in warm and cold fronts. The task continues with upper air maps representing 850 mb, 500 mb and 300 mb; the participants are asked to annotate troughs and ridges, shade areas of cold and warm air advection, positive and negative vorticity advection, and divergence and convergence. Finally, given a blank map of the United States, the participant predicts and marks the location of lowest pressure twelve hours later. An external expert evaluator (a university geography and meteorology department chair) developed a ten-point rubric for evaluation of each chart and completed the scoring. The entire meteorology task series is provided in Appendix B. The scoring rubric is in Appendix C.
RESULTS

We screened all variables for outliers (3.5 standard deviations from the mean) and influential cases. We identified three outliers, which were excluded leaving a final sample size of 78. All variables were evaluated to confirm that they approximated normality (skewness < 1). One case was missing mental rotation data due to incorrect test completion. Additionally, the November 2016 data collection served as an initial pilot study of all tests except the matrix span test of working memory. Therefore, for this measure only, N = 65.

Descriptive Statistics and Correlations

Descriptive statistics for the tests and tasks are provided in Table 3-3 and correlations are provided in Table 3-4.

As described in the literature (Newcombe & Stieff, 2012), independent-samples t-tests confirmed a gender difference with the test of mental rotation in our data. Males had higher mental rotation scores (M = 10.39, SD = 3.96) than did females (M = 7.43, SD = 3.82), t(77) = -3.23, p = .002. The literature also describes age related differences on tests of working memory (Hambrick & Engle 2002) that were confirmed with our data. Independent-samples t-tests demonstrated that participants under 25 had higher working memory scores (M = 24.15, SD = 6.95) than did participants 25 and older (M = 19.5, SD = 6.95), t(65) = 2.60, p = .012).

Table 3-3 Descriptive statistics for tests and tasks

<table>
<thead>
<tr>
<th>Test</th>
<th>N</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hidden Figures Test (disembedding)</td>
<td>78</td>
<td>1</td>
<td>16</td>
<td>7.10</td>
<td>3.39</td>
</tr>
<tr>
<td>Mental Rotation Test</td>
<td>77</td>
<td>1</td>
<td>19</td>
<td>9.31</td>
<td>4.14</td>
</tr>
<tr>
<td>FMI (domain knowledge)</td>
<td>78</td>
<td>11</td>
<td>34</td>
<td>26.03</td>
<td>5.81</td>
</tr>
<tr>
<td>Matrix Span Test (working memory)</td>
<td>65</td>
<td>.22</td>
<td>1.00</td>
<td>0.62</td>
<td>0.03</td>
</tr>
<tr>
<td>DEQ (expertise)</td>
<td>78</td>
<td>.75</td>
<td>11.75</td>
<td>4.66</td>
<td>3.34</td>
</tr>
<tr>
<td>Meteorology Task</td>
<td>78</td>
<td>9</td>
<td>35</td>
<td>26.03</td>
<td>5.81</td>
</tr>
</tbody>
</table>
Table 3-4 Correlations between variables

<table>
<thead>
<tr>
<th></th>
<th>Disembed</th>
<th>Spatial visualization</th>
<th>Domain knowledge</th>
<th>Working Memory</th>
<th>Expertise</th>
<th>Met task</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disembedding(^a)</td>
<td>1</td>
<td>.227(^*)</td>
<td>.166</td>
<td>.227</td>
<td>-.013</td>
<td>.317(^**)</td>
</tr>
<tr>
<td>Mental rotation(^b)</td>
<td>1</td>
<td>.187</td>
<td>.204</td>
<td>-.072</td>
<td>.131</td>
<td></td>
</tr>
<tr>
<td>Domain knowledge(^a)</td>
<td>1</td>
<td></td>
<td>-.070</td>
<td>.474(^**)</td>
<td>.533(^**)</td>
<td></td>
</tr>
<tr>
<td>Working Memory(^c)</td>
<td>1</td>
<td></td>
<td>-.378(^**)</td>
<td>-.041</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expertise(^a)</td>
<td>1</td>
<td></td>
<td></td>
<td>.345(^**)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meteorology task(^a)</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^*\)Correlation is significant at the 0.05 level (2-tailed)
\(^**\)Correlation is significant at the 0.01 level (2-tailed)
\(^a\)N = 78; \(^b\)N = 77; \(^c\)N = 65

Results from the two tests of spatial thinking ability (Hidden Figures and Vandenberg and Kuse Test of Mental Rotations) weakly correlate with each other (r = .227, p = .047). This is lower than the r = .40 correlation reported by Vandenberg and Kuse (1978) but suggests that skills necessary for success with disembedding are associated with broader spatial visualization skills measured by tests of mental rotation. Our measures of domain knowledge and expertise also correlate (r = .474, p < .001), which confirms reasonable expectations and reinforces the validity of each measure. There is evidence that the meteorology task is a valid measure of skill as it correlates strongly with both expertise (r = .345, p = .002) and domain knowledge (r = .533, p < .001). The correlation between working memory and expertise is significant and negative (r = -.378, p = .002) due to a strong correlation between expertise and age (r = .784, p < .001) and the aforementioned age related differences on tests of working memory. Disembedding positively correlated with meteorology task performance (r = .317, p = .005). The lack of significant correlation between working memory and the remaining variables is noteworthy and discussed in a later section.
Regression Analysis

To address our first hypothesis, we performed a hierarchal regression analysis using domain knowledge, disembedding and expertise to predict performance on the meteorology tasks. We entered domain knowledge in Step 1, ($\Delta R^2 = .284$, $\Delta F(1, 77) = 30.21, p = .000$), disembedding in Step 2 ($\Delta R^2 = .054$, $\Delta F(1, 77) = 6.09, p = .016$), and expertise in Step 3 ($\Delta R^2 = .017$, $\Delta F(1, 77) = 1.94, p = .168$). Expertise did not significantly increase $R^2$ and was not retained in the model.

To test the circumvention-of-limits-hypothesis, we created an interaction variable, domain knowledge x disembedding, and entered it as the final step. It was also not significant ($\Delta R^2 = .009$, $\Delta F(1, 77) = 1.01, p = .317$) and also not retained. Thus, the results of our final model are presented in Table 3-5. We performed a median split on the FMI score (domain knowledge) data and verified through an independent samples-samples t-test a significant difference in the meteorology task means of the two groups ($M_{low} = 18.89$, $SD = .796$; $M_{high} = 23.67$, $SD = .785$), $t(78) = -4.25, p < .001$). We created a scatterplot of disembedding regressed onto performance on the meteorology task by low and high domain knowledge groups to illustrate that disembedding skill positively predicts performance on the meteorology task at both low and high levels of domain knowledge (see Figure 3-1).

DISCUSSION

In answer to our research question, we found a strong effect of domain knowledge on performance with the meteorology task, augmented by a significant disembedding effect. Our finding that domain knowledge is the strongest predictor of performance on the meteorology task is not surprising and aligns with the results of other studies (e.g. Hegarty et al., 2010). It is also not surprising that domain knowledge and expertise are highly correlated ($r = .474$, $p < .001$); in reality, they are inextricably related. Roebber and Bosart (1996) examined the contributions that both education and experience make to weather forecasting skill and note “that the distinction between education and experience is not precise…students gain experience through the study of
Table 3-5 Results of hierarchal regression analysis predicting performance on meteorology tasks

<table>
<thead>
<tr>
<th>Variable</th>
<th>ΔR</th>
<th>β</th>
<th>ΔF</th>
<th>df</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1</td>
<td>.284</td>
<td>.465</td>
<td>30.21*</td>
<td>1,76</td>
</tr>
<tr>
<td>Domain knowledge</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step 2</td>
<td>.054</td>
<td>.379</td>
<td>6.09**</td>
<td>1,75</td>
</tr>
<tr>
<td>Disembedding</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total adjusted $R^2$</td>
<td>.320</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

N = 78. * = p < .05. ** = p < .001

Figure 3-1 Meteorology Task vs Disembedding by high/low domain knowledge

cases in a synoptic lab” (p. 27). In their analysis of nine semesters of forecast contest data, Roebber and Bosart (1996) determined that the primary advantage maintained by an experienced forecaster is the larger set of cases from which they may draw information. Experienced forecasters rely on a “library” of weather scenarios to recognize patterns in current weather data or notice deviations from a pattern and act accordingly. This is likely the advantage held by our participants with high levels of meteorology knowledge as well. By virtue of their higher knowledge level, they have been exposed to a greater number of weather scenarios, including the
classic mid-latitude cyclone featured in the meteorology task. Recognition of this weather pattern by successful participants subsequently prompted them to seek patterns associated with this type of weather scenario in the surface and upper air charts.

This practice of pattern recognition extends to skill with disembedding as well. Here, however, rather than seeking overall physical patterns that describe atmospheric dynamics and how they manifest, an individual seeks configurations embedded in a distracting design, a process related to extracting and annotating wind, temperature and precipitation patterns (among others) embedded in meteorological charts saturated with numerical and encoded data. An example of a surface chart is provided in Figure 3-2. One example of a pattern that a meteorologist might “see” is the cloud pattern represented by the encoding of percent sky cover in the fractional shading of the inside circle of each station plot on this chart. A corresponding satellite image for the same time (Figure 3-3) reveals the cloud pattern that is represented by the surface chart and makes apparent what a trained meteorologist perceives in this type data. (For a qualitative description of the disembedding process with the meteorology task among low, medium and high disembedders, see McNeal et al., in prep)

The remaining cognitive factors (mental rotation and working memory) were not significant predictors of success with the meteorology task. Considering that their inclusion was theoretically informed, we are compelled to contemplate why this is so. Our first intuition is that mental rotation, representative of intrinsic-dynamic spatial skills, involves holding a configuration in mind in order to rotate it whereas disembedding, (because it is static) does not—it is envisioned externally (in this case on a piece of paper). We suggest, therefore that meteorology tasks, such as the one we provided, solicit spatial thinking relevant to interpreting charts rather than visualizing atmospheric processes and hypothesize that this may be the case with many meteorological tasks, considering the heavy need to interpret data displays and imagery, both physical and computerized, in forecasting offices. It may also be that the mental rotation test, which involves rotating a rigid solid, does not align well with the task of mentally visualizing fluid rotation and motion. This presents an interesting question for further investigation.

We also note that although mental rotation skill did not show a significant correlation with the meteorology task, it did correlate with disembedding skill. We suggest that our participants may be among those individuals who mentally rotate using pattern recognition and
rules (Just & Carpenter, 1985), potentially displaying a preference for pattern seeking that is beneficial to interpreting meteorological charts. The additional consideration of Hegarty and Waller’s (2005) suggestion that mental rotation may be partially dependent on working memory due to the necessity of holding the figure “in mind” in order to rotate it, may simultaneously explain the lack of correlation between mental rotation, working memory, and the meteorology task and support the notion that our participants do not rely heavily on spatial visualization, but favor pattern recognition instead.

Since working memory displayed a strong negative correlation with age, but was not a significant predictor of performance on the meteorology task, we reasoned that the age correlation may be confounding the analysis and reran the regression only with participants

![Figure 3-2 An example of a surface chart from Plymouth State Weather Center (http://vortex.plymouth.edu)](http://vortex.plymouth.edu)
under 35 years of age. There was still no significant result. Thus, our work is unable to contribute to the claim that working memory positively predicts performance, but our results do support the knowledge-is-power hypothesis.

Overall, our findings suggest that meteorology knowledge and disembedding skills predict performance on the meteorology task and that disembedding has a positive effect at both low and high levels of meteorology knowledge. This contrasts with the circumvention-of-limits hypothesis, however we propose that it contributes illuminating evidence to the developing model of complex skill acquisition of which the hypothesis is a part. Regarding the circumvention-of-limits hypothesis, Hambrick et al. (2012) write, “We speculate that another potentially important factor is whether the task input is static or dynamic” (p. 6). For example, in the case of geologic mapping, the input does not change over time, thus individuals can encode information in long-term memory and potentially bypass the need to think spatially or rely on other cognitive skills. However, when solving meteorological problems, individuals necessarily deal with constantly changing input— the weather— and may need to rely on relevant cognitive skills, such as disembedding, with each new task.
LIMITATIONS AND FUTURE WORK

In an effort to address continuing questions regarding the role of working memory in meteorology task performance, we propose expanding aspects of this study that we consider limiting, in future work. In particular, our measurement of working memory, along with its influence on the task may have experienced a ceiling effect that confounded our results. Working memory capacity is context specific and our task may not have provided adequate context for demonstrating a working memory effect. By designing a meteorology task that stresses working memory to a greater degree, we may create a better opportunity to elicit such an effect, if present. Incorporating a naturalistic design that involves time pressure and high-risk decision making, (such as during storm chasing) could test this.

The addition of multiple types of complex-span tests of working memory (visuospatial, verbal, arithmetic) may additionally capture a more nuanced depiction of participants’ working memory. Moreover, by working with a homogenous age sample, we may rid the data of issues potentially biased by declining working memory capacity with age. As a final consideration, we recognize that the majority of participants in our sample have completed upper level meteorology courses requiring a math progression through Calculus III. This raises the possibility that the working memory scores in our sample were significantly higher than the average population, especially since working memory can be considered a proxy for fluid reasoning. We are unsure if this affected our data and its analysis.

As an early study situated at the intersection of cognitive science and DBER in meteorology, we hope that our work will serve as a springboard for subsequent research. The potential for impacting the field is great, including the development of new learning interventions to inform meteorology education communities broadly, encompassing university meteorology courses for majors and non-majors, military weather forecaster preparation and professional training for operational meteorologists.

