Changes in Visual-spatial Cognition when Adults Learn American Sign Language and How Pre-existing Visual-spatial Cognition Predict Success in Learning

by

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Abstract

Visual space has unique importance in signed languages because, unlike spoken language, signed languages use space to encode multiple linguistic features. For example, space is used for grammar, where spatial locations, and movements between them, are used to mark grammatical features such as subject and object. This implies that visual-spatial cognition is involved in processing signed languages, and indeed, compared to non-signers, native signers have been shown to have superior visual-spatial short-term memory (STM), working memory (Wilson et al., 1997; Lauro et al., 2014), and mental imagery abilities (Emmorey et al., 1993; Emmorey and Kosslyn, 1996). Fluent, non-native signers also have demonstrated enhanced visual-spatial working memory (Keehner and Gathercole, 2007), and hearing children learning sign language show visual-spatial cognitive benefits after one year of experience (Capirci et al., 1998). It is not known, however, how visual-spatial cognition changes in adults as they first begin to learn sign language. Furthermore, beyond improvements in visual-spatial skills with sign language learning, it is not clear if pre-existing individual differences in visual-spatial cognition can predict success in ASL learning.

In the present study, adult English speakers with no prior sign language experience were recruited from first level ASL courses and performed tasks that assessed their visual-spatial cognition, verbal memory, and ASL proficiency before and after one academic semester of ASL instruction. To determine whether changes in visual-spatial cognition are specific to learning a visual-manual language, I also recruited adults learning any first level spoken language to serve as controls. Verbal STM/working memory was assessed with Digit Span Tasks and the OSPAN task. Visual-spatial STM/working memory was assessed by the Movespan task, which evaluated working memory for human actions, and by the Corsi block-tapping task (regular and rotated). The ability to mentally generate images was assessed by the mental clock imagery task, while mental rotation was assessed with the 3D mental rotation task and the rotated Corsi block- tapping tasks. The ASL proficiency of the participants was assessed with an ASL Picture Naming test and an ASL Recognition test.

The results showed that the ASL learners, when compared to the controls, improved on the non-rotated Corsi block-tapping task and the MoveSpan task. There were no group differences in the clock task or mental rotation task. I conclude that even limited sign language experience can improve visual-spatial memory, and I hypothesize that more sign language experience is needed to see improvements in mental imagery abilities. Additionally, the evidence suggested that the participants' pre-learning Corsi score was a good predictor of their changes in ASL proficiency compared to the Ospan score. This implies that visual-spatial STM might be able to predict how well adults learn sign language as a second language and appears to be more predictive than verbal memory. However, the relationship between visual-spatial memory and changes in ASL proficiency was not clearly established and warrants further investigation.

List of Abbreviations and Symbols Used

American Sign Language — ASL

British Sign Language — BSL

Italian Sign Language — LIS

Short-term memory — STM

Operations Span — Ospan

Perspective Taking/Spatial Orientation Task — PTSOT

Reaction time — RT

Akaike's Information Criterion — AIC

Akaike weights — w_i,

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Chapter 1: Introduction

Sign Languages – Visual-manual modality

Sign languages are natural languages that are produced through the hands, body, and face. American Sign Language (ASL) is the sign language that is most commonly used by Deaf[1] individuals in Canada and the United States. Historically, sign languages have been discredited and not recognized as real languages (Schein & Stewart, 1995). ASL was once thought to be a primitive language (Lane, 1989) that was not based on any linguistic principles. Instead people thought that ASL was made up of transparent iconic gestures and contained no conventions, such as phonological structures or grammar (Emmorey, 2002; Klima & Bellugi, 1979). Opinions on ASL and Deaf culture started to shift in 1965 when William Stokoe, a professor at Gallaudet University, published the *Dictionary of American Sign Language* which supported that ASL, and other sign languages, have their own valid phonological structure. Years later, Klima and Bellugi (1979) published *The Signs of Language* and were the first to describe a grammatical system of ASL. These books supported the idea that ASL was not just a coding system for spoken language. They helped influence the hearing population's opinions on ASL, and had a large impact on ASL being recognized as a true language.

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[1] The upper case "D" for Deaf refers to people belonging to a cultural group who have varying degrees of hearing loss and use sign language (for example, American Sign Language) as their primary form of communication. A lower case "d" for deaf refers to the audiological classification for hearing loss.

This change in opinion was very important in sign language research. Emmorey (2002) stated that "…once signed languages are recognized as natural human languages, a world of exploration opens up" (Emmorey, 2002, p.1) and that the biggest interest in studying sign languages is their modality. Sign languages are visual-manual languages, which require visual and motion processing for perception, and a complex motor system for production. Sign languages challenge the older views of what defines a language because they use the visual-spatial modality to represent grammatical structure spatially. However, sign languages still share the same underlying linguistic structure of spoken language. The fact that sign languages involve a different input and output than spoken languages invokes many questions about the similarities and differences between sign languages and spoken languages, and people have explored the similarities and differences to show that ASL and other sign languages are real human languages. For example, researchers have investigated sign language acquisition and development (Bonvillian, Orlansky, & Novack, 1983), and sign language organization in the brain (Campbell, MacSweeney, & Waters, 2008; Newman, Bavelier, Corina, Jezzard, & Neville, 2002). Despite the increasing amount of sign language research, and despite the fact that opinions are changing, there are still unanswered questions. One particular domain that interests researchers is the impact sign languages have on visual-spatial cognition.

Visual-spatial cognition – Definitions, cognitive processing, neural systems

People use visual-spatial cognition to interact with the visual world on an everyday basis. Many complex cognitive processes are involved to allow us to see, pay attention, touch objects, navigate, remember places that we have been, and plan where we need to go. Visual-spatial cognition has been described as lower-level processing of visual and spatial information. It refers to how people integrate all visual and spatial cues in the environment, and it also describes how people create, maintain, and analyze mentally constructed images (Possin, 2010; Sack, 2009). Visual-spatial cognition involves brain systems that are required for attention, visual processing, and motion processing, and these make use of bottom-up sensory input and top-down executive control of attention and planning (Possin, 2010). They also engage both the ventral “what” and dorsal “where” pathways of the visual system (Lambert, Sampaio, Scheiber, & Mauss, 2002; Milivojevic, Hamm, & Corballis, 2009; Possin, 2010). Widely distributed neural networks are thought to be involved in performing tasks that require visual-spatial cognition, and research has suggested that these skills are predominately mediated by the right hemisphere (Corballis, 1997; Harris et al., 2000; Iachini, Ruggiero, Conson, & Trojano, 2009; Milivojevic et al., 2009; Newcombe & Russell, 1969). However, bilateral and even left-lateralized activation during visual-spatial tasks has been reported (as reviewed in Kalbfleisch & Gillmarten, 2013). The brain regions involved include the parietal lobes, lateral prefrontal cortex, medial temporal lobes, inferior temporal cortex, occipital lobes, and basal ganglia (as reviewed in Possin, 2010).

For the purposes of this research, I define visual-spatial cognition as a encompassing visual-spatial attention, mental imagery, and visual-spatial memory. Visual-spatial attention is a person’s ability to direct their attention to a location in space to process visual stimuli, while ignoring other visual cues in different locations in space (Cave & Bichot, 1999). Mental imagery describes the ability to replicate or simulate visual experiences in a person's mind. It involves generating, maintaining, and inspecting mentally constructed images. For example, mental rotation, a common measure of mental imagery abilities, involves generating and transforming an image (Pearson, Deeprose, Wallace-Hadrill, Burnett Heyes, & Holmes, 2013). Visual-spatial memory can be broken down into visual-spatial short-term memory — the temporary storage of visual and spatial information — and visual-spatial working memory — the interaction and transformation the temporarily stored visual and spatial information.

Generally, short-term memory (STM) refers to the ability to temporarily store information, while working memory refers to the ability to interact with that temporary information to perform complex tasks, such as reasoning and learning (Baddeley, 2010). An accepted concept of working memory is that it contains separate mechanisms to store visual-spatial, and verbal, information (Jonides, Lacey, & Nee, 2005). A popular model of working memory put forward by Baddeley (2001) is a multicomponent model composed of a "central executive" that receives and manipulates information from three separate systems. The first system, "phonological loop", is responsible for temporarily storing and rehearsing verbal information. The second system, "visuo-spatial sketchpad" is responsible for storing and rehearsing visual and spatial information. The third system, "episodic buffer", combines information from long-term memory and the other two systems. Visual-spatial memory (STM and working) is essentially the "visuo-spatial sketchpad" component and its integration to the "central executive" of Baddely's model. Visual and spatial information, either being processed through the senses or from long-term memory, are combined in this component, temporarily stored and/or manipulated (Baddeley, 2001).

Visual-spatial cognition – Enhanced by experience

Research from multiple fields has suggested that visual-spatial cognition can be enhanced through experience and expertise. In the field of medicine, for example, research has shown that medical and surgical students' visual-spatial cognition, in particular mental rotation and imagery, are affected by their education and training. Researchers also suggested that certain visual-spatial cognitive skills may be predictive of acquiring certain abilities – like laparoscopic surgical skills and surgical knot tying, and of the students' success in their educational program (Anastakis, Hamstra, & Matsumoto, 2000; Brandt & Davies, 2006; Hegarty, Keehner, Khooshabeh, & Montello, 2009; Lufler, Zumwalt, Romney, & Hoagland, 2012; Schlickum et al., 2011; Wanzel, Hamstra, Anastakis, Matsumoto, & Cusimano, 2002).

Visual-spatial cognition has been compared in people who have "expert" experience in certain domains versus non-experts, and the experts are often shown to have enhancements. For example, studies have indicated that expert music readers have enhanced visual spatial resolution (Wong & Gauthier, 2012), expert musicians have enhanced mental imagery (Brochard, Dufour, & Després, 2004), pilots have better mental imagery and metric spatial judgments (Dror, Kosslyn, & Waag, 1993), and expert action video gamers have enhanced visual-spatial attention (Green & Bavelier, 2006; Green & Bavelier, 2003). In fact, those studies using video games also trained non-video game players on action video games for 1 hour a day for 10 days and found improvements in visual-spatial attention. This demonstrates that at least some aspects of visual-spatial cognition are trainable by some experiences, and that relatively little training may be required — visual-spatial cognition is malleable and can be affected by leisure activities, work, education, and training. Likewise, experience and environment can shape the brain and cognitive processes through changes in the brain (Jacini et al., 2009; Lillard & Erisir, 2011; Papagno & Vallar, 2014). Given the evidence that visual-spatial cognition can be improved through experience, it seems reasonable to predict that experience with signed languages — which is in the visual-spatial domain and rely of visual and spatial attention, visual-spatial memory, and mental imagery— may also affect visual-spatial cognition.