CONCLUSION

To conclude with implications for education, we return to our overall purpose— to inform meteorology education. Our study provides evidence that disembedding is a skill that
predicts performance on typical meteorology problems required of undergraduate meteorology students. Additionally, disembedding skill positively affects meteorology skill at low and high levels of meteorology knowledge. The advantage appears to lie in the ability to identify patterns, be they embedded in distracting background displays, repeated in weather scenarios or present in observational data. We propose that there is value simply in raising instructor awareness of the potential limitations of low disembedding students so that it is recognized as a source of confusion— not all students are able to detect patterns that may be immediately apparent to an instructor. The training effect of targeted disembedding instruction is less than promising, however, practice with pattern identification, especially within a meteorology context may yield positive results. This is an area ripe for future research.

Our findings do not contribute to the claim that working memory capacity predicts task performance in a meteorology context. However, Jaeger, et al. (2017) review how classroom activities and curricular materials might be structured to account for limited working memory capacity and cognitive load induced by lessons heavy on visualizations; we refer the interested reader to this work.

Finally, our study corroborates previous research (Roebber & Bosart, 1996) and provides evidence for the claim that meteorology knowledge and expertise are the strongest predictors of performance on typical meteorology problems required of undergraduate meteorology students. Additionally, our findings support the knowledge-is-power hypothesis. Therefore, supporting this finding in the meteorology classroom through frequent and sustained opportunities for practice with realistic forecasting scenarios and weather case studies may the best way build a mental library of weather scenarios from which to support pattern recognition.

**ACKNOWLEDGEMENTS**

We thank the Graduate College at Western Michigan University for funding our research. In addition to our participants, we owe a debt of gratitude to Dr. Teresa Bals-Elsholz, who graciously shared her content knowledge, expertise, and students in support of this project. We additionally thank Dr. David Chagnon, Dr. Sandra Yuter, Dr. William Burnett, and John Dumas for facilitating access to study participants.
CHARACTERIZING THE DISEMBEDDING SKILLS OF UNDERGRADUATE METEOROLOGY STUDENTS

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ABSTRACT

Disembedding, or recognizing configurations in a distracting background, is a spatial thinking skill that is particularly relevant to the interpretation of meteorological surface and upper air charts. Difficulty “seeing” patterns such as cyclonic flow, thermal ridges, or pressure gradients can make weather analysis challenging for students with limited disembedding skills. In this study, undergraduate meteorology students were tested for disembedding ability and categorized as having low, medium or high disembedding skill. The students completed a series of meteorological tasks while verbalizing their thought processes, which were video recorded. The videos, transcribed verbal data, and participant products were analyzed for instances of disembedding. Results suggest that individuals with greater disembedding skill rely more on observing patterns embedded in meteorological charts in conjunction with rule-based reasoning whereas individuals with lower disembedding skill show preference for generalized application of rules. A characterization of each level describes behaviors observed along a continuum. These results can serve to aid meteorology instructors in recognizing students who struggle with disembedding data and patterns and inform the development of instructional interventions.
INTRODUCTION

Undergraduate meteorology coursework involves learning to analyze the spatial patterns of meteorological variables on surface and upper air charts. Acquiring skills to identify subtle signals, patterns and trends through hand-analysis, along with the diagnosis of patterns, remains an important precursor for learning to produce a coherent and robust forecast, even in today’s computer-driven age (Vasquez, 2008). However, identifying subtleties, recognizing signals, and noticing patterns are highly individual endeavors. Differences in proficiency, experience, and cognition all contribute to the subjective nature of interpretation and prevent forecasting from being an activity that is easily prescribed (Hoffman et al., 2017). For example, the ability to isolate and attend to one aspect of a complex display is variable among individuals (Newcombe & Shipley, 2015). “Disembedding”, or perceiving objects, paths, and spatial configurations amidst distracting background information (Newcombe & Shipley, 2015), is one of several spatial thinking skills important in science, technology, engineering and math (STEM) education (Uttal & Cohen, 2012), and a skill particularly relevant to the interpretation of meteorological surface and upper air charts. In this paper, we focus on the disembedding skills of undergraduate meteorology students with the intent to inform meteorology education.

BACKGROUND

Previous Work Investigating Interpretation of Weather Maps

Previous work has considered the effect of visual salience, domain knowledge, representation of schema, and expert-novice differences on information extraction and interpretation of typical weather maps. In 1993, Lowe investigated the nature of mental representations by meteorologists versus non-meteorologists. Using a task that required subjects to recall and copy weather features onto blank maps, Lowe found that the non-meteorologists failed to capture aspects with central semantic significance for completing meteorology tasks. He suggested that his results reflect the findings of expert-novice studies (i.e., Chi, Feltovich and Glaser, 1981), with meteorologists concerning themselves with features that hold meaning and have semantic structure. However, non-meteorologists, who lack a mental schema upon which to
hang the features found on weather maps, tend to focus on superficial aspects. Lowe also proposed that abstract diagrams, when used as learning tools, may present potential learning problems, rather than be instructional aids when users of the diagrams lack sufficient domain knowledge to interpret them (Lowe, 1993).

Hegarty, Canham, and Fabrikant (2010) used eye-tracking to compare how the visual salience of weather maps, in conjunction with newly acquired domain knowledge affects performance extracting relevant data from complex displays. They found that making relevant features on weather maps more visually prominent made little difference before instruction increased the subjects’ level of meteorology knowledge. Once subjects received meteorology instruction, the increased visibility of relevant features improved subjects’ accuracy with the assigned tasks. Hegarty, Canham and Fabrikant (2010) concluded that by simply increasing subjects’ declarative meteorology knowledge relevant to the task, they increased subjects’ attention to the most task-relevant areas of the displays. Thus, domain knowledge and visual salience can work together to increase data extraction from complex displays and improve performance on tasks relying on such data extraction.

However, Trickett and Trafton (2006) argued that current psychological models of graph and complex display comprehension are too simplistic when focusing exclusively on perceptual processes. They claim that a focus on how subjects use information explicitly represented in graphs investigates “bottoms up encoding processes” (p. 286) but neglects more complex interpretations where information must be retrieved through the use of inferences. The latter, they argue, requires complex visualizations, and necessitates making spatial transformations and using spatial processing. They claim that their work with Navy meteorologists, involving analysis of verbal protocol and interview data, demonstrated that meteorologists use a great deal of spatial processing to extract and use information from data for spatial visualizations. Thus, their thesis strongly encourages including spatial processing as an important step in building comprehensive models of graph comprehension (Trickett & Trafton, 2006).

Collectively these studies indicate that domain knowledge is important to the interpretation of weather maps and chart—one must have the requisite knowledge to know what to look for in order to make good use of the information. However, beyond, making use of the information, Trickett and Trafton (2006) claim that meteorologists take their interpretations a
Spatial Thinking in STEM Education

Spatial representations and spatial data form the backbone of learning and practicing meteorology with its rich dependence on maps, charts, plots, and images representing geographically situated, three-dimensional phenomena that change temporally. Newcombe and Shipley (2015) write, “Spatial information concerns shapes, locations, paths, relations among entities and relations between entities and frames of reference.” (p. 2). The Science Education Resource Center at Carleton College (SERC) defines spatial thinking as “thinking that finds meaning in the shape, size, orientation, location, direction or trajectory, of objects, processes or phenomena, or the relative positions in space of multiple objects, processes or phenomena” (SERC, 2017). Cognitive scientists working with geoscientists (e.g., Shipley et al., 2013) have broadly identified types of spatial thinking used by geoscientists. As part of this effort Manduca and Kastens (2012) describe six spatial thinking skills defined at the intersection of cognitive science and geoscience research. They are:

- **Object location memory**: Remembering the spatial location of previously seen objects or phenomenon
- **Perspective taking**: Envisioning how something would appear from different vantage points
- **Mental rotation**: Rotating mental representations of two-dimensional and three-dimensional objects
- **Disembedding**: Observing and recognizing patterns and isolating the important aspects from distracting, nonessential ones
- **Mental animation**: Developing a plausible scenario of a sequence of events based on static information
- **Visual penetrative ability**: Envisioning the three-dimensional geometry of structures inside a volume using mostly two-dimensional clues from the edge of a volume
The Spatial Intelligence and Learning Center (SILC), maintains a vigorous spatial thinking research agenda built on three evidence-based premises: 1) Spatial thinking is important to STEM education; 2) Spatial thinking is malleable; and 3) STEM outcomes can be improved by improving a learner’s spatial skills through the use of spatial learning tools (Newcombe, 2015). SILC has established a fruitful research collaboration with geoscience education researchers that has resulted in a rich understanding of the spatial skills necessary for understanding complex STEM concepts and how to improve students’ spatial thinking skills in context.

As an example, Atit, Weisberg, Newcombe, and Shipley (2016) investigated student interpretation of topographic maps in undergraduate geology courses. Students were assigned to different groups and one group was instructed to use pointing and tracing gestures to focus attention on contour lines. Another group was instructed to use shape gestures in conjunction with three-dimensional models and key language that focused on elevation and shape information. The authors found evidence suggesting that students’ use of gestures and speech was critical for understanding topographic maps. Their findings provide evidence for scaffolding students’ spatial abilities as they learn introductory geology concepts. Because we consider interpreting contour lines on topographic maps analogous to interpreting isopleths on weather maps, we find this type of research especially promising and likely transferable to meteorology education.

Disembedding

In this study, we focus on one particular spatial thinking skill, disembedding. Disembedding, flexibility of closure, field independence, restructuring closure and adaptive flexibility are all terms that have been used interchangeably in cognitive science and spatial thinking literature to describe “the ability to hold a given visual percept or configuration in mind, so as to disembed it from other well-defined perceptual material” (Ekstrom, et al., 1976, p. 19). Manduca and Kastens (2012) define disembedding as observing and recognizing patterns in a way that separates important aspects from distracting, nonessential ones. Similarly, Newcombe and Shipley (2015) define disembedding as “perceiving objects, paths, or spatial configurations amidst distracting background information” (p. 7). Newcombe and Shipley also categorize
disembedding as an intrinsic-static spatial skill; it describes “within object” relationships that require mentally coding spatial features, including size and the arrangement of parts. Fortunately for investigations such as ours, disembedding ability can be measured using tests such as the Hidden Figures Test. This test requires an individual to search a distracting perceptual field to find a given configuration (Ekstrom, et al., 1976) and will be discussed in detail in a later section.

PRIOR WORK LEADING TO THE CURRENT STUDY

With little to guide our inquiry in spatial thinking in meteorology, we began our investigation as an exploratory study to identify which spatial thinking skills meteorologists report using when working with meteorological charts and images (McNeal, Ellis & Petcovic, in review). Results of the study suggest that mental animation, disembedding and perspective taking are important to interpreting such images. Furthermore, we found a significant difference in how student and professional meteorologists reported their use of disembedding. Student meteorologists reported using disembedding with a surface analysis plot at a much lower rate when compared to professional meteorologists. Referencing classic expert-novice findings (see Chi, Feltovich and Glaser, 1981), we hypothesized that student meteorologists make superficial interpretations of surface analysis plots without attempting to disentangle deeply embedded, underlying patterns, such as a professional meteorologist may attempt to do.

These results informed a comprehensive investigation that encompassed the current study. The larger investigation (McNeal et al., in prep) examined the effects of five narrow intelligence factors on performance with a series of meteorological tasks with a sample of 81 meteorologists representing a spectrum of expertise (student to professional) and various meteorology vocations (academia, National Weather Service, and military). In this investigation, we collected data on participants’ disembedding and mental rotation abilities, working memory, meteorology knowledge, and expertise. We additionally developed a series of novice-level meteorology tasks similar to case study problems typically provided to undergraduate meteorology students. A regression analysis demonstrated that meteorology knowledge and disembedding skills significantly predict performance on the meteorological tasks. Our results suggest that meteorology knowledge is the dominant predictor, accounting for approximately
five times as much variance as disembedding. However, by regressing task performance on to disembedding skills categorized across knowledge level, we also found that disembedding skills continue to have a positive effect on performance, at both low and high levels of meteorology knowledge. We hypothesize that this may be due to the constantly changing nature of weather that necessitates disembedding new patterns with different data each time (see Hambrick, et al., 2012 for discussion). Because our results demonstrate that disembedding skills remain important at both high and low levels of meteorology knowledge, we were interested in further describing the use of this skill, especially among student meteorologists.

THEORETICAL APPROACH

We approached this study through the lens of Cattell-Horn-Carroll (CHC) Theory of Cognitive Abilities (McGrew, 2009). CHC theory is the consensus psychometric-based model for understanding human intelligence as well as a working taxonomy of intelligence factors that address various aspects of human cognition. Within the context of the theory, disembedding/flexibility of closure is part of a broader category, visual processing (referred to as Gv). This broad category emphasizes, “the ability to generate, store, retrieve, and transform visual images and sensations” (McGrew, p. 5). CHC theory also provides a basis for development and evaluation of intelligence tests that target specific intelligence abilities. In our study, we use CHC theory to substantiate our focus on one discrete aspect of intelligence (disembedding) within the context of meteorology, as well as our use of psychometric testing to establish participants’ level of disembedding skill.

CHC theory also guided our verbal data collection methods, specifically our use of think-alouds. Because the think aloud approach (described in a later section) is an ideal method for investigating cognitive processes used during problem solving, its use was appropriate for collecting data for our qualitative analysis (Someren, Barnard & Sandberg, 1994).