Visual-Spatial Properties of ASL

All aspects of ASL — including vocabulary, grammar, and meaning — are conveyed visually in a physical space. Just like spoken languages, ASL (and other sign languages) can be described as having phonological and morphological structure. Stokoe (1965) was one of the first to describe the phonological features of ASL and he classified three aspects (phonological parameters) of a sign: 1) The place where it is made in signing space (the three-dimensional area located in front of the signer's body that starts from the signer's hips and extends to just over the signer's head); 2) The configuration of the hand or hands (hand shape — the flexion or extension of one or more fingers — and the orientation of the hand or hands relative to the body); and 3) the action (movement) of the hand or hands. All three parameters co-occur during sign production, and a change in any of the parameters changes the meaning of a sign (Stokoe, 1965).

Other features of ASL are non-manual markers and classifiers. Non-manual markers consist of facial expressions, head movements, and mouth shapes used for grammatical purposes (Liddell & Johnson, 1989). For example, when asking a "what" question the signer's eyebrows should be down, but in a "yes or no" question the signer's eyebrows should be raised. Classifiers are a complex class of sign that use specific hand shapes in a variety of different ways. For example, classifiers are used to represent objects or people (semantic classifier), describe shape or size (extension classifiers), or describe how objects are being handled (handling/instrument classifier; Morgan & Woll, 2007).

Phonological parameters, non-manual markers, and classifiers follow strict rules and spatial constraints within the signing space. Skilled production and perception of a signed language thus necessarily relies on visual-spatial cognitive skills, including the abilities to attend to and track the phonological features of the language. Below are some examples of how ASL uses space to convey linguistic information that is encoded only in sound in spoken languages.

Pronominal use of space. Spatial locations are used for a grammatical function to represent subjects/and or objects of a sentence. A signer must first assign the person, place, or thing (referent) to a specific location in signing space. Each spatial location is specific to that referent and remains constant over the conversation, so the signer can later "point" to a certain location to refer to a referent. Although it resembles a pointing gesture used by non-signers, in ASL and other signed languages this is a lexicalized sign corresponding to a pronoun; the direction of the extended index finger in signing space marks the person of the pronoun (1st person points towards the signer, 2nd person towards the interlocutor, and 3rd person towards another location in signing space where a referent was previously established). Although the locations in signing space may have a topographical relationship to a real world space, in most cases they do not – the location of referents in signing space is arbitrary and fulfils a purely grammatical function. Both signer and addressee must remember these spatial locations in order to understand the conversation (Emmorey, 2002; Klima and Bellugi, 1979), which indicates a critical role of visual-spatial short-term and/or working memory.

Verbs and space. Two types of sign language verbs — agreeing verbs and spatial verbs — can be used in conjunction with the pronominal use of space described above. Both types of verbs involve movements. In *agreeing verbs* the movement is directed from the object or person performing the action towards the object or person receiving that action. For example, in the ASL sentence meaning "I blame you", the verb would start from the signer's chest and move outward towards the person being addressed. However, for "Sally blames Tom", the verb would start from the location that Sally was previously assigned to Tom's previously sign location (Emmorey, 2002; Meir, 2012). *Spatial verbs* use movement to describe locative information. For example, they can describe how a person or an object moves from one place to another. The verbs MOVE, PUT and IRON[2] are examples of

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[2] By convention, ASL signs are represented in text as "gloss", by writing their English semantic equivalents in all capital letters.

spatial verbs, and they look very much like handling classifiers but they are distinct from handling classifiers due to the frequency of use (Sandler & Lillo-Martin, 2006).

Using space to describe spatial relationships. In addition to conveying grammatical information, space is used in sign languages to describe how objects or people look and move, and how people and objects interact. This is most commonly done using classifiers. Space can be used to convey real-world spatial locations, but on a miniaturized scale. This is often called *topographic function* (Quinto-Pozos et al., 2013) or *diagrammatic space* (Emmorey, 2002). Real-world locations can alternatively be represented on real-life scale. This is often called *depictive function* (Quinto-Pozos et al., 2013) or *viewer's space* (Emmorey, 2002). The narrator (person who is signing) typically sign in first person perspective, so the addressee has to imagine the narrators' perspective, essentially rotating the narrator's signing space.

Discourse, narratives, and role shifting. Just like in spoken languages, users of sign language may tell stories that involve multiple characters. To convey multiple characters, signers may use space, facial expression, eye gazes, and/or head movements. Signers will shift from character to character, sometimes literally tilting their body from side to side. This is often called "role-shifting" or referential shifting (Emmorey, 2002; Quinto-Pozos et al., 2013).

When role-shifting, the signer must make sure their eye gaze and agreeing verbs are appropriately directed toward the referents that are being conceptualized. For example, if the referent is taller than the person whose role the signer has assumed, the signer must ensure his or her eye gaze is angled upward. However, when the signer switches to assume the role of the taller character, their eye gaze shifts down. Likewise, some agreeing verbs should be directed toward specific body location, for example the verb ASK is directed towards the chin, so if the referent is tall, ASK should be directed at an upward angle (Liddell, 1990).

Visual-Spatial Attention, deafness, and Sign Language Experience

As noted, sign languages rely on visual-spatial cognition, and this might lead to enhancements of certain visual-spatial cognitive abilities. Studies have compared deaf signers with hearing signers and non-signers to understand the effects of sign language experience on visual-spatial attention. Some research has found that deaf signers have enhancements in orientating to stimuli (Bosworth, 2001; Bosworth & Dobkins, 2002; Colmenero, Catena, Fuentes, & Ramos, 2004; Prasad, Patil, & Mishra, 2015), peripheral attention (Bosworth, 2001; Chen, Zhang, & Zhou, 2006; Proksch & Bavelier, 2002), and detecting motion (Bosworth, 2001; Shiell, Champoux, & Zatorre, 2014). The enhancements, however, are selective. Not all aspects of visual-spatial attention are enhanced: studies have found no difference in motion sensitivity to stimuli presented in the central visual field (Bosworth, 2001), brightness discrimination (Bosworth, Petrich, & Dobkins, 2013), or divided attention (Bosworth, 2001). Additionally, in some cases, deaf signers performed poorer on some attention tasks than hearing non-signers, and auditory deprivation may actually hinder attention development (Dye & Bavelier, 2010; Dye, Hauser, & Bavelier, 2009; Quittner, Smith, Osberger, Mitchell, & Katz, 1994). These studies indicate that deaf signers have a different distribution of attention than hearing people — non-signers and, in some cases, signers. This suggests that these differences are most likely due to auditory deprivation and not sign language experience. The difference between auditory deprivation and sign language experience is an important distinction. When examining how sign language affects visual-spatial cognition, the effect of auditory deprivation has to be taken into consideration. To do this, studies have to compare Deaf signers to hearing signers, or compare Deaf signers to deaf non-signers, or hearing signers to hearing non-signers. This topic will be touched on later when I discuss some specific visual-spatial cognitive abilities.

Cerebral Lateralization in Signers

Visual hemifield studies investigate which side of the brain is faster at processing stimuli, by taking advantage of the crossed visual pathways. Stimuli presented in the right visual field initially activate the left hemisphere, while stimuli presented in the left visual field initially stimulate the right hemisphere. Faster reaction times to stimuli presented in one visual field indicate which hemisphere has the advantage at processing that kind of stimuli. Emmorey (2002) reviewed visual hemifield studies involving sign language stimuli and found that the left hemisphere had advantages, presumably due to language being lateralized to the left hemisphere. Emmorey (2002) noted that static line drawings of signs were not enough to show a left hemisphere advantage, and instead the signers had to be required to make semantic judgements on the static line drawings or view moving signs in order to see left hemisphere advantages. These left hemisphere advantages were not seen in hearing non-signers, but were seen in hearing signers, which suggested that — in contrast to changes in spatial attention — the left hemisphere/right visual field advantage for sign language stimuli is due to sign language experience and not deafness (Emmorey, 2002).

Research has also suggested that signers may have altered hemispheric specialization for non-linguistic stimuli. A left hemisphere advantage for motion has been seen in deaf signers, (Bavelier et al., 2001; Bosworth, 2001; Bosworth et al., 2013; Brozinsky & Bavelier, 2004) and hearing signers (Bavelier et al., 2001; Bosworth, 2001) while non-signers have a right hemisphere advantage. Similarly, left hemisphere dominance has been indicated in Deaf signers for other visual-spatial tasks like spatial memory (Cattani & Clibbens, 2005) and object recognition (Weisberg, Koo, Crain, & Eden, 2012), while right-hemisphere dominance has been seen in Deaf signers while performing a mental imagery task (Emmorey & Kosslyn, 1996). These studies support the idea that sign language experience can affect brain organization for motion perception and visual-spatial stimuli. Therefore, sign language experience could also affect other visual-spatial cognitive abilities.

Visual-Spatial Cognition and Sign Language Experience

Consistent with the evidence reviewed above, studies that have investigated other aspects of visual-spatial cognition in signers have found that, while there is evidence for enhancement, these benefits are selective, and not generalized to all abilities involving the visual-spatial domain. When compared with non-signers, evidence suggests that signers (Deaf and/or hearing) have enhanced visual-spatial STM/working memory (Capirci, Cattani, Rossini, & Volterra, 1998; Keehner & Gathercole, 2007; Lauro, Crespi, Papagno, & Cecchetto, 2014; Wilson, Bettger, Niculae, & Klima, 1997), mental imagery or mental rotation abilities (Emmorey &

Kosslyn, 1996; Emmorey, Kosslyn, & Bellugi, 1993; Talbot & Haude, 1993), face discrimination (Bellugi et al., 1990; Bettger, Emmorey, Mccullough, & Bellugi, 1997; Emmorey & McCullough, 2009), and categorization of linguistic and non-linguistic motion (Corina & Grosvald, 2012; Knapp, Cho, & Corina, 2008). Conversely, there were no apparent differences between signers (Deaf or hearing) and hearing non-signers in face recognition (Mccullough, 2010; Mccullough & Emmorey, 1997), or visual-spatial constructive abilities like copying, drawing, and block construction (Bellugi et al., 1990; Hauser, Cohen, Dye, & Bavelier, 2006).