PURPOSE STATEMENT

In addition to finding that disembedding skills positively predict performance on some tasks typically provided to undergraduate meteorology students, we have experienced this effect
in our classrooms firsthand. It is not unusual to encounter students who are simply unable to “see” patterns in complex data displays that are readily apparent to others. Based on their meta-analysis of multiple spatial training studies, Uttal and Cohen (2012) suggest that spatial thinking skills, such as disembedding, may serve as an early filter in undergraduate STEM courses. Students with higher spatial abilities are often able to circumvent limits imposed by underdeveloped content knowledge (an advantage that diminishes with expertise), whereas students with lower spatial abilities may experience difficulty and give up (Hambrick et al., 2012). Thus, guided by our intuition as meteorology instructors, and acknowledging findings from empirical research—our own and others—our purpose was to further investigate how disembedding manifests in students with varying ability. Specifically, our purpose was to characterize student use of disembedding while engaging with meteorology tasks—what does it look like, where do students have trouble, and what types of accommodations do they use? Such characterizations can assist meteorology instructors in identifying sources of student difficulty and are a preliminary step to addressing deficiencies through targeted interventions.

METHODS

This study is an extension of prior work where we collected data from November 2016 through September 2017. In order to capture data representing a range of expertise (novice to expert) we recruited participants from three universities, a National Weather Service Forecasting Office, a U.S. Navy Fleet Weather Center and a professional conference. Using professional networks, we identified gatekeepers at host institutions. The gatekeeper generated an email directing individuals interested in participating in the research to contact the first author, who arranged for time and place to meet at the host institution. Upon meeting, individuals were briefed on the research and signed informed consent (McNeal, et al., in prep). The current study is an independent investigation that followed the research design of a basic qualitative study (Merriam & Tisdell, 2015). We drew our participants from the larger sample, specifically, we asked for volunteers who were willing to participate in an additional “think-aloud” while they completed the series of meteorology tasks. This gave us a smaller sample of ten participants who

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4 Per Merriam and Tisdell (2015) a basic qualitative study focuses on meaning and understanding. Data is collected via purposeful sampling and analysis is inductive and comparative. Findings are richly descriptive and presented as themes or categories.
provided verbal data for our qualitative study. Data collected as part of the larger study, addressing disembedding skill, demographics and expertise, were used to supplement and contextualize the verbal data.

**Data Collection**

We collected data using the Hidden Figures Test, a Demographic and Experience Questionnaire, and a series of meteorology tasks (all described below). To collect verbal data, we followed procedures outlined by Someren, Barnard & Sandberg (1994) for think-aloud methods.

**Educational Testing Service (1975) Hidden Figures Test**

The ETS (1975) Hidden Figures Test is a paper and pencil test that requires a subject to search in a perceptual field containing irrelevant or distracting material in order to find one or more given configurations. The test is an adaptation of the Gottschaldt Figures Test published in 1926 and popularized by Thurstone (1887-1955), a pioneer in the field of psychometrics (French, Ekstrom & Price, 1963). The test requires subjects to decide which of five geometrical figures is embedded in a complex pattern. We provide a sample in Figure 4-1. The test consists of two similar sections, each containing sixteen items and participants have twelve minutes to complete each section. The ETS Hidden Figures Test is the current method for measuring skill with disembedding/flexibility of closure in the field of cognitive psychology. We administered one section of the test to reduce overall test time and diminish test fatigue.

![Figure 4-1 Sample item from the Hidden Figures Test (Ekstrom, et al., 1976)](image-url)
In our larger study (N=81), scores on the Hidden Figures Test ranged from 1 to 16. Thus, to categorize disembedding skills, we divided scores into thirds to form categories: low (1-5), medium (6-11), and high (12-16).

**Domain and Experience Questionnaire (DEQ)**

To measure expertise, we modified a valid and reliable DEQ that was used in previous work with geologists (Baker et al., 2012; Petcovic, Ormand & Krantz, 2016) by revising the items to align with the experiences of forecasters, meteorologists, and atmospheric scientists. We pilot tested the DEQ with a small group of meteorology students and faculty and made small revisions to the scoring as a result, including weighting the scoring to favor operational and professional experience. We provide the DEQ in Appendix A. Expertise scores for the participants in the larger study (N=81) ranged from 0.75 to 11.75.

**The Meteorology Tasks**

To evaluate participants’ ability to interpret surface and upper air charts, evaluate the atmospheric processes represented therein, and predict an accurate future scenario, we developed a series of novice-level meteorology tasks based on a mid-latitude cyclone event from 2013. We collected requisite charts and plots from archived data maintained at the Plymouth State University Weather Center, developed the tasks using multiple examples of exercises from upper-level undergraduate meteorology courses and pilot tested the tasks with a small group of meteorology students and faculty to resolve ambiguities (McNeal et al., in prep\textsuperscript{b}).

The tasks include a plotted surface data map with instructions to mark the low-pressure center and draw in warm and cold fronts. Upper air maps representing 850 millibar (mb), 500 mb, and 300 mb include instructions to annotate troughs and ridges, shade areas of cold and warm air advection, positive and negative vorticity advection, and divergence and convergence. Given a blank map of the United States, the participant is asked to mark the location of lowest pressure twelve hours later. It generally takes a participant 15 to 30 minutes to complete the task series. We provide the entire series of tasks in Appendix B. The third author developed a ten-
point rubric for evaluation of each chart and completed the scoring. The scoring rubric is provided in Appendix C. Total scores for the participants in the larger study (N=81) ranged from 9 to 35.

The Think-Aloud Process

We used a think-aloud method to facilitate verbalization of thought processes and captured the processes via video recording. The think-aloud method was developed from older introspection methods established in conjunction with psychological research in the early 1900’s. Dunker (1945) and De Groot (1946 & 1965) were among early researchers who successfully used the think-aloud method in their work. Newell and Simon (1972) also had a major influence on promoting the method by showing that detailed verbal explanations and data are reliably obtainable. The method gained acceptance and is today used by a large part of the scientific community in psychology research, problem solving research, and in the development of artificial intelligence (Someren, Barnard & Sandberg, 1994). In addition to its use by, Chi, Feltovich and Glasser (1981), the method has been used successfully in numerous geoscience education research studies (e.g., Callahan, 2013; Dickerson, et al., 2005; Jolley, Jones & Harris, 2013; Petcovic, Libarkin & Baker, 2009) as well as investigations of weather forecasting ability (e.g., Josslyn & Jones, 2006: Trafton, et al., 2000).

The think-aloud method requires subjects to keep talking and speak aloud whatever thoughts come to mind while performing a task. There are no interruptions, suggestive prompts or questions, greatly enhancing the validity of the data over other methods such as retrospection. We collected think-aloud data as participants completed the series of meteorological tasks. Before beginning the think-aloud, we warmed up participants using a script with instructions and a practice scenario obtained from a study (Tenbrink & Taylor, 2015) that followed methods outlined by Ericsson and Simon (1998). This opportunity to practice with an unrelated scenario allowed the participants to become familiar with the think-aloud process while giving us an opportunity to train the participant to continuously verbalize their thoughts. We video recorded the process using a camera and tripod that captured the participant’s voice, along with gestures and annotations upon papers, weather maps and charts. We uploaded the videos into iMovie, and converted them into MP4 files. We transcribed the audio portion of the recording and used the
video for interpretation of the transcribed data.

Data Analysis

For the purpose of this study, we concentrated on three of the ten collected transcripts (n = 3). Our rationale for this tight focus was to portray disembedding across a skill range — high, medium and low. Thus, to focus exclusively on disembedding skills while controlling as much as possible for other factors, we purposefully selected three transcripts for further, in-depth analysis. The transcripts represent three participants similar in age, experience, and level of expertise due to their role as undergraduate students in a meteorology program at the same Midwest university. Thus, because they are enrolled in the same program of study, their classes, professors and meteorology instruction are comparable. Their university offers a B.S. in meteorology, requiring a foundational course in physical meteorology, a two-course sequence in synoptic meteorology, a two-course sequence in atmospheric dynamics, and remote sensing, among other courses. All three participants were enrolled in upper level meteorology coursework. Although the meteorology program at their university is among the largest in North America, class sizes are small, averaging between 25 and 30 students per class.

In order to analyze the data with these three transcripts, we used both emergent and a priori coding schemes. The coding schemes along with examples of text assigned to each code are provided in Table 4-1 and our codebook is included in Appendix D. The first set of codes emerged through open-ended initial coding (Saldana, 2015), resulting in the first three codes. Of these, the first two captured participants’ verbalizations when it was evident that they were not disembedding patterns in the data. For example, by recognizing areas where “boxes” are created with the 850 mb height contours and isotherms, a participant is in a good position to pinpoint areas of cold and warm air advection. In comparison, we witnessed participants who lacked this pattern recognition and identified broad areas east and west of the trough or broad areas along warm and cold fronts. Thus, the first two codes attempt to capture strategies used to accomplish the task without disembedding and accommodations used to circumvent disembedding. The third emergent code captured explicit expressions indicating difficulty resolving patterns, such as “it’s kind of muddled up there”.
The balance of the codes were developed a priori by considering the patterns that a meteorologist is expected to “see” within the context of each map, i.e., what does the meteorologist look for and need to disembed in order to successfully complete the task at hand? We used personal expertise, Vasquez’s (2008) *Weather Map Handbook*, and Haby’s “Ultimate Weather Education Website” to guide development of these codes.

We coded standardized units of text (Campbell, et al, 2013) and coded only units of text that were relevant to the coding scheme. Each unit of text was assigned to only one code. Because the a priori codes include several possible factors, some have no examples from the transcripts of the three participants in this study. We felt that it was important to include them, however, to identify patterns that these participants did not “see”. After establishing both sets of coding schemes, the first two authors coded the three transcripts using qualitative analysis software (QSR International’s NVivo 11 Software). We compared coding to determine a level of inter-rater reliability; this yielded an average Kappa coefficient of 0.89 across all coded text, which is indicative of excellent agreement

**Trustworthiness**

Qualitative research must meet rigorous standards of trustworthiness that establish the equivalence of reliability in quantitative studies. Researchers rely on several methods, alone or in combination, to ensure trustworthiness (see Merriam & Tisdell, 2015 for a full discussion of this topic). Our study incorporated the use of triangulation—using multiple investigators, data sources, or data collection methods to confirm findings. Our data sources included video recordings of our participants that assisted greatly in interpretation of the verbal data, the written transcripts, which two authors coded independently, and the participant products, scored by the third author. Triangulation between these sources and collaborators provided opportunities to corroborate findings and resolve inconsistencies. Additionally, the coding comparison of the three transcripts serves as a measure of trustworthiness.

Another method for establishing trustworthiness is sustaining a prolonged engagement with data collection. Adequate time collecting data is necessary such that the data becomes saturated and continued data collection produces no new information or insight (Merriam & Tisdell, 2015). We collected our entire set of verbal data (ten participants) over the course of a
year and this included data collection from six students, two university professors, a National Weather Service forecaster and U.S. Navy Aerographer’s Mate. At this point, we observed repeated patterns in the data and reached consensus regarding data saturation.

Our final method for establishing trustworthiness regards using thick descriptions (Merriam & Tisdell, 2015). Here, detailed descriptions about setting, participants, and the products of the research contextualize a study so that readers can determine how well their situation aligns with the research context. For this reason, detailed information about our participants, their university and a thick description of their verbal data is included.

**Locating the Researchers**

In qualitative research, it is important to be transparent about “who the researchers are” to understand what they individually and collectively bring to the study, to recognize the perspective from which they approach data analysis, and to identify any biases. We (the four authors) represent diverse backgrounds, have varying levels of expertise, and come from different content domains. It is our hope that by coming together, we collectively capitalize on individual areas of expertise, while simultaneously maintain accountability to an authentic characterization of student use of disembedding in a meteorology context.

The first author is a geoscience educator with experience conducting qualitative and quantitative education research. She has a proficient knowledge of meteorology and forecasting, and experience teaching undergraduate introductory atmospheric science courses. The first author met with the participants and collected the data, including all of the verbal think-aloud data. The second author is also a geoscience educator and researcher with expertise in geology. She has extensive experience with qualitative research, especially analysis of verbal data collected in multiple geoscience and geoscience education studies. The first and second authors worked together to develop and apply the coding schemes used in the study, as well as interpret the data.

The third author is an associate professor of meteorology and department chair at a midsize Midwest university and thus, intimately familiar with undergraduate meteorology students and content. The third author developed the rubrics and scored the meteorology task used in the larger study, from which the data was drawn. She additionally served as a content
expert for the current study. The fourth author, an atmospheric scientist, was instrumental in developing the meteorology task and research design. The combination of our individual skill sets served to complement each other as researchers and balance the interpretation of data.

**Introduction to the Participants**

We gave our participants (all males) the pseudonyms Abe, Bart and Cole. They represent a continuum of disembedding skills (as measured by the Hidden Figures Test) that we grouped according to the low, medium, and high categories previously described. The data in Table 4-2, demonstrate that Bart and Cole have much closer Hidden Figures Test scores than either have to Abe, and this is sometimes evident in the results. All three participant’s DEQ (expertise) scores fall in the bottom 20% of scores represented in our larger study (N = 81). Their scores on the meteorology task series are similar. Our focus in the analysis was on how participants performed the task (through disembedding), and less on how well they performed the task.

Abe, characterized as a low disembedder, is a 20 year old, undergraduate student majoring in meteorology who has completed courses in weather analysis, dynamic meteorology and forecasting. He enjoys storm chasing and has strong interests in severe and winter weather as well as computer models, programming and remote sensing. Of the three participants, Abe verbally expressed the most difficulty with disembedding data and expressed a lack of confidence toward the end of his analysis. He also spent the most time (33 minutes) working through the series of meteorology tasks. We collected data from Abe in November 2016.