Auditory deprivation vs. sign language experience. It is important to note that some of the studies listed above (Bettger, 1997; Emmorey et al., 1993; Emmorey & McCullough, 2009) also compared Deaf native signers and hearing native signers and they showed similar performance in face discrimination and mental imagery tasks. Likewise, some of the studies listed above compared hearing non-native signers to hearing non-signers (Capirci et al., 1998; Keehner & Gathercole, 2007). The hearing non-native signers still had superior performance on visual-spatial working memory tasks to hearing non-signing controls. All of this research suggests that some of the enhanced visual-spatial cognitive abilities are not due to deafness but are instead due to sign language experience.

Verbal short-term memory in sign language. Serial span tasks — for example letter, word or digit span — can be used to assess verbal STM by examining how many items can be recalled in the correct serial order (forward span), or reverse order (backward span). Span tasks that are presented in sign languages are in the visual domain, which may affect memory. Indeed, research has shown that

STM spans for signs are smaller than spans for spoken language stimuli, in both Deaf and hearing native signers (Boutla, Supalla, Newport, & Bavelier, 2004; Geraci, Gozzi, Papagno, & Cecchetto, 2008; Wilson et al., 1997). Bilingual hearing ASL-English signers also show a decreased span when performing a digit span task in ASL compared to English (Boutla et al., 2004; Hall & Bavelier, 2011). Some studies used the backward digit span and found that signers showed less of a hindrance for backwards ASL digit recall and had better performance than non-signers performing backwards English digit recall, suggesting that it is easier to perform reversals on lists that are presented spatially (Wilson et al., 1997). However, this finding has not always been replicated (Bavelier, Newport, Hall, Supalla, & Boutla, 2008).

The discrepancy between span capacity for sign or spoken languages has been attributed to the difference in modality (Hirshorn, Fernandez, & Bavelier, 2012). During serial spans, signers do make use of phonological rehearsal (Wilson & Emmorey, 1997) but research suggested that phonological processing, and temporal order processing, is better suited towards auditory stimuli as compared to signs (Bavelier et al., 2008; Hirshorn et al., 2012; Rudner, Andin, & Ronnberg, 2009; Wilson et al., 1997). Furthermore, a neuroimaging study showed that phonological processing is similar for both sign languages and spoken languages but STM memory networks were activated at different times in Deaf signers and hearing non-signers (Bavelier et al., 2008).

Visual-spatial STM and working memory. The Corsi block-tapping task (Corsi, 1972) is used to measure visual-spatial STM. It consists of participants' memorizing and repeating a pattern of taps on a panel of blocks. In one study, Deaf native signing children outperformed hearing non-signing children on this task (Wilson et al., 1997). A more recent study compared Deaf signing adults (who learn sign before the age of 6) to hearing non-signing adults on forward and backward versions of the Corsi task. The backward version required the participants to tap the reverse order of the spatial sequence, which assessed visual-spatial working memory. The results showed that Deaf signers outperformed the hearing non-signers on both versions of the task (Lauro et al., 2014). These studies taken together provide evidence that Deaf native signers have superior visual-spatial memory.

Keehner and Gathercole (2007) examined visual-spatial STM/working memory in hearing British Sign Language (BSL) interpreters, who learned BSL in adulthood, and in hearing non-signers. The researchers modified the Corsi task by using two panels of blocks instead of one. The panels sat between the experimenter and participant, and the panels were either in identical orientation (0^0; similar to the original Corsi task), or one panel was rotated either 90^0 or 180^0. The signers did not outperform the non-signers on the 0^0 version. This does not coincide with the other studies showing signers' superior performance on the Corsi tasks (Wilson et al., 1997, Lauro et al., 2014). However, the signers in Keehner and Gathercole (2007) did outperform the non-signers on the 180^0 rotated version. The 180^0 rotated version of the task requires not only visual-spatial working memory, but also mental rotation. So perhaps the non-native signers, in this study, were only showing enhanced mental rotation as opposed to visual-spatial working memory.

Although these studies suggest that sign language experience may enhance visual-spatial memory, other studies using the Corsi block-tapping task have shown inconsistent results. In one study, non-native deaf signers, some with cochlear implants (CIs), did not perform better than hearing individuals who knew no sign language or knew minimal sign language (Marschark, Morrison, Lukomski, Borgna, & Convertino, 2013). Furthermore, Marschark et al. (2015) investigated both deaf participants (some had CIs, some knew sign language, some did not) and hearing individuals (some who knew sign language and some who did not) on a computerized version of the Corsi block-tapping task. They also tested language skill (ASL or English). There was no difference between the groups, but the deaf participants' Corsi scores were related to their language proficiency regardless of modality – the more proficient in the deaf participants' language of choice, the higher the score (Marschark et al., 2015). This suggested that visual-spatial memory might be affected by language proficiency, unrelated to modality. However the Corsi scores were only related to proficiency in deaf participants and not the hearing participants, so the effect might not apply to the hearing population.

Mental Imagery – Mental rotation and image generation. Researchers have hypothesized that mental imagery is essential to the production and comprehension of sign language (Emmorey & Kosslyn, 1996; Emmorey, Klima, & Hickok, 1998; Emmorey et al., 1993). There are many aspects of sign language — including pronominal use of space, verb agreement, and role-shifting — that require signers to conceptualize referents and scene descriptions. Furthermore, the signer typically signs from their own perspective, so the addressee must perform an 180^0 rotation of the narrators' signing space in order to understand the conversation.

Studies have used both mental rotation tasks and image generation tasks to assess signers' mental imagery. The mental rotation tasks involved comparing shapes that were either the same shape but rotated along a vertical axis, or a mirror image shape, and deciding whether the two shapes were the same or mirror images. The image generation task required the participants to remember a particular letter shape shown over a grid, and then determine whether a series of probes overlapped with the remembered/imagined shape. On both tasks, Deaf native and non-native signers and hearing native signers had similar reaction times, which were faster than those of hearing non-signers (Emmorey et al., 1993). Emmorey and Kosslyn (1996) also showed that for the image generation task, Deaf signers showed faster reaction times than hearing non-signers.

Talbot and Haude (1993) compared hearing people with various degrees of ASL experience on a mental rotation task. Interpreting students and certified interpreters, with an average of six years' experience, had higher accuracy than participants with less than one year's experience or participants with no sign language experience — there was no difference between the latter two groups. These findings suggest that more than one year of sign language experience is needed to see enhancements in mental rotation abilities. However, the study did not state what kind, or duration, of ASL instruction the people with less than one year's experience had.

Reflections on studies investigating hearing non-native signers. Two of the studies mentioned above, measuring visual-spatial working memory (Keehner and Gathercole, 2007) and mental rotation (Talbot and Haude, 1993), provided evidence that enhancements in those skills can be obtained by learning sign language in adulthood. However, it is important to note that those studies only compared visual-spatial memory and mental imagery between groups and retrospectively inferred that sign language experience improves those visual-spatial cognitive abilities. It is not clear, however, if sign language instruction improved the participants' abilities in these studies or if individuals with better visual-spatial cognition are more inclined to persist with learning sign language to a higher level, and work in interpreting fields. Only a longitudinal learning study investigating changes in visual-spatial cognitive abilities will definitively answer the question of whether learning sign language in adulthood can affect visual-spatial cognition.

Hearing Individuals Learning Sign Language as a Second language

Numerous studies have investigated different aspects of how hearing native spoken language users learn sign language as a second language (L2), including some that have focused on which aspects of the language are more challenging to learn. For example, phonological parameters, in particular hand shape and movement, were hard to learn (Ortega & Morgan, 2015b; Williams & Newman, 2016). Students also found it difficult to use a different modality and to adjust to using their body and facial expressions (McKee & McKee, 1992; Woll, 2012). Iconic signs — signs that resemble their linguistic meaning like the verb DRINK, which looks like the action of drinking — appear to play an important role in sign language learning because they are easier to translate and recognize (Baus, Carreiras, & Emmorey, 2013) but harder to articulate accurately than non-iconic signs (Ortega & Morgan, 2015a, 2015b).

To my knowledge, only one study has investigated changes in visual-spatial cognition in sign language L2 learners, and that was in children. Capirci and colleagues (1998) investigated the causal effects of sign language experience by examining hearing children taking a second language course. Their study used the Corsi block-tapping task to examine visual-spatial STM in hearing grade-one students before and after taking an Italian Sign Language (LIS) course for a year. These children's performance was compared to that of classmates not learning LIS, but instead learning English, as well as classmates not learning any second language. The LIS group outperformed the other two groups after a year of language training (Capirci et al., 1998). This suggested that teaching hearing children sign language is beneficial to their cognitive development, and that enhancements in visual-spatial STM can be seen after one year of sign language training. It is not known, however, if similar changes in visual-spatial STM can be seen in adults learning sign language as a second language. This is an important distinction because research indicates that, on average, children learn second languages with greater proficiency than adults (DeKeyser, 2000; Francis, 1999; Singleton, 2001) so sign language experience may impact adults' visual-spatial cognition differently.

Predicting sign language acquisition. In addition to understanding how adult L2 sign language learners acquire a language, some researchers have focused on what skills predict sign language proficiency by comparing learners' pre-existing skills to their later sign language knowledge. Gestural abilities — the amount and type of gestures and ability to use space (Taub, Galvan, Pinar, & Mather, 2008) — and the natural use of facial expressions (Mcintire & Snitzer Reilly, 1988) is predictive of ASL production. To my knowledge, other than these two studies, no other research has examined the relationship between visual-spatial cognition and sign language L2 outcomes. On the other hand, there has been relatively more research in what predicts spoken L2 outcomes

Predicting spoken language acquisition. Numerous factors have been shown to influence spoken second language learning. For example, socioeconomic status, type of instruction, the learners' motivation, and other learners' characteristics have all been shown to affect second language outcomes (as reviewed in Dixon et al., 2012). In terms of cognitive skills, individuals with better phonological STM and working memory show better L2 outcomes (Martin & Ellis, 2012; Nicolay & Poncelet, 2013; Robinson, 2005; Wen, 2012; Williams, 2011). Indeed, a large meta-analysis with over 3000 participants found that verbal working memory was positively associated with L2 proficiency outcomes (Linck, Osthus, Koeth, & Bunting, 2014).

Taken together, these studies provide evidence that at least some cognitive skills are related to second language acquisition. To date, however, no studies have examined what cognitive skills may predict sign language L2 outcomes. Although verbal STM and working memory may be relevant to sign language learning, it is possible that visual-spatial STM and spatial working memory plays a more important role in learning a visual-manual language than a spoken one.

Other Unexplored Domains in Sign Language Acquisition and Visual-Spatial Cognition

Memory for observed actions. Sign language requires individuals to observe and produce actions. Researchers have investigated human action observation and categorization in signers and found that, when compared to hearing non-signers, Deaf signers were better at detecting both signs and non-linguistic actions that were either inverted 180^0 (Corina and Grosvald et al., 2012) or embedded in visual noise (Knapp, Cho, & Corina, 2008). One aspect of action perception that has not been investigated, however, is signers' ability to memorize human actions. Based on evidence that signers have an enhanced visual-spatial memory (Capirici et al., 1998; Keehner and Gathercole, 2007; Lauro et al., 2014; Wilson et al., 1997), that actions are inherently a visual-spatial stimuli, and that Deaf signers have an enhanced ability for human action detection (Knapp, Cho, & Corina, 2008; Corina and Grosvald et al., 2012), it is reasonable to assume that signers might have a superior memory for observed action.

Perspective taking and spatial orientation abilities. As previously discussed, signers will use topographic function/diagrammatic space in order to describe real-world locations on a reduced scale, or they will use depictive/viewer's space to describe real-world location on a real-life scale (Emmorey, 2002; Quinto-Pozos et al., 2013). When doing this, the narrator normally describes the scene from their perspective and this leads to the addressee having to mentally rotate and adopt the narrator's viewpoint – called a non-egocentric viewpoint (see Emmorey, 2002, and Pyers et al., 2015 for more details).

Perspective-taking abilities are important in understanding and coordinating a signed conversation. However, to my knowledge, only one study has compared signers' perspective abilities to non-signers and it found that signers were able to interpret signed and gestured descriptions non-egocentrically but the non-signers were not (Pyers, Perniss, & Emmorey, 2015). However, that study was very specific to sign language, as it used signs and gestures, and it did not investigate more general perspective taking and spatial orientation abilities. Quinto-Pozos and colleagues (2013) did investigate perspective-taking abilities more generally in a Deaf native signer who struggled with the spatial aspects of ASL using the Perspective Taking/Spatial Orientation Task (PTSOT; (Hegarty & Waller, 2004). The signer performed poorly on this task and other perspective-taking tasks. Perhaps signers who do not struggle with spatial aspects of sign language would perform better than non-signers on this task. However, the difference between signers' and non-signers' general perspective taking and orientation abilities, to my knowledge, have never been examined.

The Present Study

The present study was one of the first to investigate both which visual-spatial cognitive abilities predict ASL learning, and which abilities may change during learning, in adults who were beginning to learn ASL as a second language. Assessments of a range of cognitive abilities were made at the beginning and end of the students' first semester of academic ASL instruction. ASL learners' performance was compared to that of demographically comparable students enrolled in their first year of spoken language instruction. I sought to answer two research questions: (1)

Does ASL instruction improve visual-spatial cognition and (2) can pre-existing individual differences in visual-spatial cognition predict their success at learning ASL?

Question 1 – Does ASL instruction improve visual-spatial cognition? As discussed previously, visual-spatial STM memory and working memory (Lauro et al., 2014; Wilson et al., 1997) and mental imagery abilities (Emmorey et al., 1993; Emmorey & Kosslyn, 1996) in native signers were enhanced compared to non-signers. Non-native signers also have enhanced visual-spatial working memory (Keehner & Gathercole, 2007) and mental imagery abilities (Emmorey et al., 1993; Talbot & Haude, 1993) compared to non-signers. However, it is not clear if learning sign language enhances certain visual-spatial cognitive abilities, or if individuals with better visual-spatial cognition tend to achieve higher levels of sign language fluency. It has been shown that visual-spatial STM in children can improve after one year of sign language instruction (Capirci et al., 1998), however no studies have investigated the early stages of sign language L2 acquisition in adults. Additionally, no studies have investigated individual changes in visual-spatial cognition in adults learning sign language; previous studies of adult non-native signers only compared visual-spatial cognitive abilities across groups cross-sectionally.

In the present study, English speakers with no prior sign language experience were recruited from first-level ASL courses and asked to perform tasks that assessed their visual-spatial cognition and ASL proficiency before and after one academic semester of ASL instruction. To determine whether any changes in visual-spatial cognition that might be observed would be specific to learning a visual-manual language, and to control for practice effects on the assessments used, we also recruited adults enrolled in a comparable-level spoken second language class.

Question 2 – Can visual-spatial cognition predict ASL proficiency?

Research has shown that individuals with better phonological STM and verbal working memory have superior L2 outcomes (Linck et al., 2014; Martin & Ellis, 2012; Nicolay & Poncelet, 2013; Wen, 2012; Williams, 2011). Space is important in sign languages, so perhaps visual-spatial working memory, visual-spatial STM, and other visual-spatial cognitive abilities, like mental imagery, are important in acquiring ASL. To answer this question, I investigated the relationship between learners' pre-existing visual-spatial cognitive scores (measured at the start of the study) and their ASL learning (measured as the change between their pre-learning and their post-learning ASL proficiency scores). Additionally, to examine how verbal memory predicts learning, and compare that to how visual-spatial memory predicts learning, I also examined the relationship between the participants' verbal working memory scores and their change in ASL proficiency.

Experimental tasks. Both the ASL learners and the control participants performed seven cognitive tasks and two ASL proficiency tests. Some of the cognitive tasks assessed visual-spatial domains that have been relatively well explored (e.g., Corsi block-tapping task, digit span task, mental rotation task). However, to examine other possibilities, I chose other cognitive tasks that assess visual-spatial domains that have never been investigated with signers.

I used four cognitive tasks to investigate visual-spatial cognition that have been previously explored in signers: 1) Corsi block-tapping task - both non-rotated

(Capirci et al., 1998; Wilson et al., 1997), and rotated (Keehner & Gathercole, 2007); 2) Mental rotation task (Emmorey et al., 1993); 3) Mental clock task, which has never been used in sign language context but it assesses image generation abilities (Paivio, 1978; Pearson et al., 2013; Sasaoka, Mizuhara, & Inui, 2014); and 4) Digit span task (Hall & Bavelier, 2011; Wilson et al., 1997). The Corsi block-tapping task (rotated and non-rotated) assessed visual-spatial STM/working memory. The rotated version of the Corsi block-tapping task and the mental rotation task assessed the participants' mental rotation abilities. The mental clock task assessed the participants' ability to mentally generate images. The visual span task was used to assess phonological STM. This study used three versions of the digit span task – English, ASL, and a Hand Shape Span task that used hand shapes that did not exist in ASL.

The remaining three cognitive tasks were: 1) OSPAN task, which assessed verbal working memory; 2) MoveSpan task, which assessed visual-spatial working memory, specifically working memory for observed actions (Wood, 2007); 3) a modified version of the perspective taking spatial orientation task (PTSOT) (Hegarty and Waller, 2004). The OSPAN task was chosen since verbal working memory has previously been shown to be an important predictor of spoken L2 learning; as well it allowed us to determine whether any effects of working memory observed were specific to verbal versus visual-spatial working memory. The Movespan task and the PTSOT were chosen to explore the changes in the learners' memory for observed actions and in perspective and orientation abilities, respectively.

Predictions for Question 1. I predicted that the ASL learners would improve on the ASL proficiency tests, while the control group would not improve. I hypothesized that both groups would show improvements on all tasks due to practice effects, however I predicted that, because ASL is a visual-spatial language, ASL learners would show larger improvements than the control group on the tasks that assessed the following visual-spatial cognitive abilities: visual-spatial STM and working memory, mental imagery (image generation and mental rotation), perspective taking and spatial orientation, and STM for ASL digits (see Table 1).

Table 1. Summary of Cognitive Tasks and Predictions.

Skill	Task	Previous use in sign language research? (Reference)	Question 1 Prediction *ASL group improve more than control group*	Question 2 Prediction *ASL participants' pre-test score will be related to change in ASL proficiency*
Visual-spatial memory				
STM and Working memory	Corsi block-tapping task (non-rotated and rotated)	(Capirci et al., 1998; Keehner & Gathercole, 2007; Wilson et al., 1997)	✓	✓
- Working memory for Observed actions	MoveSpan		✓	✓
Mental Imagery				
Generation	Mental Clock Task		✓	✓
Mental Rotation	3D Block Task	(Emmorey et al., 1993)	✓	✓
Perspective taking and spatial orientation	Perspective Taking and Spatial Orientation task (PTSOT)	(Quinto-Pozos et al., 2013)	✓	✓

Skill	Task	Previous use in sign language research? (Reference)	Question 1 Prediction *ASL group improve more than control group*	Question 2 Prediction *ASL participants' pre-test score will be related to change in ASL proficiency*
Verbal Memory				
Working Memory	Operation span task (Ospan)			
STM	Digit Span	(Hall & Bavelier, 2011; Wilson et al., 1997)		
	English			
	ASL		✓	
	Random Hand-Shape			

Visual-spatial STM and working memory. Based on previous research, I predicted that the ASL learners would improve on the Corsi block-tapping task, both non-rotated (Capirci et al., 1998; Lauro et al., 2014; Wilson et al., 1997) and rotated (Keehner & Gathercole, 2007). Those tasks assess visual-spatial working memory, so the ASL learners would also improve on other visual-working memory tasks like the MoveSpan task (Wood, 2007) as memory for observed actions may be important in learning a visual-manual language.

Mental imagery tasks. The ASL learners were predicted to have increased accuracy and/or faster reaction time on the mental rotation task and the mental clock task (Emmorey et al., 1993).

Perspective Taking/Spatial Orientation Task (PTSOT). This task tested the participants' ability to imagine different spatial perspectives. As previously mentioned, perspective taking skills are important in signed conversation (Emmorey, 2002; Pyers et al., 2015), and in a case study, a young female Deaf native signer who struggled with spatial aspects of ASL performed poorly on this task (Quinto-Pozos et al., 2013). Therefore, I predicted that the ASL learners would improve on this task after their ASL training.

ASL Digit Span Task. I hypothesized that the ASL learners would improve on the ASL digit span task, largely because the ASL learners would have learned the ASL digits in their course. Before the course, the ASL digits would be arbitrary symbols, but after the course the digits would be meaningful. Participants might recode ASL digits into English and use their English verbal STM for the task. Another possible mechanism for improvement would be that ASL learners were likely to improve at remembering hand shapes generally, and therefore also improve on the shape span task. I predict the former mechanisms, and that the ASL learners will improve on the ASL digit span but not the Random Hand shape span. I also predicted improvement for ASL but not spoken language learners.