Bart, characterized as a medium disembedder, is also a 20 year old, undergraduate student majoring in meteorology that has completed courses in weather analysis, synoptic meteorology and physical meteorology. Bart’s experience growing up in the Midwest exposed him to several weather extremes, including tornados, blizzards, lake effect snow and derechos, year after year. We collected data from Bart in April 2017.

Cole, who according to his Hidden Figures Test score is a high disembedder, is a 21 year old, undergraduate student majoring in meteorology who has completed courses in weather analysis, synoptic and dynamic meteorology, physical meteorology, and forecasting. Like Bart, his experience growing up in the Midwest, especially experiences with severe weather, sparked
Table 4-1 Coding scheme and examples of text units assigned to each code

<table>
<thead>
<tr>
<th>CODE</th>
<th>EXAMPLE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Emergent codes</strong></td>
<td></td>
</tr>
<tr>
<td>1. Broad identification of features in relation to troughs and ridges</td>
<td>Convergence is usually found on the left side of these trough lines.</td>
</tr>
<tr>
<td>2. Broad identification of features in relation to warm or cold fronts</td>
<td>I’m going to go ahead and put cold air advection along this area of this cold front.</td>
</tr>
<tr>
<td>3. Explicit expressions indicating difficulty resolving patterns or items on the charts</td>
<td>There’s a lot of clutter on the surface maps.</td>
</tr>
<tr>
<td><strong>A priori codes</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Surface chart</strong></td>
<td></td>
</tr>
<tr>
<td>1. Pressure</td>
<td>You have 1000.7 mb right here at this station plot, which appears to be about the lowest pressure that I can see.</td>
</tr>
<tr>
<td>2. Pressure falls</td>
<td>But you have your greatest pressure falls north.</td>
</tr>
<tr>
<td>3. Wind direction</td>
<td>Shift in winds here at the Illinois border</td>
</tr>
<tr>
<td>4. Wind speed</td>
<td>No example</td>
</tr>
<tr>
<td>5. Temperature</td>
<td>Looking at temperature plots, we have 48 and 59 within a small gradient</td>
</tr>
<tr>
<td>6. Cloud cover</td>
<td>No example</td>
</tr>
<tr>
<td>7. Present weather</td>
<td>No example</td>
</tr>
<tr>
<td>8. Dew point</td>
<td>Where the dew point begins to drop</td>
</tr>
</tbody>
</table>
Table 4-1 —continued

<table>
<thead>
<tr>
<th>850 mb chart</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Shortwave</td>
<td>No example</td>
</tr>
<tr>
<td>2. Height contours (independently)</td>
<td>No example</td>
</tr>
<tr>
<td>3. Isotherms</td>
<td>Especially down here, temperature gradients are very, very tight</td>
</tr>
<tr>
<td>4. Wind speed</td>
<td>That would be the main area of highest winds</td>
</tr>
<tr>
<td>5. Wind direction</td>
<td>There’s northerly flow coming down from Canada, so it’s going to bring some cold air advection.</td>
</tr>
<tr>
<td>6. Angle of intersection</td>
<td>Height lines are parallel (to isotherms) so you don’t have any advection until we get up here where they start crossing again.</td>
</tr>
<tr>
<td>7. Temperature (independently)</td>
<td>No example</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>500 mb chart</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Shortwave</td>
<td>A little bit of a shortwave right here</td>
</tr>
<tr>
<td>Shear</td>
<td>No example</td>
</tr>
<tr>
<td>Curvature</td>
<td>You have vorticity at the trough…um, that would be positive vorticity advection</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>300 mb chart</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Difffluence/confluence</td>
<td>No example</td>
</tr>
<tr>
<td>Speed divergence/convergence</td>
<td>That wind is going to start to slow down so we’re going to have that upper level convergence</td>
</tr>
<tr>
<td>Wind speed</td>
<td>I’m going to look at wind speeds at 300 mb. So we have about 75 or 70 knots or so.</td>
</tr>
<tr>
<td>Jet streak</td>
<td>So, you have your jet streak through here</td>
</tr>
<tr>
<td>Shortwave</td>
<td>I have a shortwave over here</td>
</tr>
</tbody>
</table>
Table 4-2 Participant information, n = 3

<table>
<thead>
<tr>
<th>Name</th>
<th>Hidden Figures Tests score</th>
<th>Disembedding level</th>
<th>DEQ score</th>
<th>Meteorology task score</th>
<th>Meteorology concept inventory</th>
<th>Time spent completing meteorology tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abe</td>
<td>4</td>
<td>Low</td>
<td>0.75</td>
<td>21</td>
<td>19</td>
<td>33.0 minutes</td>
</tr>
<tr>
<td>Bart</td>
<td>10</td>
<td>Medium</td>
<td>1.00</td>
<td>19</td>
<td>24</td>
<td>20.5 minutes</td>
</tr>
<tr>
<td>Cole</td>
<td>12</td>
<td>High</td>
<td>2.25</td>
<td>20</td>
<td>31</td>
<td>22.0 minutes</td>
</tr>
<tr>
<td>Range</td>
<td>1-16</td>
<td>-</td>
<td>0.75-11.75</td>
<td>9-35</td>
<td>11-34</td>
<td></td>
</tr>
</tbody>
</table>

his interest in weather. His higher DEQ score is the result of an internship. We collected data from Cole in November 2017.

RESULTS

We present our results by chart type, working from the bottom of the atmosphere (the surface chart) and moving up through the upper air charts representing conditions at 850 mb, 500 mb and 300 mb. Upper air and surface weather charts are printed with relevant data that is intended to inform understanding of current atmospheric processes at each level. Textbooks, weather map handbooks, and meteorology instructors prescribe a particular use for each chart and convey what to look for to gather pertinent information. Thus, we first review each chart and give examples of what to look for, because in order to understand each of our participant’s use of disembedding, it is important to recognize what features are helpful to disembed. Following each review we provide a thorough description of each participant’s analysis along with examples of participant products.

The Surface Chart

The main feature on a surface chart is the station plot. These plots represent an encoded, compilation of multiple forecast offices’ observational data (see Figure 4-2). Information about wind speed and direction, pressure, sky cover, dew point, temperature and current weather for individual locations is quickly available to readers familiar with the format. However, the real
value of the data is not in the information contributed by any single forecast office, but in the overall patterns and trends that emerge when viewing the data synoptically (across a large region). Because it is at the synoptic scale that the data assumes additional meaning for the meteorologist, it is important that he/she is able to disembed these patterns from what can appear to be a very chaotic data display (Figure 4-3).

On the surface chart that we provided our participants, we asked them to “Mark a center of low pressure with an ‘L’. Draw a warm front associated with this low in red and a cold front associated with this low in blue.” In order to complete the first part of this task (marking a center

![Diagram of a weather chart](image)

**Figure 4-2** A sample station plot. Source: National Weather Service

![Surface chart](image)

**Figure 4-3** An example surface chart. Source: Plymouth State Weather Center.
of low pressure), one could explicitly hunt for the lowest pressure reading among station plots. However, seeking an area of strong cyclonic (counter-clockwise) wind flow greatly assists this effort because surface winds tend to converge in areas of surface low pressure. Thus, by observing the direction of the “wind barbs”, on the station plots, one can begin to hone in on an area likely to contain the lowest pressure. Other indicators exist as well. For example, because low pressure is associated with rising and cooling air that condenses water vapor, low pressure regions are typically cloudy, potentially with precipitation. Information such as sky cover and current weather can therefore point users to a probable area of low pressure. The most efficient meteorologist likely uses a combination of the above and maximizes use of the data.

A surface cold front represents the leading edge of a cold and dry air mass, so temperature and moisture characteristics (dew point) are important to consider. Because such an air mass moves toward lower latitudes, the wind direction associated with it has a northerly component (from the north). Thus, the hallmark of a cold front is a shift in winds. Additionally, cold air, because it is denser, lifts warmer, moister air in front of it, condenses water vapor, and produces a distinct line of clouds; therefore sky cover is another way to locate a cold front. Cold fronts often produce cumulonimbus clouds and thunderstorms may be present. Cold fronts develop in conjunction with mid-latitude cyclones; thus, if this pattern is recognized, one can hunt for a cold front in an area where it is likely to be. There are, therefore, many features and patterns one should attend to on a surface chart to determine cold front placement, including temperature, dew point, wind direction, sky cover, current weather and location of lowest pressure.

Locating a warm front is notoriously trickier. The slower advance of warm air overruns a shallow layer of colder air, causing widespread steady precipitation. Thus, the differences in weather features are less distinct than with a cold front, but the same type of data and patterns assist with identification: temperature, dew point, wind direction, sky cover, current weather and location of lowest pressure. Again, in a mid-latitude cyclone scenario, which our task represented, situating a center of low pressure will guide the placement of the cold and warm fronts to achieve the characteristic structure of a mid-latitude cyclone (Figure 4-4).

We now consider how our three participants approached the surface chart, beginning with Cole, who had the highest level of disembedding skill as measured by the Hidden Figures Test.
Cole considered wind direction first while seeking counter-clockwise rotation and noting, “It’s [the center of low pressure] probably in here somewhere.” He inspected pressure readings next, noting the congested data and saying, “it looks like a lot in a small space”, but he proceeded by looking at individual station pressure readings and remarking, “So it looks like that’s the low right here. I’ll put the low on the 1001. So you can see it.” He marked this as a center of low pressure, but repositioned it later when he discovered even lower pressures, saying, “Move the low down to the 1001.5, which is lower than 1001.9. So that would be, that would be the lowest pressure now.” To locate the warm and cold fronts, he looked at changes in wind direction, changes in temperature, and dew point before marking the final placement of the fronts, for example: “Change in wind direction is here and temperature and dew point. So, it would probably be down here in between that 75 and 65 where the dew point begins to drop.” He spent approximately six minutes with this process, carefully checking the data and going back over it (Figure 4-5).

![Figure 4-4 Characteristic structure of a mid-latitude cyclone (in North Dakota) with cold and warm fronts. Image source: National Weather Service.](image)

Similarly, Bart (medium disembedding skills) extracted different data types from multiple station plots to place his low and fronts. He considered changes in wind direction before isolating information about temperature and pressure. He lightly sketched a cold front to assist in locating the low and then concluded, “You see winds feeding into it [the low] in a counter
clockwise motion. You have 1000.7 mb right here at this station plot, which appears to be just about the lowest that I can see”. He next went back to check his cold front placement: “So, looking at temperature plots, we have 48 and 59 within a small gradient. Let’s see, here we have, it appears to be 49 and 62. So, it looks like this cold front is going to run right along this line here.” He located the warm front using temperature information from 13 different station plots and attended to how temperatures changed by noting, “There’s a pretty big gradient there”. Like Cole, he also spent approximately six minutes on this particular task and we provide his annotation of the low and fronts in Figure 4-6.

Figure 4-5 A portion of Cole’s surface chart with low pressure and fronts annotated.

Abe (low disembedding skills) struggled with the surface chart and spent 10.5 minutes grappling with the data and attempting to make sense of it. What is notable about his analysis of the surface chart is that of all of the data available on the chart, he only looked at wind direction to determine his placement of the warm and cold fronts, and the lowest pressure. He used his 850 mb chart extensively and transferred portions of his previous plotted analysis on the 850 mb chart to his surface chart. He made multiple references to difficulty with “seeing” data and patterns (other than wind direction) inherent in the data:
There’s a lot of clutter on the surface maps.

Oh boy, it gets really cluttered up here.

I’m not seeing a really large shift in winds here.

There’s much less clutter on my 850 map and I can kind of…I don’t know what the word would be, I guess interpolate, maybe?

Now I’m just going to try to identify the area of this low. According to the surface map, it’s kinda hard to tell where that would be.

I’m having a hard time kind of seeing that.

It’s kind of muddled up there. This is a tough map.

After marking the warm and cold front using solely wind data, Abe proceeded to locate the center of low pressure. To accommodate for the difficulties that he was having disembedding data and patterns, he referred to his 850 mb and 500 mb charts for help in locating the surface low, but realized that this did not correspond to wind directions that he observed in the surface chart. Abe ultimately placed the low in Missouri, “because I do have this sort of circulatory area”. This however, offset his low from the apex of his warm and cold fronts. He knew this was incorrect and seemed uncomfortable, so he spent additional time inspecting the chart, but in the end, resigned and stated, “I’m not seeing anything else that’s popping out”. His completed surface chart is provided in Figure 4-7.

**The 850 mb Chart**

The 850 mb chart represents a layer of the atmosphere referred to as the planetary boundary layer (PBL). Here, friction and thermal advection play an important role in creating turbulent winds and eddies. Thermal advection, representing horizontal transport of air of a

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5 This section references “The 850 mb Chart” by Jeff Haby found on theweatherprediction.com website.
Figure 4-6 A portion of Bart’s surface chart with low pressure and fronts annotated.

Figure 4-7 A portion of Abe’s surface chart with low pressure and fronts annotated.
different temperature, is most intense in the PBL. Such movement of a cold or warm air mass into a region contributes to large scale sinking or rising of air, which in turn, determines areas of surface level high or low pressure and associated weather patterns. Thus, a major purpose of analyzing an 850 mb chart is to identify regions of thermal advection. The greatest areas of thermal advection are where wind blows across temperature gradients—a change in temperature over a given distance. Thermal advection is of two types: warm air advection (WAA) and cold air advection (CAA).

The 850 mb chart, representing the PBL is specifically used for identification of these regions of WAA and CAA. Both height contours (isoheights) and temperature contours (isotherms) are plotted on the 850 mb chart for this purpose. The 850 mb height contours represent the level of the atmosphere where the pressure is 850 mb. Winds generally flow parallel to height contours and the spacing of the height contours represents the pressure gradient force, which drives winds, thus the spacing is a proxy for the strength of the wind. Therefore, where the height contours (winds) cross the isotherms (temperature gradient), one finds the maximum potential for WAA and CAA, as air of a different temperature blows across a thermal gradient.