Predictions for Question 2. Based on previous studies in spoken L2 language that showed a positive relationship between STM, working memory, and L2 proficiency (Linck et al., 2014; Martin & Ellis, 2012; Nicolay & Poncelet, 2013; Wen, 2012; Williams, 2011), I predicted that the ASL leaners' pre-learning performance on tasks that assess visual-spatial STM/working memory (Corsi block-tapping task, MoveSpan) would be positively related to their improvement in ASL proficiency. The ASL learners' pre-learning performance on the verbal

STM/working memory tasks (English and ASL digit span, Ospan), may also predict their change in proficiency. However, because ASL is a visual-manual language, I hypothesize that visual-spatial memory will be more important in acquiring the language, and show a stronger relationship with the ASL participants' change in proficiency than verbal memory. Also, because visual-spatial cognition is important to understanding ASL, I predicted that mental imagery (mental rotation, mental clock), and perspective abilities (PTSOT) would also have a positive relationship with ASL improvement. The spoken L2 learners were not involved in this question, as they did not learn sign language, and we did not measure their L2 proficiencies in their respective languages.

Chapter 2: Methods

Subjects

ASL group. Twenty-five native English speakers were recruited (20 female, mean age: 19.84, age range: 18-27) who were enrolled in a first level ASL course. The participants were recruited via posters and in-class recruitment letters either from the Nova Scotia Community College (NSCC) in the Halifax area (n=2) or from Carleton University in Ottawa (n=23). Participants were all right-handed by self-report. One participant only had some high school education, while the rest of the participants completed some undergraduate degree, and one participant previously completed an undergraduate degree. The two participants taken from the NSCC were from one class, while the other twenty-three participants were from one of five classes (three instructors). The NSCC ASL Level 1 taught from the Signing Naturally curriculum, Units 1-6 (Smith, Lentz, & Mikos, 2008). The instructors at Carleton University did not teach from a specified curriculum, however the material was consistent between instructors. I also confirmed that many of the Signing Naturally items were taught at Carleton University.

The NSCC course was a 60-hour course, approximately six hours a week for approximately eleven weeks, while the Carleton University course was a semester long course (13 weeks), approximately four hours per week. Table 2 shows the timeline of the study. Participants were first tested two to six weeks after their course started and were tested again zero to three weeks after their course ended. Therefore, the participants had approximately 40 hours of class between the pre-test session and the post-test session.

Control group. I recruited 11 native English speakers (9 female, mean age: 18.64, range: 18-22) who were enrolled in an introductory spoken language course via posters and the Dalhousie SONA participation system. All participants self-reported themselves as right handed, and the participants either completed high school or some undergraduate university. The introductory courses were Japanese (n = 1), French (n = 4), Italian (n = 2), Spanish (n = 3), or Mandarin (n = 1) offered either at Dalhousie University or Saint Mary's University. These courses were full year, two semesters long, with approximately three hours of instruction a week. Participants were tested four to twelve weeks after their course started and tested again four to nine weeks before their course ended. Therefore, the participants had approximately 33 hours of class between sessions, as shown in Table 2.

Table 2. Group demographics and timeline.

	ASL	Control (Spoken Language)
N (male)	25 (5)	11 (2)
Age (range)	19.84 (18-27)	19.64 (18-22)
Average amount of education (range)	14.56 years (11-18)	14.18 (12-17)
Average number of known languages (range)	2.52 (1-4)	2.55 (1-4)
Average number of class hours prior to pre-learning session (SD)*	14.2 (4.08)	22.9 (6.57)
Average number of class hours between pre-learning and post-learning session (SD)*	40.28 (4.60)	33 (4.84)
Average number of days between pre-learning and post-learning session (SD)	71.26 (10.82)	102.7 (15.66)

*The time-line was based on the known start state of the course, number of hours a week the course ran, the date of the pre-testing session and the post-testing session with assuming 100% class attendance. Therefore the hours are only an approximation.

Design

This study was a 2 × 2-mixed factorial design, between groups and within two sessions. All procedures were identical for both groups, and both sessions. Two of the ASL participants and all of the control participants were tested in the Neurocognitive Imaging Lab at Dalhousie University. The remainder of the ASL participants were tested in the HotSoft Lab at Carleton University. The author conducted all of the participants' pre-learning test sessions, and most of the participants' post-learning sessions, however another graduate student conducted some of the control participants' post-learning sessions. The order in which the participants performed the cognitive tasks and proficiency tests were: Corsi block-tapping task, ASL Naming Test, ASL Recognition Test, 3D Mental Rotation task, Ospan task, Perspective Taking and Spatial Orientation task (PTSOT), Mental Clock task, Digit Span task, and the MoveSpan task. The order was the same for the pre-learning session and the post-learning session. Each session took about two hours.

Between the sessions the participants also filled out a Language Experience and Proficiency Questionnaire (LEAP-Q; Marian, Blumenfeld, & Kaushanskaya, 2007). As shown in Table 2, the ASL group and the control group had similar ages, proportion of males, and amount of education. However, Welch's *t*-test, performed because of the unequal sample sizes, showed that the control group had significantly more class hours prior to the pre-learning session, $t(12.05) = 3.21$, $p < .001$, and more days between sessions, $t(14.38) = 6.05$, $p < .001$ and less amount of class hours between sessions, $t(18.32) = 4.22$, $p < .001$.

ASL Proficiency Tests

ASL Picture Naming (Recall) Test. This test had the participants recall and translate simple ASL signs. Participants saw a line drawing representations of basic ASL signs taken from the level one *Signing Naturally: Student Workbook* (Smith, Lentz, & Mikos, 1993) and were asked to type a one to two word description of the sign's meaning using a standard keyboard. The participant saw the image as they typed the answer, and then pressed enter to see the next image. There was no time limit to answer the question. The participant could also skip the question if they did not know the answer, however they were encouraged to make their best guess.

Before the test started the experimenter gave the participants a brief description of the task and then the participants read more detailed instructions on the computer screen followed by one example. The example was the same for every participant, and did not change from the pre-test session to the post-test session. The test has 40 questions and to prevent practice effects, we used two sets of 40 images, one used at the pre-test session and one used at the post-test session. The images were presented in random order. The two sets of images were balanced for topic (i.e., colour, day, transportation), and for the unit in which the sign appears (Units 1-6), and I did not repeat any signs. The signs were presented in random order via PsychoPy v1.82.01 (Peirce, 2007).

Some of the line drawings were apparently ambiguous and could have more than one meaning, and some of the participants made spelling mistakes. Therefore, rather than score the answers automatically, I scored the answers by hand (correct or incorrect), and used my judgement when assessing the answers.

ASL Recognition Test. This test had the participants recognize a sign and choose the best option out of four multiple-choice answers. Participants saw a short video of a male native signer performing a basic ASL sign (all signs were taught in Level I of the *Signing Naturally* curriculum). Some of the signs in this test overlapped with the signs in the naming test. The videos lasted approximately three to four seconds and the native signer performed the sign relatively slowly. Following the video, the participants saw four English words and pressed the letter on the keyboard (A, B, C or D) corresponding to the word that matched the sign's meaning. The video played only once, and the participants were forced to choose an answer; they could not skip a question. The multiple choice options were designed to allow for graded analysis of the participant's errors. On each question, one of the three incorrect options were either semantically related, or the ASL translation to the incorrect option had the same hand shape or had the same location to the sign in the video.

Before the test started, the experimenter gave the participants a brief description of the task, and then the participants read more detailed instructions on the computer screen followed by four examples. The examples were the same for every participant, and did not change from the pre-learning session to the post-learning session. The actual test had 40 questions. To prevent practice effects, I used two sets of forty videos that were balanced for topic and for the unit in which the sign appeared and did not repeat any signs. One set of stimuli was used at the pre-test session and one set of stimuli was presented at the post-test session. Each video was presented in a random order and the test was presented via PsychoPy v1.82.01

(Peirce, 2007). The PsychoPy program recorded the participants' key responses, which were later automatically scored; each trial was either correct or incorrect.

Visual-Spatial STM and Working Memory Tasks

Corsi Block-Tapping Task (non-rotated and rotated). The non-rotated version measures visual-spatial STM, while the rotated measures visual-spatial working memory (Berch, Krikorian, & Huha, 1998; Keehner & Gathercole, 2007; Kessels, Zandvoort, Postma, Kappelle, & Haan, 2010; Vecchi & Richardson, 2001), and both versions have previously been used in sign language research investigating non-native signers (Capirci et al., 1998; Keehner & Gathercole, 2007). The task involved the experimenter tapping a spatial pattern on a panel of cubes and the participant memorizing and tapping the same pattern. The materials and procedure were similar to the materials and procedures used in Keehner and Gathercole (2007), where two panels of blocks sat in between the experimenter and participant and the panel of blocks in front of the participants were either rotated 0^0 (non-rotated) or 180^0 (rotated). Figure 1a shows a diagram of the two identical panels of cubes, which were made out of wood. Each panel had nine black-coloured cubes (30 x 30 x 30 mm) on a black-coloured board (225 x 205 mm), the measurements and placement of the blocks matched the panel used in a previous study attempting to standardize the task (Kessels et al., 2010).

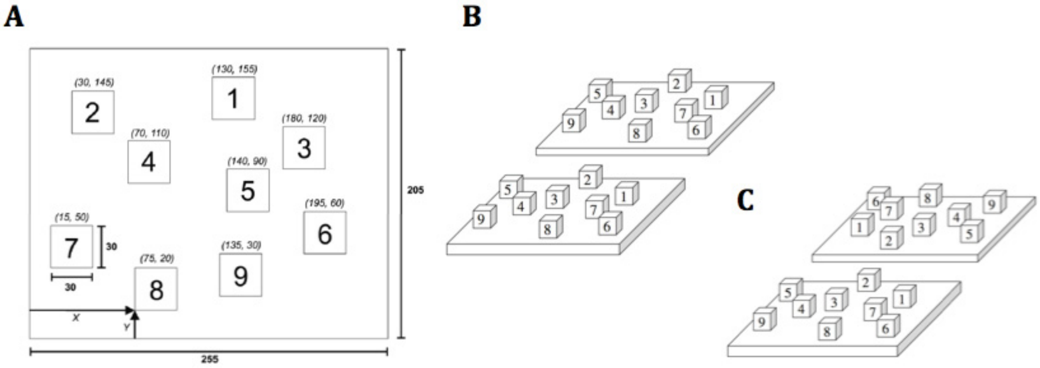


Figure 1. Corsi block-tapping task: A) the blueprint of the panels used in the present study. The coordinates above the block (in mm) are measured from the left-bottom corner of the board to the left-bottom corner of each cube. Image taken from (Kessels et al., 2010). B) Apparatus setup used in the non-rotated version. The panels are in identical orientation (0^0 rotation). C) Apparatus setup used in the rotated version. The panels are in opposite orientation (180^0 rotation). Images B and C were taken from (Keehner & Gathercole, 2007). The numbers representing corresponding blocks were only visible to the experimenter

During the trials, the experimenter and the participant sat directly in front of each other with a table in between them. One panel was placed on the tabletop immediately in front of the experimenter, and the second panel was positioned directly opposite to the first panel immediately in front of the participant. Figure 1b shows an example of the layout for the non-rotated condition where the orientations of both panels were identical. In the rotated condition the panel in front of the participants was rotated 180^0 relative to the panel in front of the experimenter, as shown in Figure 1c. This condition forced the participants to not only remember the correct sequence, but also mental rotate the pattern. Numbers were only visible to the experimenter indicating corresponding cubes on the two panels.

This task used two stimulus sets that contained sequences which were chosen from previous Corsi block-tapping studies that used the same block layout (Busch, Farrell, Lisdahl-Medina, & Krikorian, 2005; Capitani, Laiacona, & Ciceri, 1991; Smirni, Villardita, & Zappala, 1983), or were generated by the experimenter with consideration of the path complexity of the sequence (the number of times the sequence path crossed). Each stimulus set had two practice blocks and eight experimental blocks. The practice blocks consisted of 3 sequences of length 1, and 3 sequences of length 2, which were randomly generated by sampling without replacement from digits one to nine. Each of the eight experimental blocks had four sequences of numbers. The length of the sequences in the first block was one, and thereafter each block after the length of the sequences increased by one so the last block consisted of sequences of a length of eight. Each stimulus set had the least complex paths possible and the two sets of stimuli sequences were balanced for path complexity, which can affect performance (Busch et al., 2005).

Each participant performed both conditions (non-rotated and rotated), and in between each condition the participant stepped outside the room so the experimenter could set up the panel of cubes to ensure that the participant did not see the panel being rotated or see the numbers on the panel. The condition the participants started with, and the stimulus set the participant started with, were counterbalanced across participants and across sessions. A given participant had the same starting condition for both sessions, but the stimulus set used for the condition changed.

Prior to testing in each orientation condition, the participant was familiarized with the panels and task. The experimenter explained the relationship between the panels and gave verbal instructions followed by the practice blocks. The experimenter corrected any errors during the practice trials, and allowed more practice if the participant wanted.

During the experimental blocks the experimenter tapped the spatial sequence on their panel at a rate of about one cube/second. At the end of the sequence the experimenter place their hand back on the table, and the participant was then required to tap the same sequence on their panel, preserving the correct order and taking account the angle of rotation, if any. The experimenter did not give any corrections at this time. The participant had to correctly perform at least two out of the four sequences in each block in order to move on to the next block. The task ended if the participant failed three out of four sequences in a block or when they finished the eighth block. The task always ended after a block, meaning that the participants were tested on all four sequences in that block even if they failed to complete the first three sequences. Performance was scored live; a positive score was given if the participant correctly tapped the entire sequence. The raw score, the number of sequences correctly performed, and the span, the sequence length of the last block the participant completed, was recorded for the non-rotated and rotated versions.

Movement Span (MoveSpan). This task assesses working memory for observed actions. The version used was developed in Dr. Gail Ekes' lab at Dalhousie University (Heffernan, 2014) which modified the original version (Wood, 2007) to resemble the Operation Span task (Turner & Engle, 1989; Unsworth & Engle, 2005). The participants were required to memorize some simple actions while they simultaneously performed reaching movements to distract them. The task was presented on the computer screen and the participants were required to stand. The participant first read out loud a sentence describing a reaching movement (e.g., “Touch your left shoulder with your right hand”) and performed this movement. The participant then saw an avatar complete a to-be-remembered action (e.g., the avatar extended its left arm), which the participant was instructed not to copy. Following this, the participant was presented with another sentence with a reaching movement to perform, followed by another avatar action, and so on until the recall instructions. Figure 2 gives an example of a sequence with a length of two avatar actions. The participants were instructed not to remember the reaching movements they read and performed, but to remember the actions that they observed the avatar perform. When presented with the recall instructions, the participants were required to physically replicate the avatar actions in the order that they appeared. There were 2, 3, 4, or 5 avatar actions provided before the recall instructions. The participants were allowed to skip a movement by saying “I don’t know” and were allowed to start over, by verbally indicating they made a mistake.

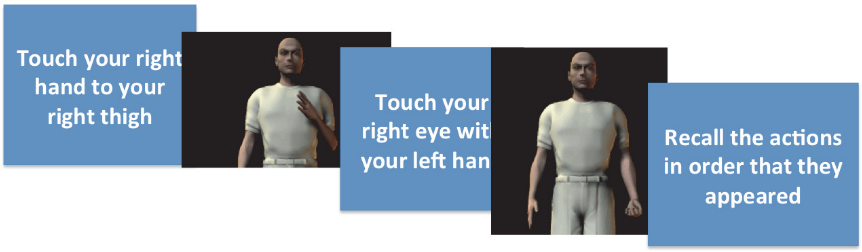


Figure 2. An example of a 2-length sequence trial in the MoveSpan task, the participant was required to read the reaching sentences out loud and perform the reaching movement, but did not have to remember theses movements. The participant was required to view the avatar performing an action, and memorize the action. When the participant saw the recall instructions, they had to physically replicate the avatar action in the order that they appeared.

The experimenter gave the participants verbal instructions before the start of the task followed by two practice trials, each with a length of three avatar actions. The experimenter gave verbal corrections and ensured the participants' understanding. The experimental trials consisted of 12 blocks, the length of the blocks (2, 3, 4, 5 avatar actions) were in a pseudorandom order, each length was presented three times. There were two sets of stimulus lists, one presented at the pre-learning session and one presented at the post-learning session, that differed in the order of the sentences and the avatar movements but kept the same pseudorandom order of block lengths. Each participant was scored live, and was also videotaped to confirm the scoring. Participants' overall performance (number of actions they performed correctly), number of blocks performed correctly, and the span (largest length of block correctly performed) were assessed. The task was presented on the computer via Python version 2.7.

Verbal Working Memory Tasks

Operation Span (Ospan). Participants performed an automated version of the Ospan task, which measures verbal working memory (Turner & Engle, 1989; Unsworth & Engle, 2005). This task involved memorizing letters while alternately performing simple math equations. Seventy-five mathematical equations that contained complex order of operations (i.e., [(2 * 6) + 1]) were generated. To make the questions relatively easy, the integers in the equations did not exceed 16 and the answers for each equation did not exceed 16. The target letter stimuli for this task were the following consonants: Y, Q, K, T, P, J, S, N, H, R, L, F. These letters were chosen because they are not vowels, and are visually and phonologically distinct from each other (i.e., the letter names do not rhyme, which could cause confusion). The amount of time that participants were allowed to view each equation depended on the amount of time spent during the practice blocks. The equation to derive the maximal time allowed viewing an equation was: mean amount of time + 2.5 times the standard deviation of that individual's times during practice.

Prior to beginning the Ospan task, participants received visual instructions as well as demonstrations on how to complete the task. Participants saw an equation that they had the mentally solve. After solving the equation, they used a mouse to click the screen and advance. Participants were then shown an integer and had to determine whether it was the correct answer for the previous equation. Participants indicated whether the answer was correct by clicking on either the "True" or "False" buttons located under the integer. In order to ensure that responses were collected, participants were provided with as much time as they required. After the response was recorded, a letter appeared on the screen for 800 ms. Participants were instructed that they must remember the letters that were displayed, and the order of the letters. At the end of each trial, participants were shown all 12 possible letters used in the task, and had to select (via mouse click) the correct letters in the proper order that they had been displayed. If participants did not remember a letter, they had an option to input a 'blank' letter to maintain the correct order. If a mistake was made, participants were also able to clear their responses and start over. Participants were instructed to try and maintain at least 85% accuracy for the mathematical equations.

Following the instructions and demonstration the participants performed a practice block, which involved accurately recalling three series of two letters. The participants were given feedback after every series. The participants then continued on with the experimental section. The experimental section was divided into five blocks; each block consisted of three series of these equation-letter pairs before advancing to the next block. Participants received feedback after every series. At the beginning of the task, participants were shown equation-letter pairs of length 3 (i.e., 3 equations and 3 letters); after each block the length of the letter span increased by one until eventually at the end of the task the participants saw equation-letter pairs of length 7. A participant's overall score was based on a sum of the number of consecutively correct letters over the duration of the experiment. The minimum score a participant could receive was zero while the maximum score was 75. The task was presented on the computer via Python version 2.7.

Verbal STM Tasks

The study used two digit span tasks and a random hand shape span task. Each task had a forward and reverse condition. The order that the participants performed the different versions of the task was: English, ASL, and then a non-ASL; the forward condition always preceded the reverse condition in each version. These tasks were presented on the computer via Python version 2.7.

Forward Digit Span – English. The participants viewed single digits flashed on the computer screen, in random order, and were required to recall the integers in the order that they appeared. The digits were from one to nine and were allowed to repeat but the same digit was never allowed to appear twice in a row.

Before the task began, the participants read the instructions and preformed four practice trials. The practice block contained two trials with the length of two digits, and two trials with the length of three digits. The digits appeared on the screen for 1000 ms, followed by a blank screen for 250 ms, then another digit. Following the last digit in the sequence the participant saw the digits 1-9 in a 3 by 3 grid on the screen, and used the mouse to choose the correct digits in the order they appeared. If participants did not remember a number, they had an option to input a 'blank' number to maintain the correct order. Participants were also able to clear their responses and start over if they felt they had made a mistake. Once the participant completed their answer, they clicked "Done" with the mouse and the next trial started. The participants were given feedback (correct or incorrect) during these practice trials. If the participant response was incorrect, the feedback also included the correct sequence.

Following the practice block, the participants continued with the rest of the task. The task started with a blank screen presented for 250 ms followed by a digit presented for 750 ms, followed by another 250 ms blank screen in between each digit. The task started with two trials with sequence length of two. The length of the sequence then increased by one and each length of sequence was presented twice. The task ended either when the maximum sequence length of nine was completed or when the participant could not complete the length of sequence (got both trials of that length incorrect). The participants' accuracy was recorded for each trial.

Reverse Digit Span – English. This task used the exact same procedure as the English forward digit span task, however the participants were instructed to recall the numbers in the reverse order in which they appeared. The participants still received instructions and four practice trials.