Therefore, in terms of disembedding on the 850 mb chart, in order to identify areas with maximum thermal advection, one needs to identify areas with:

1. Closely spaced isotherms
2. Closely spaced height contours
3. Isotherms perpendicular to height contours

In particular, one looks for where the height contours and isotherms form “boxes”. Tighter boxes with angles approaching 90° represent stronger areas of CAA and WAA (see Figure 4-8) resulting from high wind speeds and strong thermal gradients.

Conversely, areas with minimal CAA and WAA are represented by:

1. Widely spaced isotherms
2. Widely spaced height contours
3. Isotherms parallel to height contours

and appear like the pattern seen in Figure 4-9.
We now consider how the three participants approached the 850 mb chart. Directions on the chart read, “Mark the location of all trough axes with dashed lines and all ridge axes with zigzagged lines. Shade areas of warm air advection in red and cold air advection in blue.” A trough is a region with relatively lower height lines and a ridge is a region with relatively higher heights. Relatively cooler and warmer air creates these areas, respectively. During analysis, meteorologists designate troughs with dashed lines and ridges with zigzagged lines as shown in Figure 4-10.

![Figure 4-8](image.png)

**Figure 4-8** Areas with maximum thermal advection identified on an 850 mb chart. Retrieved from: theweatherprediction.com and used with permission.

![Figure 4-9](image.png)

**Figure 4-9** Areas with minimal thermal advection identified on an 850 mb chart. Retrieved from: theweatherprediction.com and used with permission.
Figure 4-10 Designation of a trough and ridge on an upper air chart. Retrieved from: theweatherprediction.com and used with permission.

We begin with Cole again, characterized as a high disembedder based on his score on the Hidden Figures Test. After marking a trough and two ridges on his 850 mb chart, Cole immediately located an area of CAA and stated, “Cold air advection you would have down here because you’re crossing your wind, your crossing your wind heights across the temperature lines.” He spent extra time looking to include additional regions of CAA and said, “We still have it crossing, into the, the wind blowing into the high values (temperature). Cold air advecting, so shade that.” Figure 4-11 shows his area of shaded CAA in blue, which is notable for the distinct rectangles, formed by the isotherms (lighter dashed lines) and height contours. With WAA, Cole identified a rather small pocket of WAA and commented, “It looks like a little bit here. You sort of have the winds going across, blowing warmer temperatures in.” After limiting his shading to a small region, he noted, “Then temperature and height lines are parallel so you don’t have any advection until we get up here where they start crossing again” and he shaded a larger region north of the first shaded area. Figure 4-11 also exhibits Cole’s two red shaded regions and the non-shaded area between, which is notable for parallel isotherms and height contours.

Next, we consider Bart’s (medium disembedding skills) treatment of the 850 mb chart. From analysis of his video-recorded think-aloud, we conclude that either Bart misinterpreted lines representing isotherms as height contours or he intentionally located a thermal trough and ridge (instead of a pressure trough and ridge). We base this conclusion on how Bart gestured with his pencil along isotherms, made references to wind flow and placed both his trough and
ridge in areas with maximum isotherm curvature. We assume that he mixed up the two lines, mainly due to his reference to wind flow, but this is unclear. The isotherms are printed lighter than the height contours on the 850 mb chart, making them likely more difficult to disembed, but they seem to be the focus of Bart’s attention.

Bart then proceeded to identify CAA and WAA. His first statement regarding WAA is, “We have a southerly wind coming off of the Gulf and the part of the Atlantic just east of Florida. That’s going to bring in some warm air advection”. Here, he is noting the wind direction (either from the wind barbs or the height contours) and reasoning that air moving from the south will be warmer and replace cooler air found to the north. This exhibits a degree of disembedding (extracting information about wind direction) but without seeking and finding the more explicit patterns formed by crossing isotherms and height contours. With the southerly wind identified, Bart began shading a broad area from Florida, along the east coast and continuing up to the Canadian border. He stated:

We’re going to shade in just about everywhere that’s southerly flow. So, start down here pretty much all through Florida and through the Gulf, up north through the southeast. And then keep going. The wind kind of starts to get westerly as

**Figure 4-11** Areas exemplifying Cole’s 850 mb chart analysis
soon as you get to Illinois so we’re going to start fading east more. And you still have that southerly flow pretty much all the way through to the top of this ridge here. So, pretty much along through the east coast here and then all the way down through the southeast and into the Gulf. That’s where I have this warm air advection.

Whereas Bart distinguished southerly from westerly winds, his broad shading does not distinguish between warm air moving into colder regions versus warm air moving along a region with uniform temperature characteristics (no “boxes” formed with crossing isotherms and height contours). See Figure 4-12 for an illustration of this difference on Bart’s 850 mb chart. Because he neglected to consider temperature data within the WAA region, Bart captured within his shading areas that were not specifically under the influence of WAA.

Bart’s treatment of CAA was essentially the same (Figure 4-12). He disembedded patterns of wind flow and distinguished areas of northerly flow (movement of a cold air mass) from westerly flow. He used this analysis to infer CAA, but in the process, included regions with minimal CAA because he overlooked temperature information embedded in the data. He described his process:

Cold air advection, if you look by this trough area, there’s northerly flow, coming down from central Canada, so it’s going to bring some cold air advection. Um, so you have kind of a westerly flow here coming off the west coast, so it’s not going to be too much of a cold air advection situation. So, you have that northerly flow also going through the plains here and then kind of rounding off right about here in western Texas. So I guess we’ll start down there in western Texas and the northern part of New Mexico, and just go straight north and go a little bit east as you start to get into the plains. And then just straight up through the plains and into Canada. So there’s your cold air advection.

Finally, we consider Abe’s treatment of the 850 mb chart, noting his characterization as a low disembedder per his score on the Hidden Figures Test. He first identified one trough and two ridges using curvature of the height lines and stated, “It’s really all about just defining these areas of whether it’s really distinctly curved or whether it’s not.” Next, in order to identify CAA, Abe disembedded information regarding isotherm spacing and indicated where “temperature gradients are very, very tight.” With this as guidance, he referred to a generalization to locate CAA: “I would imagine that this would be a cold front here. I’m going to go ahead and put cold
air advection along this area of this cold front which is associated with this large extra-tropical cyclone.” and shaded a blue line that bordered the region with closely spaced isotherms. Thus, he identified CAA by disembedding one component of thermal advection accompanied by a general knowledge of cyclonic systems. Abe’s identification of warm air advection was similar. He relied on isotherm spacing, but additionally extracted wind direction data, saying “You’ve got a lot of really strong southerly flow”, gesturing how the air would move in a northerly direction. Finally, he shaded small regions of CAA and WAA: “I’m going to go ahead and …circle those areas where it’s very, very strong.” He gave no rationale for why he identified these “strong” areas and it is not apparent from the placement of his shading why he designated these areas (see Figure 4-13). His placement of smaller areas of CAA and WAA are not entirely incorrect, but he misses additional areas. The “shaded lines” are incorrect and paint out fronts more than regions of WAA and CAA. Although Abe disembedded some patterns (thermal gradients and wind direction), he did so in a way that did not particularly help him with the task.

Figure 4-12 A portion of Bart’s 850 mb chart
The 500 mb Chart

The 500 mb level is considered the middle of the troposphere (the atmospheric layer where weather takes place) and on a 500 mb chart, it is easy to discern the wavy path of the 500 mb height contours. Factors such as the Coriolis force, pressure gradient force, and the diminishing role of friction at this height cause the wind to flow parallel to these height contours. Thus, the contours are used to visualize the movement of upper level winds. The troughs and ridges created by this waviness impart vorticity—a spin to the air as it moves through these regions. Vorticity advection (transport of vorticity) occurs “downstream” of areas of maximum vorticity. The ensuing loss or gain of angular momentum generates areas of divergence and convergence (discussed in the next section), which, in turn produces rising or sinking air. Thus, determining areas of maximum vorticity is important to determining to where vorticity will subsequently advect (move).
There are two types of vorticity, positive and negative, depending on whether the air takes on a counter-clockwise or clockwise spin. There are three processes that produce vorticity: curvature vorticity, shear vorticity and Earth vorticity. Here we will consider the first two that can be inferred from the data on a 500 mb chart. (Earth vorticity results from the Coriolos force generated by the spinning Earth.) First, as air travels through a ridge or trough, it acquires curvature vorticity simply through the motion of rolling over the ridge or through the trough (see Figure 4-14). This type of vorticity is inferred through identification of troughs and ridges in the jet stream. The second type of vorticity, shear vorticity, results from horizontal differences in wind speeds that are akin to different current speeds in a stream of water. If a log were traveling perpendicular to a water current with different current speeds on either side, the log would naturally start to spin. These processes cause air to likewise spin in the jet stream when wind speeds vary horizontally. This type of vorticity (Figure 4-12) is determined by inspecting the wind barbs superimposed on the chart (wind speed information is contained in the flags and pips that extend from the barbs).

Curvature, shear and Earth vorticity exist independently or in concert with each other, depending on atmospheric conditions. Thus, in addition to identifying where they exist, one must evaluate how they amplify or cancel each other. Figure 4-15 illustrates an example of each type of vorticity analyzed on a 500 mb chart and is provided to show the complex level of disembedding that is required to visualize these patterns. In addition to identifying vorticity, determining how well it will advect downstream requires consideration of the strength of upper air level winds.

Vorticity and vorticity advection are more advanced concepts than the other concepts required in our series of meteorology tasks. Although each of our participants was familiar with these terms and concepts (as evidenced by their comments and level of completed coursework), we assume that their cursory treatment of the 500 mb chart was a function of the difficulty of the concept and the complexity of the disembedding required. In our larger sample, some participants considered shear vorticity, however, among the three participants discussed here, curvature vorticity was the only factor considered when determining vorticity advection. The directions to participants on the 500 mb chart read, “Mark the location of all trough axes with dashed lines and all ridge axes with zigzagged lines. Shade areas of positive (cyclonic) vorticity.
advection in red and negative (anticyclonic) vorticity advection in blue.” Note: PVA denotes positive vorticity advection and NVA is negative vorticity advection.

Figure 4-14 Illustrations of positive and negative curvature and shear vorticity. In the bottom two sketches relative wind speed is represented by the length of the vector. Retrieved from: theweatherprediction.com and used with permission.

Across all three participants, the least amount of time was spent on the 500 mb chart; Cole spent three minutes and twenty seconds, Bart finished in a speedy two minutes and forty seconds, and Abe spent four minutes and forty-five seconds on the 500 mb chart. Their completed charts look similar, with PVA designated east of the trough and NVA designated west of the trough, however, the rationale given by each participant for the placement of PVA and NVA gives us a glimpse into how they determined this placement.

Cole identified one trough, then gestured with his finger east of the trough in a counterclockwise motion. He traced with his pencil to indicate his determination of positive curvature vorticity through the trough region, while he commented, “You have vorticity at the trough…um, that would be positive vorticity advection.” He isolated wind speed data to determine an area of maximum PVA: “Vorticity advection, down, well, you’d have your vorticity at the base so it
would advect [downstream], so what, strong winds.” He spent less time contemplating NVA, and placed it simply in relation to the trough, on the west side: “so NVA down here, in that general area.”

Bart identified one trough and one ridge, and then based his designation of PVA and NVA entirely in relation to the trough, thus exhibiting a simple rule of thumb and generalization. While shading red, he stated, “So, here you have your vorticity max at the base of this trough, so that means that your PVA is going to be right here, just east, northeast of that trough base.” Similarly, as he shaded blue, he said, “And your negative vorticity advection is going to be just west of that trough base as you approach that subgeostrophic flow down there and as you approach that vort max. So there’s going to be your negative vorticity advection. OK, that’s it for the 500 millibar.” This generalization (west/east of the trough) is reminiscent of Bart’s placement of WAA and CAA on the 850 mb chart.

Figure 4-15 Illustrations of identification of different vorticity types on a 500 mb analysis. Retrieved from: theweatherprediction.com and used with permission.
In addition to difficulty identifying areas of PVA and NVA based on data contained in the 500 mb chart, Abe expressed less familiarity with the concept and a preference for rule-based reasoning and computer model interpretation as illustrated by the following comments:

I know that in the right exit region, over here, I would imagine that we would get a large area of positive vorticity advection and that’s just kind of a rule that I learned a few weeks ago in my MET 300 class.

This is something that I definitely rely on the [computer] models for is identifying areas of vorticity.

I would not consider myself an expert with PVA and NVA, so I am definitely going to not spend as much time on this map as I normally would for the other maps.

I think that’s about all that I would be comfortable with for that.

Like Bart, Abe based his designation of PVA and NVA in relation to the trough, thus exhibiting a large degree of generalization.

Between the three participants, they used slightly different rationale, but the products look very similar with a dashed line down the middle of the trough, blue shading (NVA) to the west of the trough and red shading (PVA) to the east of the trough (Figure 4-16). In sum, the 500 mb chart was challenging for all three participants. Whether this was due to a lack of knowledge and expertise or difficulty extracting patterns necessary to completing the task is uncertain. We note again that none of our participants attempted to seek patterns indicative of shear vorticity, which is information that may have informed a more sophisticated identification of PVA and NVA.