Forward and Reverse Digit Spans – ASL Signs. This task used the exact same procedure as the English forward and reverse digit spans, however instead of digits, participants saw line drawing images of the hand shapes representing the numbers 1-9 in ASL (Col, 1998). The answer keypad that the participants had to choose from were arrange the exact same way, in a 3 by 3 grid, with the hand shapes representing 1-9.

Forward and Reverse Digit Spans- random Hand shapes. This tasked used the exact same procedures as above, however instead of images of ASL hand shapes, random hand shapes that did not exist in ASL were taking from hand shapes that exist in German Sign Language (Hanke, 2000). These images were also line drawings of hand shapes and aesthetically looked very similar to the ASL images.

Mental Imagery Tasks

Three-dimensional Mental Rotation Task. This task measures the transformation and manipulation domain of mental imagery (Pearson et al., 2013). Participants received the same stimuli and performed the same protocol outlined in Ganis & Kievit (2015). This task required the participants to determine if two objects, presented on a computer screen, were the same or not. The objects were three-dimensional shapes made of blocks. Within one trial, the object on the left of the screen was always one of a set of 48 "baseline" objects. For trials in which the two objects were the same, the object on the right was identical to the baseline object but rotated around the vertical axis by 0 (i.e., unrotated; identical to the object on the left), 50, 100, or 150 degrees clockwise. For trials in which the objects were not the same, the object on the right was a mirror image of the object on the left, reversed along the vertical axis, and was rotated by 0, 50, 100 or 150 degrees. Examples of theses two types of trials can be seen in Figure 3.

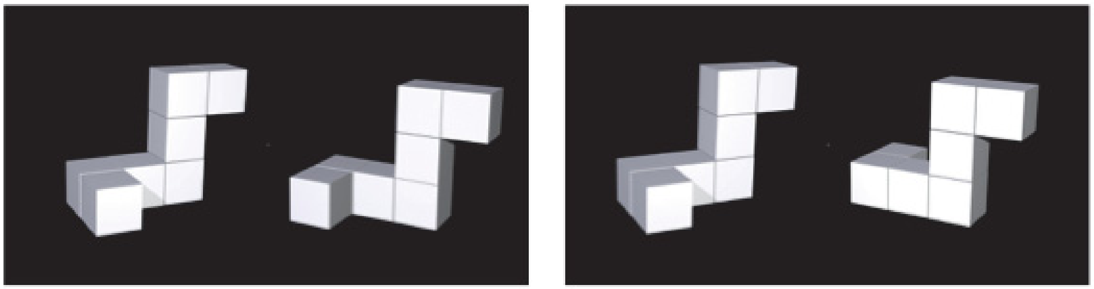


Figure 3. Examples of stimuli used in the mental rotation task. On the left is an example of a trial where the objects are the same, but rotated 50^0. On the right is an example of a trial where the objects are not the same and rotated 50^0. The participant would press the up arrow key for the stimulus on the left, and would press the down arrow key

Participants received visual instructions, a demonstration, followed by twelve practice trials. The participants received feedback, whether they were correct or incorrect, after each practice trial. The participants were instructed to press the up arrow key on the keyboard if the objects were the same, and the down arrow key on the keyboard if the objects were different. The participants were instructed to respond as fast as possible without sacrificing accuracy.

Following the practice block the participants then performed the experimental block, which consisted of 48 trials of object pairs. Each trial started with a 250 ms blank screen followed by an object pair stimulus. This stimulus was presented until the participants pressed one of the arrow keys or until time ran out. Participants had 7500 ms to respond and did not receive feedback. The 48 experimental trials were presented in random order, and were balanced to have equal amounts of same object and mirror object trials and equal amounts of degrees of rotation. Two different sets of stimuli were used, one for the pre-learning session and one for the post-learning session. Participants' reaction time and accuracy (correct or incorrect) for each trial were recorded via Python version 2.7.

Mental Clock Task. This task assessed participants' ability to generate mental images (Grossi, Modafferi, Pelosi, & Trojano, 1989; Paivio, 1978; Pearson et al., 2013). Participants saw a pair of digital times presented on a computer screen and were asked to imagine how each time would be represented on an analog clock, then to decide in which time the hands formed a larger angle.

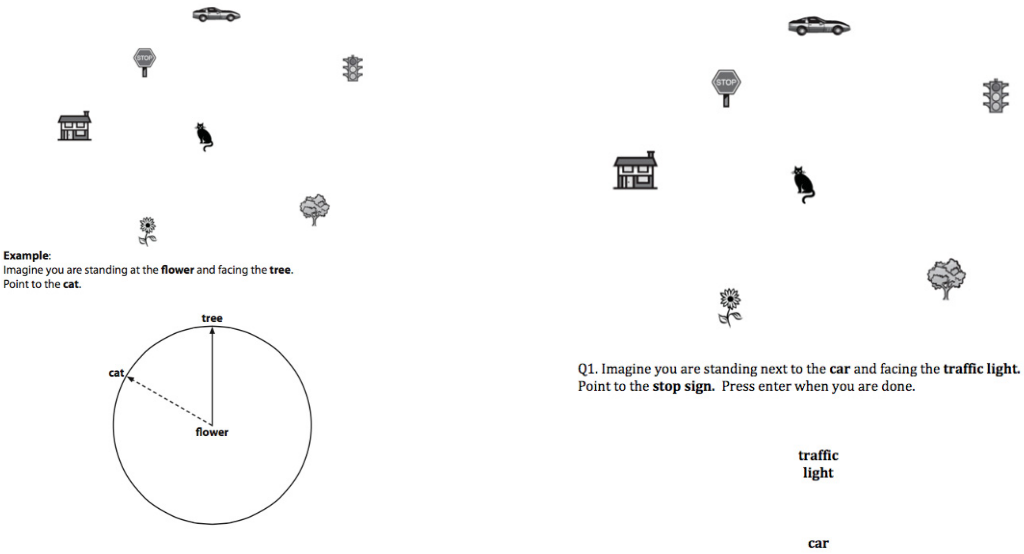
First the participants were presented with visual instructions and three practice trials. One digital time was presented on the left side of the screen and one was presented on the right side of the screen. When determining the angle of the hands, the participants were instructed to start at the top of the clock (in their mind) and move in a clockwise direction until they reach any hand (minute or hour) and then start to measure the angle. The digital times in the practice trials did not appear in the rest of the task. The participants were given feedback (correct or incorrect) and an image of the clocks with a red arrow showing the angle on each clock. The participants were instructed to press the left arrow if the time with the left side of the screen formed the larger angle, and the right arrow if the time with the larger angle was on the right side of the screen. The participants were asked to respond as fast as possible without sacrificing accuracy.

Following the practice trials the participants then performed the experimental trials. There were 32 pairs of digital times that contained only 0, 15, 30, or 45 minutes. Each trial started with a 500 ms blank screen, followed by a pair of digital times. The times displayed until the participant responded by pressing one of the arrows, or until 20 seconds passed.

The pairs of times were balanced for the angular difference between the two times (30^0, 60^0, 90^0, 120^0; Paivio, 1978). The time-pairs were also balanced for the side of the clock the hour and minute hand fell into: on equal numbers of trials, both hands were on the left side of the clock, both hands were on the right side of the clock, or the hands were on opposite sides of the clock. In half the trials the larger time (numerically) had the larger angle and the other half the smaller time had the larger angle (Luigi Trojano, Conson, Maffei, & Grossi, 2006; Luigi Trojano et al., 2004; Sack, Camprodon, Pascual-Leone, & Goebel, 2005). The time-pairs were presented in a random order. The participants' reaction time and accuracy (correct or incorrect) for each trial were recorded via Python version 2.7.

Orientation and Perspective Abilities

Perspective Taking/Spatial Orientation Task (PTSOT). Participants performed a modified version of the paper and pencil PTSOT (Hegarty & Waller, 2004). Participants saw a picture of an array of objects and were ask a question about the direction between some of those objects. The participants were instructed to imagine they were standing at one object in the array and facing another object. Their task was to point to a third object in the array while in that imagined facing orientation. The original version of this task had the participants draw a vector on a circle. Figure 4 shows an example of a question in this task. Each question had the picture of the array of objects and a circle below it. The object they had to imagine that they were standing next to was in the center of the circle, and the object they were facing was on the top of the circle.



Example:
Imagine you are standing at the **flower** and facing the **tree**.
Point to the **cat**.

Q1. Imagine you are standing next to the **car** and facing the **traffic light.**
Point to the **stop sign.** Press enter when you are done.

Figure 4. On the left is the example question for the original Perspective Taking/Spatial Orientation task (PTSOT) from Hegarty and Waller (2004). On the right is an example of what a participant in this study saw on the computer screen during the computerized version of the PTSOT.

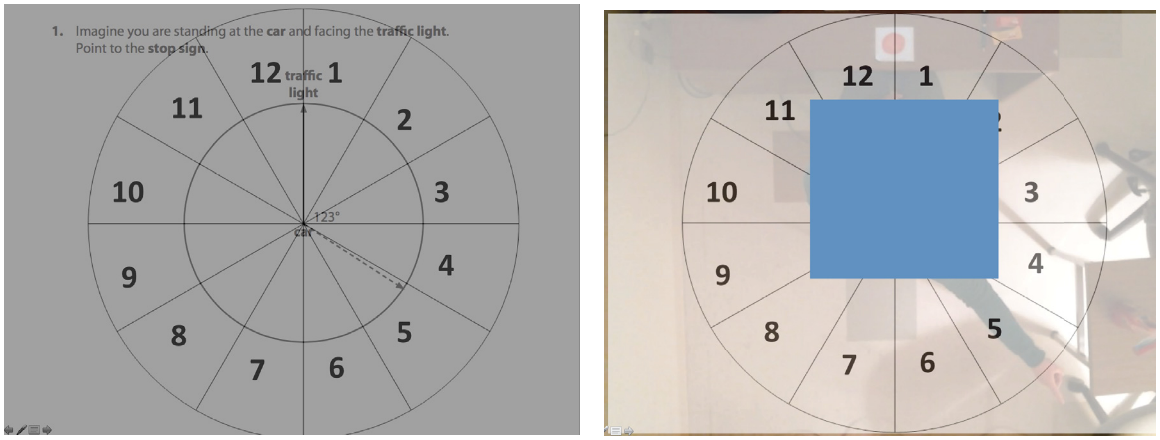
The version used in this study was computerized. Instead of drawing a line vector, the participants were required to physically point in the room, while a camera above videotaped them. This version had the same picture of the array of objects and the same 12 questions as the original. However, instead of a circle below the array of objects, there were two words, the word at the bottom of the screen was the object they were standing next to, and the word above it was the object they were facing, Figure 4 shows an example a question presented on the computer screen. This version also contained very similar instructions to the original version. However, the participant was also required to read the question out loud before they pointed because this helped the experimenter score the videos. Just like the original version, the participants were informed that they only had five minutes to complete 12 questions.