**The 300 mb Chart**

Depending on the season, either a 200 mb or 300 mb chart is used to depict the strength and path of the polar jet stream, which is the overall feature analyzed in these charts. At this level meteorologists identify areas of diverging and converging air along with the presence of jet streaks, which are regions of higher wind velocity embedded in the overall jet stream pattern. In
addition to troughs and ridges, we only asked our participants to identify regions of divergence (red) and convergence (blue). However, because one participant further sought to identify a jet streak, we include a discussion and illustration of it here.

![Figure 4-16 From left to right, Cole’s, Bart’s, and Abe’s analysis of the 500 mb chart.]

Divergence and convergence of air in upper atmospheric levels are important due to the effect they have on surface weather. As air diverges, it evacuates an area. Aristotle correctly stated, “nature abhors a vacuum”, thus air rushes to fill any potentially empty spaces—the source of this air is the region below. Thus air rises from the surface, creating surface low pressure and bringing about the associated weather. Convergence of upper level air works in the opposite direction. As air piles up it has nowhere to go but down (the warmer stratosphere above prevents rising motion), and thus sinks toward the surface creating surface high pressure.

Divergence and convergence in the upper atmospheric can be identified on a 300 mb chart in two ways:

1. Through the horizontal spreading or converging of winds (known as diffluence and confluence) as identified by the spreading or converging of height contours (Figure 4-17); or
2. Through the horizontal speeding up or slowing down of winds (known as speed divergence and convergence) as identified by winds speeds represented on wind barbs (Figure 4-18).

The patterns that one seeks to disembed on a 300 mb chart resemble those in the figures. It is typical, however, that these processes occur predictably in relation to identified troughs and ridges and thus, generalized regions of divergence and convergence might be identified through simple rules of thumb if one neglects to consider processes and disembed patterns that are more complex.

![Figure 4-17 Illustrations of diffluence and confluence at 300 mb. Retrieved from: theweatherprediction.com and used with permission.](image1)

![Figure 4-18 Illustrations of divergence and convergence. Relative wind speed is represented by the length of the vector. Retrieved from: theweatherprediction.com and used with permission.](image2)

Finally, meteorologists use the 300 mb chart to identify jet streaks, which are cores of higher wind speeds within the overall jet (Figure 4-19). Jet streaks are found in areas with the highest winds—since the pressure gradient force drives winds, regions where height contours are closely spaced are candidates for finding jet streaks. The speeding up of winds through a jet streak, together with forces such as pressure gradient and Coriolis, create concentrated areas of upper level divergence and convergence, hence, jet streaks are important to forecasting.
Meteorologists refer to (and sometimes annotate a chart with) quadrants that are associated with these areas of divergence and convergence to describe jet streak dynamics (Figure 4-20).

**Figure 4-19** Identification of a jet streak at 300 mb. Retrieved from: theweatherprediction.com and used with permission.

**Figure 4-20** Jet streak dynamics diagram. Retrieved from: theweatherprediction.com and used with permission.

Beginning again with Cole (high disembedder), in his first statement after marking troughs and ridges, he referenced a jet streak while pointing out the closely spaced height contours with his finger: “So you’d have divergence in the exit region of where your jet streak would be which would be here. We have the stronger winds and the tight packing of the height lines. Um, it looks like the strongest winds in through here so you probably have your divergence in this area.” He also referenced speed convergence: “Down here is where you’d have your convergence. That would make sense when you’re in the base of the trough. So convergence
here, which makes sense because the winds would be backing up.” It is unclear whether Cole was using knowledge about the movement of air through a trough or disembedding wind speed data from the chart; the former is likely. Additionally, although he used disembedding to recognize the jet streak, he converted to using rules of thumb that are associated with jet streak dynamics once he identified the jet streak—which is logical and expected. In sum, Cole’s annotated 300 mb chart (Figure 4-21) is not entirely correct, however, it illustrates his attempts to disembed patterns from the data.

**Figure 4-21** Cole’s annotated 300 mb chart

Bart (medium disembedder) made quick work of the 300 mb chart by applying knowledge of the behavior of air moving through troughs and ridges and broadly shading areas of divergence and convergence accordingly:

OK, now shade areas of divergence and convergence…so, your upper level divergence is going to be right here, right as you start to approach, as the wind starts to get more geostrophic and approach that supergeostrophic flow at the top of the ridge. So our upper level divergence is going to be right here through…the western Midwest and the northern part of Texas, right around there. Our upper level convergence is going to occur right here in the west as you approach that subgeostrophic flow at the trough base. That wind’s going to start to slow down
so we’re going to have that upper level convergence right here through California and Nevada and into the western Rocky Mountains. And there’s your upper level convergence. And that’s it for our 300 millibar.

Thus, Bart accomplished this part of the task without disembedding any data from the chart and relied entirely on rules of thumb (Figure 4-22). We again see here Bart’s tendency toward identifying broad regions in relation to identified troughs and ridges without seeking underlying patterns in the data that would promote a more nuanced interpretation.

Figure 4-22 Bart’s annotated 300 mb chart

Finally, Abe’s 300 mb chart is interesting because he was especially conscientious about identifying multiple “shortwaves” (kinks) found in the overall jet stream pattern. Such shortwaves can be indicative of upper level fronts and therefore important to understanding the atmosphere as a whole. We recognize that Abe’s identification of these shortwaves involved disembedding incongruous patterns from the overall jet stream flow. However, with this accomplished, Abe used very simplistic rules of thumb to identify divergence and convergence: “Convergence is usually found on the left side of these trough lines, so I’m going to go ahead and just shade that in right there. And then on the other side, we’ve got divergence.” So in this case, he used the same method to identify divergence and convergence as Bart, however, his
chart looks very different because of the extra disembedding he performed to extract multiple shortwave patterns (Figure 4-23). Bart’s 300 mb chart is also not entirely correct, but it illustrates his use of disembedding together with broadly applied rule-based reasoning.

Figure 4-23 Abe’s’s annotated 300 mb chart

DISCUSSION

Our observations and analysis of the think-aloud data allowed us to characterize the disembedding of each of our three participants. Beginning with Abe, a low disembedder, his treatment of the surface chart is noteworthy considering all of the information that is encoded in the station plots. The only information he extracted was wind direction (he did not isolate pressure data to find the lowest pressure). This, coupled with eight separate comments indicating difficulty discerning information encoded in the station plots clearly demonstrates that he struggled to identify relevant information from the distracting background. With the 850 mb chart he fittingly used both temperature and wind information to identify areas of cold and warm air advection, and isolated areas with tight temperature gradients. He did not take the next step,
however, and seek areas where height contours intersected isotherms. Instead, he shaded areas of advection in relation to where he “imagined” a cold front to be. Abe was keen on identifying every bulge and kink in the contours on the 500mb and 300 mb charts, which suggests a level of disembedding skill, at least with this feature. His straightforward shading of PVA/NVA and divergence/convergence in relation to troughs and ridges, was essentially correct, but he relied solely on rule-based reasoning rather than combining rules with higher-level pattern recognition. We characterize his task processing as a straightforward interpretation of salient features (wind direction, temperature gradients, troughs and ridges), with a reliance on rule-based reasoning, and accompanied by expressions of difficulty visualizing sought after patterns. Rule-based reasoning is an effective strategy for approaching the assigned tasks: we additionally recognize it in this context, as an accommodation for limitations with disembedding.

Such rule-based reasoning continued to characterize the task processing of Bart, our medium disembedder. He too broadly shaded PVA/NVA and divergence/convergence in relation to troughs and ridges. He fostered his identification of divergence and convergence through his recognition of speed convergence, however, this may have stemmed from his knowledge of air flow through the jet stream rather than wind information embedded in the chart. As with Abe, we recognize this as an approach for accomplishing the task without engaging disembedding skills, and thus a reasonable accommodation. Bart disembedded wind patterns on the 850 mb chart, but without the addition of thermal patterns, his shading of warm and cold air advection was too generalized and included areas not affected by CAA and WAA. He also appears to have confused the isotherms for height contours. Bart’s identification of surface features added considerably to the repertoire seen with Abe; observations of the temperatures and pressures from multiple stations, along with tendencies for each, informed his decision making. Additionally, comments regarding difficulty disentangling data on the surface chart were absent. Thus, we characterize Bart’s disembedding as further progressed than Abe’s, largely due to his increased interrogation of the charts, in particular, the surface chart, which resulted in recognizing patterns associated with the warm and cold front and a more accurate placement of each.

In addition to isolating multiple features including changes to dew point on the surface chart, Cole’s analysis was characterized by instances of attending to embedded aspects in the charts that were not identified by the other participants. With the 850 mb chart, he disembedded
the intersection of isotherms and height contours to discern more precise regions of cold and warm air advection. On the 500 mb chart he referenced curvature vorticity and identified areas of strong winds that would support vorticity advection. On the 300 mb chart he resolved wind patterns within the jet stream, attempting to identify an axis of strongest winds and potential for the existence of a jet streak. Once identified, he engaged his knowledge of jet streak dynamics, an additional example of rule-based reasoning. In this case, we note that Cole used higher-level disembedding and rule-based reasoning together, and we recognize this as a further sophistication of skill. Overall, Cole demonstrated purposeful pattern seeking and an enhanced ability to extricate patterns from the complex graphics displayed in the charts. Figure 4-24 summarizes our findings based on our three participants. We suggest that this characterization may extend to undergraduate students in similar university meteorology programs and portray approaches made by students with varying disembedding skills.

Figure 4-24 Our continuum characterizing analysis and disembedding by participants in our study

We counted the units of text that we coded using our a priori coding scheme and associated with “instances of disembedding” for each participant, expressed them as a percent of the total of each participants’ coded verbal data, and displayed the data graphically in Figure 4-25. We found an increasing trend when compared by participant in order of increasing disembedding skill. We did the same with portions of the text that we coded using our emergent
coding scheme. Those units of text that we designated as “alternatives to disembedding” included broad identification of features and therefore captured the application of rules. Thus, we see some use of alternatives by all three participants, but emphasize the decreasing trend. We also note that rule-based reasoning is logical and justified, however it is most effective when used in conjunction with weather features and patterns that are retrieved from the data. We note that Abe and Bart used alternatives to disembedding at a very similar rate. The two differ, however, in Bart’s greater use of disembedding and Abe’s explicit expressions of difficulty. This, of course, could be because he experienced more difficulty, or his expressions could merely be an artifact of his personality.

Overall, we recognize the importance of both knowledge and disembedding skill to successful performance with the types of meteorology tasks presented, with knowledge being the dominant predictor. How much of our participants’ disembedding was driven primarily by knowledge is unclear— the data we collected did not facilitate this interpretation. However, we propose that skill with disembedding, as categorized in our participants, did influence their exercise and application of disembedding. We additionally suggest that disembedding, when it is

![Figure 4-25 Code assignment by percent of participants' total codes](image)
used, facilitates a much more sophisticated application of rule based reasoning that when such reasoning is applied broadly and without the guidance of information gleaned from disembedded patterns. Our results, reminiscent of the findings of Lowe (1993), as well as Hegarty, Canham, and Fabrikant (2010), indicate that domain knowledge and disembedding are greatly intertwined and form the foundation of complex data interpretation. We did not, however, see evidence for complex visualization, such as Trickett and Trafton (2006) propose.

LIMITATIONS AND FUTURE WORK

When considering these results, we recognize some limitations of our work. First, when dealing with human subjects, a multitude of unacknowledged factors potentially influences results. Factors arising from the affective domain, i.e., values, motivation, attitudes, stereotypes, and feelings (SERC, 2017), could lead to incorrectly interpreted participant behavior. We attempted to control for as many factors as possible in our selection of participants, nevertheless, variation in human behavior and our analysis thereof is not without room for misinterpretation.

Secondly, using the think-aloud method naturally disrupts mental processing even as it attempts to capture it authentically. Although highly regarded, the method’s validity is sometimes questioned (Someren, Barnard & Sandberg, 1994). Affective factors, such as embarrassment over a lack of knowledge, can result in cognitive processes different from those that might take place when thoughts remain internal. Additionally, talking takes longer than thinking and synchronization can be an issue leading to silent periods that are difficult to interpret. For complex tasks that already tax working memory capacity, thinking aloud can add additional cognitive load. In our case, fortunately, meteorologists (and meteorologists in training) become accustomed to giving forecast briefings, which from the standpoint of psychology are a natural analog to the think-aloud method (Hoffman et al., 2017). We propose that this diminishes some concern with using the think-aloud method for data collection in our case, and reiterate the robust history of the think-aloud method in established research.

Obviously, individuals rely on a different repertoire of experiences, knowledge levels and expertise. We cannot know for sure if the differences we identified were due predominantly to varying disembedding skills or prompted more by knowledge. After all, you cannot disembed information that you do not even know to look for. Our evaluation of participants’ completed
coursework and undergraduate standing leads us to believe that they have learned the concepts that we asked them to apply. However, as educators we also recognize that this does not ensure proficiency. However, therein lies the point—we wish to identify where students confront hurdles to their understanding, skill, and application of knowledge.

Finally, our results rest on the characterization of individuals in a single university setting. Transferring findings to similar contexts (undergraduate meteorology students in comparable college programs) is a reasonable and reliable extension, however, we do not claim to have characterized disembedding in general, including for non-student meteorologists or individuals outside of the field.

Recognizing these limitations, there is much to be learned about the role of disembedding in meteorological tasks and this leaves room for future research. Our study focused on synoptic scale weather analysis using black and white, paper charts. In addition to expanding our current investigation, examining how disembedding skills affect interpretation of computer displayed data, and satellite and radar imagery at a variety of spatial and temporal scales are potential areas of study. Another area of interest is scrutinizing the actual thought and cognitive process that occur in conjunction with disembedding meteorological data to begin to disentangle disembedding-knowledge dependency. Interviewing participants with probing questions that begin to chip away at such an understanding presents a fascinating line of research.

CONCLUSION

We believe that one of the most productive applications of this research is promoting instructor awareness of students’ disembedding skills in undergraduate meteorology classrooms. Recognizing students who struggle while extracting information and looking for patterns in meteorological data is an important first step to tailoring instruction and scaffolding learning.

Spatial thinking skills are generally considered malleable and many research studies have demonstrated improved spatial thinking ability with training. However, a meta-analysis (Uttal et al., 2012) of studies purporting to train a variety of spatial skills showed that intrinsic-static spatial skills such as disembedding do not demonstrate the same degree of malleability as other types of spatial skills. Average effect size (Hedges’ g) over multiple intrinsic-static training scenarios was 0.32 (compared to 0.69 for extrinsic-static training). Thus, Uttal et al. (2012)
propose that intrinsic-static type skills, such as those measuring disembedding, respond less to training. This may be a function of the training or the testing. It is a problem worth studying and we wonder if specific disembedding training in a meteorology context could improve skills in meteorology students. The use of pointing and tracing gestures with elevation contours on topographic maps has been the subject of study, and we conceive of similar opportunities for research in meteorology.

With that said, developing instructional interventions is a natural outgrowth of this work. Such interventions are already being used in other STEM education domains. Sorby and Baartmans (2000), recognizing that visualization of engineering problems is an essential ingredient for student understanding in early engineering courses, developed a pre-graphics course for freshman engineering majors who demonstrate weak spatial visualization ability on standard spatial thinking tests. The course, together with development of a multimedia software and workbook, “Developing Spatial Thinking” (Sorby, 2011) has had a positive impact on developing student spatial skills, improving student grades in follow-on engineering courses and improving retention rates (Sorby 2007).

Ormand et al. (in press) developed curricular materials for mineralogy, structural geology, and sedimentology and stratigraphy courses that support student understanding of spatially challenging concepts. Like disembedding in meteorology, penetrative thinking is identified as an important spatial skill in geology. Ormand, et al. developed a Spatial Thinking Workbook with exercises to develop penetrative thinking skills. Pre- to post-test gains show that using the curricular materials provided in the Spatial Thinking Workbook strengthens students’ ability to solve geological problems with spatial components (Ormand et al., in press). These successes exemplify the potential for enhancement of current meteorology education and training.

ACKNOWLEDGEMENTS

We thank the Graduate College at Western Michigan University for funding our research and Dr. David Changnon for facilitating access to participants. Special thanks goes to our participants for agreeing to let us observe and film them.
SUMMARY AND CONCLUSION

Summary

Investigating cognitive factors that affect performance in meteorology is one way to peer inside the black box and attempt to answer, “How do they do it?” The collection of manuscripts presented here investigates specific spatial thinking skills that meteorologists report as important in their work, examines the effects of discrete intelligence abilities on performance on a series of meteorology tasks typically assigned to undergraduate meteorology students, and characterizes the use of disembedding among students with low, medium and high disembedding skills. A summary of each manuscript follows.

The investigation outlined in the first manuscript revealed three spatial thinking skills reported as highly used by practitioners in the field. According to the Newcombe and Shipley (2012) typology, these three skills each represent a different spatial focus: mental animation is an intrinsic-dynamic spatial skill, disembedding is an intrinsic-static spatial skill, and perspective taking is an extrinsic-dynamic spatial skill. This suggests that meteorological thinking is broad-based and requires one to exhibit elasticity and fluidity of thought in order to move between and within this suite of spatial skills. Meteorological thinking involves both internal and external frameworks, the ability to interpret static displays while simultaneously visualizing motion, and the mental flexibility to work within and between these frames concurrently.

This study also elucidated differences in how student and professional meteorologists report their use of spatial thinking. Especially noteworthy is the finding that novices did not report using mental animation as highly as professionals with the surface analysis plot did. Our proposal that professionals have an established mental library of weather case history with which to project how particular scenarios might evolve foreshadowed the later correlations we saw between domain knowledge, expertise and performance. Such a rich, mental library can also be a basis from which to recognize patterns and is likely highly influential to one’s ability to identify patterns and effectively apply them in meteorology tasks. Also of interest is finding that students reported lower use of disembedding with the surface analysis chart than professional meteorologists. This appears to corroborate classic findings in expertise studies that demonstrate
student focus on literal features rather than deeper principles and patterns. In light of the overall study results, placing extra emphasis on disembedding and pattern recognition skills in meteorology classrooms appears justified.

One highlight of the study described in the first manuscript is the gathering of practitioner wisdom and knowledge using an unstructured task to establish an authentic baseline for future discipline-based education research in meteorology. We hope that this will stimulate additional fruitful research in meteorology education and kindle the kind of collaboration between researchers that exists in other geoscience disciplines. Minimally, the study provided direction for the next phase of the current research, to which we turn next.

The study described in the second manuscript expanded on the findings contained in the first by considering additional aspects of cognition beyond spatial thinking, specifically, working memory, domain knowledge and expertise. Of these discrete intelligence abilities, domain knowledge and disembedding surfaced as significant predictors of performance on the series of meteorology tasks. This study also tested the circumvention-of-limits hypothesis and the knowledge-is-power hypothesis. The results provide additional evidence that some contexts fail to exhibit a circumventions-of-limits interaction effect; in this case by showing that disembedding positively predicted performance on the meteorology tasks at both low and high levels of domain knowledge. The results did not contribute to the working memory’s literature due to the lack of a significant effect of working memory as a predictor variable, except to demonstrate that context is important for elucidating a working memory effect.

This investigation is additionally notable for other findings, which replicate established conclusions in the cognitive science field, demonstrate interesting correlations with common and new sources of measurement, and provoked additional questions for understanding cognition within and outside the field of meteorology.

The results replicated:

1. Gender differences with the test of mental rotation demonstrating that males consistently outperform females
2. Age differences with the working memory test demonstrating that younger subjects outperform older subjects

The results demonstrated:
1. A positive correlation between the ETS Hidden Figures Test and the Vandenberg and Kuse Test of Mental Rotation, as tests of spatial thinking ability

2. A positive correlation between the Fundamentals in Meteorology Inventory and the Domain and Experience Questionnaire, providing validity that they both align with each other as measures of knowledge and expertise

3. A positive correlation between the series of meteorology tasks, the Fundamentals in Meteorology Inventory and the Domain and Experience Questionnaire, providing validity of the tasks’ ability to accurately assess meteorology skill

The results provoked the following questions:

1. Do meteorologists preferentially use spatial thinking to interpret visual displays rather than to visualize atmospheric processes?

2. Do meteorologists mentally rotate objects effectively using pattern recognition rather than spatial visualization?

3. Does weather, as a constantly changing input, explain why disembedding is difficult to circumvent as an influential factor in the successful completion of meteorology tasks?

The findings from the middle study led to the final investigation, which portrayed how students with different levels of disembedding skill worked through the series of meteorology tasks. This portrayal revealed the use of disembedding by a student proficient with this skill, accommodations for difficulty disembedding from a student with limited disembedding ability, and the processes of an intermediary student. An important take-away from these depictions is that each participant depended to some degree on both pattern recognition and rule-based reasoning. In the case of the high disembedder, he disembedded patterns inherent in the data display, at a finer resolution, and these patterns informed his application of rule-based reasoning. However, the accommodations observed with lower disembedding skill also rely on pattern recognition, but at a coarser scale with a broader application of rules.

The continuum characterizing the three students shows a movement away from broad identification of weather features based on rules of thumb and toward seeking nuanced patterns in data leading to a much more detailed and precise identification of atmospheric processes. This continuum can serve to help instructors recognize sources of student confusion and junctures where students confront hurdles in learning. Such awareness can be one source of feedback for
instructors and operate as a type of formative assessment. It can also inform development of instructional interventions and ways to scaffold student learning.

In general, the overall study identified aspects of cognition hypothetically important to meteorology tasks, measured those cognitive factors, confirmed two factors (domain knowledge and disembedding) and characterized disembedding among student meteorologists. We suggest that knowledge of meteorology and disembedding work together, with greater meteorology knowledge providing a richer mental library of weather cases and examples from which to support disembedding patterns both in weather displays and in the atmosphere at large.

Conclusion

Understanding the cognitive aspects necessary to becoming a successful meteorologist remains an important issue for not only university meteorology programs, but also military training pipelines, and professional ongoing training. Additionally, expanding findings from cognitive science into meteorology is significant for the opportunity it presents to test assumptions across domains and compare how different intelligence abilities operate in dissimilar contexts. Because the overall study began by establishing “what we know”, the findings of each investigation necessarily built upon the others. Through the succession of findings, some common themes have emerged.

As is true in other skill-based professional endeavors, building knowledge and expertise increases success with meteorology tasks. Meteorology knowledge is the strongest predictor of meteorology performance. This theme carried forth through all three phases. In the first phase, we suspect that odd trends in student responses to questions about radar products resulted from knowledge deficits. In the second phase, meteorology knowledge and expertise correlated, however, of the two, knowledge had a much stronger correlation with performance on the meteorology tasks. Finally, in the third phases, the think-alouds revealed some instances where a lack of disembedding was likely due to a lack of knowledge— one cannot disembed information that is unknown to them.

The second theme to emerge through these investigations is a reliance on pattern recognition. Pattern recognition follows the same thread as disembedding through the three manuscripts but illuminates why disembedding is important in meteorology. Through pattern
recognition, meteorologists attempt to bring order to chaotic phenomena and seek to make sense of erratic processes. Pattern recognition is integral to understanding the atmosphere. By selecting disembedding as a spatial thinking skill important in meteorology, the participants in the first phase indicated that pattern recognition plays a role. This was confirmed through statistical analysis in the second phase. Elucidation of thought processing through the think-alouds produced multiple instances of participants referring to patterns and exhibiting pattern seeking behaviors.

What this study emphasizes, but does not completely elucidate is the relation between the two— meteorology knowledge and pattern seeking/disembedding. Statistically, meteorology knowledge is the much stronger predictor. However, statistically, disembedding does remain important at both ends of the knowledge spectrum, so its contribution is evident and cannot be overlooked. The remaining unanswered question is: “How knowledge dependent is skill with disembedding?” The two are no doubt inextricably entangled. Unraveling the two is a task left for future research. Although, there is evidence for differences in the way that the participants in the third phase conducted their disembedding, it was impossible to control for every other variable and differences in knowledge and experience levels almost certainly were influential. My intent in phase three was to inform and contextualize the statistical results. As is the case with many investigations, in the processing of doing this, I generated many more questions.

What I can conclude is that the combined themes of building knowledge and promoting pattern recognition have important implications for meteorology education. I am interested in future work that investigates this more fully. Work by Hegarty et al., (2010) and others have investigated the use of color and salient features in weather displays. Findings from this type of research applied to the development of instructional interventions could offer great insight into the effectiveness of training students to resolve patterns in meteorological charts, maps and weather images. For example, spending class time color coding relevant features on weather maps that connect with a lesson’s topic might assist students in seeing and recognizing the atmospheric features on maps.

While recognizing the need for further investigation, the findings in this study confirm that maximizing content delivery and opportunity for practice with realistic weather scenarios and case studies is essential. Furthermore, by building the mental weather library of students, we
give them an increased knowledge base from which to recognize and compare patterns, a critical aspect of meteorological understanding.
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APPENDIX A

Domain and Experience Questionnaire

This survey is intended to summarize your education, training, and current employment experience in atmospheric science and meteorology. Please respond to all items that apply as of the current date.

1. Do you primarily consider yourself to be a(n) (circle please)
   Atmospheric scientist  Operational meteorologist  Broadcast meteorologist  Climatologist
   Other (fill in) ______________

2. Do you currently work in (circle please)
   Academia    Industry    Government    Military    Student    Other (fill in)____________

3. What is your specific area of expertise? (If you have expertise in more than one area, please circle your primary area of expertise.)
   Remote sensing    Weather analysis and forecasting    Climate change and variability
   Climate modeling    Severe weather    Other ______________

4. For how many years have you been working in your primary area of expertise, not including your education? (circle please; N/A if you are a student)
   N/A  0-5  6-10  11-15  16-20  21-25  >25

5. In your daily practice, how often do you engage in the following activities? (circle please)
   a. Interpreting/analyzing surface and upper air data (not including model forecasts)
      Often    Sometimes    Rarely    Never
   b. Using model output for weather/climate prediction
      Often    Sometimes    Rarely    Never
   c. Communicating weather/climate information to the public
      Often    Sometimes    Rarely    Never
   d. Writing research papers, reports, reviews and summaries related to weather/climate
      Often    Sometimes    Rarely    Never

6. How often have you worked in the following domains? (circle please)
   a. Mid-latitude and polar weather systems
      Often    Sometimes    Rarely    Never
   b. Tropical weather systems
      Often    Sometimes    Rarely    Never
   c. Mesoscale weather systems
      Often    Sometimes    Rarely    Never
   d. Weather observing, analysis and diagnosis
      Often    Sometimes    Rarely    Never
   e. Weather forecasting
      Often    Sometimes    Rarely    Never
7. Have you completed any of the following military training? (please check yes or no)

<table>
<thead>
<tr>
<th>Training</th>
<th>YES</th>
<th>NO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerographer’s Mate A School (U.S. Navy)</td>
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<tr>
<td>Aerographer’s Mate C School (U.S. Navy)</td>
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<tr>
<td>Officer Basic Meteorology Program (U.S. Air Force)</td>
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<tr>
<td>Air Force Enlisted Weather Specialist Training</td>
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</tbody>
</table>

8. Did you take, or are you taking, any of the following college-level courses? (please check yes or no)

<table>
<thead>
<tr>
<th>Course</th>
<th>YES</th>
<th>NO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction to Weather Analysis</td>
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<tr>
<td>Synoptic Meteorology</td>
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<tr>
<td>Dynamic Meteorology</td>
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<tr>
<td>Mesoscale Meteorology</td>
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<tr>
<td>Physical Meteorology</td>
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<tr>
<td>Climatology</td>
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<tr>
<td>Forecasting</td>
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<tr>
<td>Broadcast Meteorology</td>
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</tbody>
</table>

9. Have you completed or are you currently working on (please check yes or no)

<table>
<thead>
<tr>
<th>Activity</th>
<th>YES</th>
<th>NO</th>
</tr>
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<tbody>
<tr>
<td>An assistantship or internship in atmospheric science or a related field</td>
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<tr>
<td>Any original research in atmospheric science or a related field, including an undergraduate thesis or research project in a course</td>
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Please check yes or no:

<table>
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<th>Question</th>
<th>YES</th>
<th>NO</th>
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<tbody>
<tr>
<td>10. Are you currently pursuing an M.A./M.S. in atmospheric science or a related field?</td>
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</tr>
<tr>
<td>11. Do you hold an M.A./M.S. in atmospheric science or a related field?</td>
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<td></td>
</tr>
<tr>
<td>12. Are you currently pursuing a Ph.D. in atmospheric science or a related field?</td>
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</tr>
<tr>
<td>13. Do you hold a Ph.D. in atmospheric science or a related field?</td>
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<tr>
<td>14. Are you an AMS Certified Broadcast Meteorologist?</td>
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<tr>
<td>15. Are you an AMS Certified Consulting Meteorologist?</td>
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<tr>
<td>16. Have you earned the AMS Seal of Approval?</td>
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<tr>
<td>17. Do you currently, or have you ever, worked professionally as a meteorologist?</td>
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</table>

If you answered yes to number 17, how many years did you, or have you, worked professionally as a professional meteorologist? (please circle)

less than 5 years    5-10 years    >10 years
18. Please use the space below to tell us anything else important about your prior experiences in operational meteorology, weather forecasting, broadcast meteorology, and/or the local weather of your region.

DEMOGRAPHICS
19. What is your gender? (circle please)
   Male  Female  Transgender

20. What is your age?

21. What is your home state or territory? ____________

22. What is your race/ethnicity? PLEASE MARK ALL THAT APPLY
   [ ] African American/Black  [ ] Caucasian  [ ] Latino/Hispanic  [ ] Native American
   [ ] Asian/Native Hawaiian/Pacific Islander  [ ] Other ________________

THANK YOU
APPENDIX B
Series of Meteorology Tasks

Mark a center of low pressure with an “L”. Draw a warm front associated with this low in red and a cold front associated with this low in blue.
Mark the location of all trough axes with dashed lines and all ridge axes with zigzagged lines. Shade areas of warm air advection in red and cold air advection in blue.
Mark the location of all trough axes with dashed lines and all ridge axes with zigzagged lines. Shade areas of positive (cyclonic) vorticity advection in red and negative (anticyclonic) vorticity advection in blue.
Mark the location of all trough axes with dashed lines and all ridge axes with zigzagged lines. Shade areas of divergence in red and convergence in blue.
Based on the information in the preceding images, predict the location of the surface low 12 hours from the time of the images and indicate its location on the map with an "L".
## APPENDIX C

**Scoring Rubric for Series of Meteorology Tasks**

1. **Surface Map**

<table>
<thead>
<tr>
<th></th>
<th>Novice</th>
<th>Some skill</th>
<th>Medium skill</th>
<th>Advanced</th>
<th>Expert</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low, cold</td>
<td>Low in wrong place, cold front displaced, partial warm front</td>
<td>Secondary low, front not with wind field, or partial warm front</td>
<td>Primary low area (MO), cold front displaced, Partial warm front</td>
<td>Primary low area, Cold front, Warm front extends in straight line</td>
<td>Lowest, Cold low, Cold front, Warm front</td>
</tr>
<tr>
<td>front in</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>wrong place</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>or missing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low, cold</td>
<td></td>
<td></td>
<td>Primary low area, Cold front, Cold front extends north and east</td>
<td>Primary low area, Cold front, Warm front extends north along pressure trough</td>
<td>Lowest, Cold low, Cold front, complex warm front</td>
</tr>
<tr>
<td>front</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low in</td>
<td></td>
<td></td>
<td>Primary low area, Cold front, Partial warm front extends north and east</td>
<td>Primary low area, Cold front, Warm front extends north and east with wind field</td>
<td>Lowest, Cold low, Cold front, complex warm front</td>
</tr>
<tr>
<td>wrong place</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>or missing</td>
<td></td>
<td></td>
<td>Primary low area, Cold front, Partial warm front extends north and east</td>
<td>Primary low area, Cold front, Warm front extends north and east with wind field</td>
<td>Lowest, Cold low, Cold front, complex warm front</td>
</tr>
</tbody>
</table>

1 2 3 4 5 6 7 8 9 10

Note, Expert disagrees with NCEP/WPC analysis on warm front. Mid-60 temps with south winds are south of warm front (WPC had north of warm front in Ohio). Analysis from WPC may have been based on continuity from prior time period analysis. Zero for a blank map.
### 2. 850 hPa Map

<table>
<thead>
<tr>
<th>Novice</th>
<th>Some skill</th>
<th>Medium skill</th>
<th>Advanced</th>
<th>Expert</th>
</tr>
</thead>
<tbody>
<tr>
<td>Missed locations of trough/ridge</td>
<td>Main trough with low and ridge, CAA west of low, WAA east of low</td>
<td>Main trough with low and ridge, some CAA with north winds, some WAA with south winds</td>
<td>Main trough and ridge, CAA/WAA with major temp gradients</td>
<td>Some shortwaves, CAA &amp; WAA analyzed across map</td>
</tr>
<tr>
<td>CAA with cold air center, WAA with warm air center</td>
<td></td>
<td></td>
<td></td>
<td>Shortwaves, no areas of CAA/WAA where isotherms parallel to flow, caught WAA on backside of low</td>
</tr>
</tbody>
</table>

Note: Some analysts marked the thermal trough and ridge. Zeros for completely missed trough/ridge axes and CAA/WAA not in proper areas or even associated with cold/warm air masses.
3. **500 hPa Map**

<table>
<thead>
<tr>
<th>Missed main trough &amp; ridge, CVA with trough center, AVA with ridge center</th>
<th>Main trough and ridge, CVA with trough center, AVA with ridge center</th>
<th>Main trough and ridge, CVA/AVA east/west of trough</th>
<th>Main trough and ridge, CVA/AVA east/west of trough/ridge</th>
<th>Main troughs and ridges, a few shortwaves, major areas of CVA/AVA</th>
<th>Some shortwaves, CVA &amp; AVA analyzed across map</th>
<th>Shortwaves, no areas of CVA/AVA in trough/ridge lines</th>
<th>Shortwaves, multiple areas of CVA/AVA with each trough/ridge</th>
<th>Multiple shortwave troughs &amp; ridges, subtle CVA/AVA details</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
</tbody>
</table>
### 300 hPa Map Conv/Div Areas

<table>
<thead>
<tr>
<th>Novice</th>
<th>Some skill</th>
<th>Medium skill</th>
<th>Advanced</th>
<th>Expert</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main trough and ridge located, but still more north/south oriented, conv in center of low, div over ridge center</td>
<td>Main trough and ridge, conv into trough, div out of trough</td>
<td>Main trough and ridge, multiple areas of conv/div analyzed</td>
<td>Main troughs and ridges, some shortwaves, major areas of conv/div, with other areas also analyzed, do not cross trough/ridge lines</td>
<td>Shortwaves, flow pattern of conv/div located even across trough and ridge lines</td>
</tr>
</tbody>
</table>

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
5. Forecast low position

<table>
<thead>
<tr>
<th>Low did not move</th>
<th>Low moved west or south</th>
<th>Low moved an unrealistic distance east</th>
<th>Low moved due east</th>
<th>Low moved unrealistic distance N</th>
<th>Low moved N or NE but not in WAA</th>
<th>Low moved N or NE but not in CVA or DIV</th>
<th>Low moved N or NE but not far enough</th>
<th>Low moved N coincident with max WAA/CVA/DIV aloft and SW flow WI or MI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
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<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
</tbody>
</table>
Emergent codes: Strategies for compensating for lower disembedding skills/work arounds and expressions of inability to see patterns

These codes were emergent and arose from incidents of participants struggling with pattern identification or “alternatives to disembedding” strategies for completing the tasks. Often expressions of these strategies accompany broad shading of map regions- a clear indication that the participant is identifying large general areas (typically based on rules they learned) rather than “seeing” specific patterns that emerge from a more nuanced visualization of the data.

1. Broad identification of features in relation to troughs and ridges (east/west, ahead/behind, upstream/down stream)
2. Broad identification of features in relation to warm or cold fronts
3. Expressions of inability to disembed/the map is cluttered/the print is too small, etc.

A priori codes: Evidence of disembedding

I developed this set of codes by considering the patterns/signals that a forecaster is expected to “see” (identify/disembed) within the context of each map, i.e., what does the meteorologist look for in order to successfully complete the task at hand? Another way to say this would be- what information is included in weather maps explicitly to aid a forecaster in seeing relevant patterns? I used Vasquez, T. (2008) Weather Map Handbook, as a source.

The task asks participants to identify troughs and ridges on three of the maps. Considering all of the tasks, I assume that the relative disembedding skill required to do this is low, (you just look at the contours), so that is not a focus. When forecasting the low 12 hours in the future, more synthesis of the scenario is needed than disembedding, so this is also not a focus. Specifically, I am considering disembedding skills associated with identification of the surface low, warm and cold fronts, cold and warm air advection, PVA and NVA and divergence and convergence. In other words, what the participant is able to “see” to help him identify these factors.

The codes include all possible factors/information that a forecaster might consider and they are not all used with the three participants that I chose. I think it is important to include them, however, to note what the three participants did not consider or “see”.

Code each chunk of data only once (coded text is underlined). Not all text is coded.

I. Surface chart
   1. Pressure
   2. Pressure falls/decrease
   3. Wind direction, shift or flow
   4. Wind speed
   5. Temperatures
6. Cloud cover  
7. Present weather/precipitation  
8. Dew point  

II. 850 mb chart  
1. Shortwave  
2. Isoheights/Height contours  
3. Isotherms/”thermal packing”  
4. Wind speed  
5. Wind direction/“flow”/”blowing colder or warmer temperatures  
6. Angle of intersection between isoheights and isotherms/perpendicular or parallel to isotherms/crossing of isoheights with isotherms  
7. Temperatures/cold or warm air masses  

III. 500 mb chart  
1. Shortwave- kink in jetstream or flow-cyclonic wind shift in the prevailing flow  
2. Shear- determined by looking at horizontal wind differences  
3. Curvature- determined by looking at contours (troughs/ridges)  

IV. 300 mb chart  
1. Directional divergence or convergence (diffluence- spreading out or compacting of isoheights/contours)  
2. Speed divergence or convergence (horizontal speeding up or slowing down of winds)  
3. Wind speed  
4. Jet streak (jet core, entrance/exit regions or front/rear sections)  
5. Shortwaves
Date: December 1, 2015

To: Todd Ellis, Principal Investigator
    Peggy McNeal, Student Investigator for dissertation

From: Amy Naugle, Ph.D., Chair

Re: HSIRB Project Number 15-12-03

This letter will serve as confirmation that your research project titled “Spatial Thinking and Meteorology: an Exploratory Study” has been approved under the expedited category of review by the Human Subjects Institutional Review Board. The conditions and duration of this approval are specified in the Policies of Western Michigan University. You may now begin to implement the research as described in the application.

Please note: This research may only be conducted exactly in the form it was approved. You must seek specific board approval for any changes in this project (e.g., you must request a post approval change to enroll subjects beyond the number stated in your application under “Number of subjects you want to complete the study”). Failure to obtain approval for changes will result in a protocol deviation. In addition, if there are any unanticipated adverse reactions or unanticipated events associated with the conduct of this research, you should immediately suspend the project and contact the Chair of the HSIRB for consultation.

Reapproval of the project is required if it extends beyond the termination date stated below.

The Board wishes you success in the pursuit of your research goals.

Approval Termination: November 30, 2016
APPENDIX F

HSIRB Approval Letter for Phases 2 and 3

WESTERN MICHIGAN UNIVERSITY

Date: September 20, 2016

To: Heather Petcovic, Principal Investigator
    Todd Ellis, Co-Principal Investigator
    Peggy Mansfield McNeal, Student Investigator for dissertation

From: Amy Naugle, Ph.D., Chair

Re: HSIRB Project Number 16-09-14

This letter will serve as confirmation that your research project titled “Spatial Thinking in Meteorology: A Task Analysis of the Forecasting Process” has been approved under the expedited category of review by the Human Subjects Institutional Review Board. The conditions and duration of this approval are specified in the Policies of Western Michigan University. You may now begin to implement the research as described in the application.

Please note: This research may only be conducted exactly in the form it was approved. You must seek specific board approval for any changes in this project (e.g., you must request a post approval change to enroll subjects beyond the number stated in your application under “Number of subjects you want to complete the study.” Failure to obtain approval for changes will result in a protocol deviation. In addition, if there are any unanticipated adverse reactions or unanticipated events associated with the conduct of this research, you should immediately suspend the project and contact the Chair of the HSIRB for consultation.

Reapproval of the project is required if it extends beyond the termination date stated below.

The Board wishes you success in the pursuit of your research goals.

Approval Termination: September 19, 2017