To set up this task, the camera that was attached to the ceiling was turned on in order to get a birds-eye view of the participant. The participants moved their chair to a pre-determined spot so it was in the center of the camera's view (this spot was the same for all participants). There was a large red dot on the table in front of the participant to serve as a marker when the video was later scored.

Before the task started, the participant read the instructions on the screen and the experimenter supplemented with verbal explanations. The participant saw an example (the same example used in the original version), and the participants attempted to point in the correct direction. The experimenter was present to ensure the participant understood, and to give any corrections. The experimenter instructed the participant to keep their head pointing forward and to only imagine him or herself in the picture and not to physically twist into the facing orientation before they pointed. The experimenter also instructed the participant to point with a straight-arm and straight wrist (which help when assessing the videos later). The participant was allowed to point with either hand and was allowed to twist a bit to point backwards. If they made a mistake, the participant could say, "That was wrong", and point again.

After the instructions and the example the experimenter left the room, and the participant started the task by pressing the Enter key on the keyboard. The timer started at this time. For each question, the picture of array of object was at the top of the screen, the question was in the middle, and the two words were at the bottom of the screen. The participant read the question out loud, pointed, and then pressed enter on the keyboard to see the next question. The test ended when the participant finished the last question or after five minutes.

To score this task, the experimenter and a group of volunteers took images of the participants pointing after each question in their videos. These images were overlaid with a 12-section pie chart. The top of the pie chart was place over the red marker on the table, and the center of the chart was aligned over of the participant's head or body. An example of a correct answer the first question of this task can be seen in Figure 5. Whatever section the participant's hand or arm fell in was their answer. The participants received a score based on the absolute deviation from the correct section. For example if the participant's arm was in the first section, and the correct section was 12, the participant receive a score of 1. A score of zero would mean the participant's answer matched the correct section. The participant received a score of 3 if they did not complete a question (i.e., chance performance, since the absolute sectional deviation can range from 0 to 6; Kozhevnikov & Hegarty, 2001). The participants' total score was the sum of all trials, where a lower score was a better performance. This task was presented via Python version 2.7. Due to the time required to manually score this test, the data from this task was not available at the time of writing. Therefore, the results from this task will not be presented in this thesis.


1. Imagine you are standing at the car and facing the traffic light. Point to the stop sign.

[redacted]

Figure 5. An example of the scoring method used to score the PTSOT videos. The image on the left is the answer to the first question (Hegarty & Waller, 2004) overlaid with a 12-section pie chart. The correct section for question one is 5. The picture on the right is an example of a participant pointing for the first question. This participant's hand fell into the correct section and would receive a score of zero.

Data Analysis

Research question 1 – Does ASL instruction improve visual-spatial cognition? I compared the participants' performance on the ASL proficiency tests and the cognitive tasks across sessions and between groups. I used generalized linear mixed effect modeling (GLMM) with a logit link function, using the lme4 package in R (Version 3.3; Bates, Maechler, Bolker, & Walker, 2015), to analyze the binary accuracy data of each trial in the ASL proficiency tests, the mental imagery tasks, and digit span tasks. In the model, subjects were specified as a random factor and contained a binomial error.

The reaction time data of the mental imagery tasks (for every trial), the raw scores and spans of the working memory tasks, and the final score of the Ospan task, were analyzed using linear mixed-effect modeling (LMM) using the lme4 package in R, where subjects were treated as a random factor. Before analyzing the data, I used the LMERConvenienceFunctions package (Tremblay & Ransijn, 2015) to identify and remove any outliers that fell more then 2.5 standard deviations above or below the residuals mean. The LMERConvenienceFunctions package was also used to obtain an ANOVA summary and to perform planned and post-hoc pairwise comparisons using *t*-tests. Effect sizes were calculated by using a spreadsheet developed by Lakens (2013).

Research question 2 – Can visual-spatial cognition predict ASL proficiency? To address the second research question — how pre-existing visual-spatial cognitive abilities are related to ASL proficiency — I examined only the ASL group. I investigated the relationship between the participants' pre-learning session scores, and the participants' change in performance on the ASL Naming and ASL Recognition test across sessions. I chose to examine four pre-learning scores: 1) non-rotated Corsi raw score, 2) MoveSpan raw score, 3) average reaction time on the mental rotation task, 4) Ospan score. These measures were chosen as a representative of a specific skill. The Corsi and MoveSpan score both represent visual-spatial memory, however the MoveSpan task is specific to observed actions, which may predict ASL scores differently than the Corsi tasks. Therefore I included both tasks. The mental clock tasks represent mental imagery and the Ospan task represents verbal memory.

I created models using generalized additive mixed modeling (GAMM) with a binomial logit link function using the mgcv package in R (Wood, 2011). I created 15 models that contained the ASL proficiency tests' individual trial accuracy data by different combinations of the four variables' interaction with session as fixed factors and subjects as a random factor. The 15 models capture all possible combination of the four variables' interaction with session. Table 3 shows the models, where M0 is the most complex model containing all variable by session interactions and M15 is the least complex model, containing only the main effect of session. These models were compared using the Akaike's Information Criterion (AIC; Alaike, 1973). I used the methods discussed in Wagenmakers and Farrell (2004) to obtain the differences in AIC scores of the models with respect to the lowest AIC observed (deltaAIC). Using the deltaAIC score I calculated the Akaike weights for each model (w_i, calculated as the model likelihood normalized by the sum of all model likelihoods*)*. The Akaike weight is a measure of the strength of evidence for each model and is the probability that the model is the best model. Additionally, the ratio of the weights between two models can indicate the magnitude of how more likely one model is compared to the other model. Using this method, I calculated the ratio between the models' weights and the weight of the model with the lowest AIC, to examine how better suited the model with the lowest AIC is compared to the other models. The delta AIC scores, Akaike weights, and weight ratios were used to decide which model was more likely, and also determine which variables were more likely to predict to the changes in ASL test scores.

Table 3. GAMM models used in the second research question for both the ASL naming and the ASL recognition test, subjects were a random factor for all models.

Model #	Model
M0	Accuracy ~ Session × Rotation + Session × Corsi + Session × MoveSpan + Session × Ospan
M1	Accuracy ~ Session × Rotation + Session × Corsi + Session × Movespan
M2	Accuracy ~ Session × Rotation + Session × Corsi + Session × Ospan
M3	Accuracy ~ Session × Rotation + Session × MoveSpan + Session × Ospan
M4	Accuracy ~ Session × Corsi + Session × MoveSpan + Session × Ospan
M5	Accuracy ~ Session × Rotation + Session × Corsi
M6	Accuracy ~ Session × Rotation + Session × MoveSpan
M7	Accuracy ~ Session × Rotation + Session × Ospan
M8	Accuracy ~ Session × Corsi + Session × MoveSpan
M9	Accuracy ~ Session × Corsi + Session × Ospan
M10	Accuracy ~ Session × MoveSpan + Session × Ospan
M11	Accuracy ~ Session × Rotation
M12	Accuracy ~ Session × Corsi
M13	Accuracy ~ Session × Movespan
M14	Accuracy ~ Session × Ospan
M15	Accuracy ~ Session

Chapter 3: Results

Question One - Does ASL instruction improve visual-spatial cognition?

Table 4 provides the means and standard deviations to summarize the performance of the ASL group and control group for each session on each task.

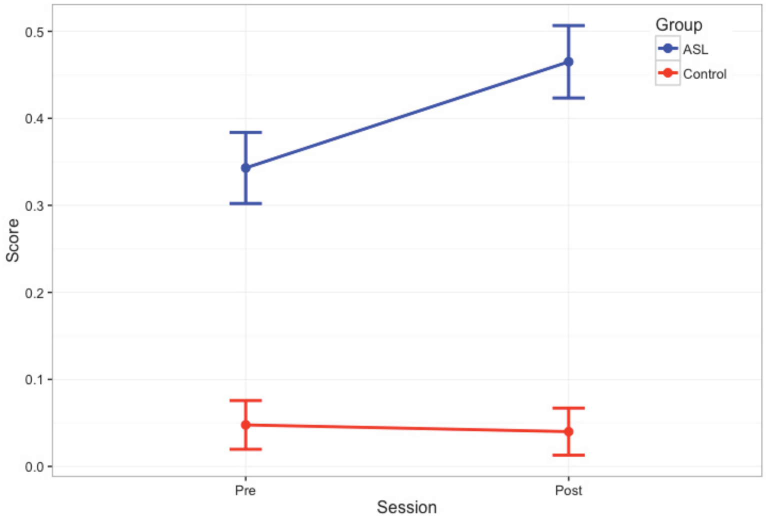
Table 4. Means and standard deviations between groups and across sessions for each cognitive task and ASL proficiency test.

Task	Measure	Session	Group	
			ASL M (SD)	Control M (SD)
Clock Task	RT	Pre	7.10 (1.82)	7.61 (1.84)
		Post	6.72 (1.73)	5.55 (1.05)
	Accuracy	Pre	0.72 (0.1)	0.73 (0.09)
		Post	0.77 (0.14)	0.79 (0.11)
Rotation Task	RT	Pre	3.02 (0.79)	2.94 (0.73)
		Post	2.65 (0.92)	2.47 (0.58)
	Accuracy	Pre	0.74 (0.23)	0.83 (0.17)
		Post	0.76 (0.25)	0.86 (0.11)
Nonrotated Corsi	Span	Pre	5.13 (1.39)	5.6 (1.26)
		Post	5.36 (1.22)	5.00 (1.10)
	Raw	Pre	19.09 (5.10)	20.30 (4.50)
		Post	20.54 (4.36)	19.09 (4.13)
Rotated Corsi	Span	Pre	2.80 (1.00)	3.36 (1.02)
		Post	2.71 (1.16)	3.36 (1.03)
	Raw	Pre	9.60 (3.79)	10.91 (2.39)
		Post	9.49 (4.12)	11.36 (3.59)
MoveSpan	Span	Pre	3.32 (0.75)	3.63 (0.51)
		Post	3.80 (0.76)	3.63 (0.81)
	Raw	Pre	23.28 (5.04)	24.82 (4.17)
		Post	25.28 (5.83)	26.36 (6.41)
Ospan	Completed Blocks	Pre	4.76 (2.01)	5.09 (1.30)
		Post	5.48 (1.58)	5.27 (1.68)
	Score	Pre	49.87 (18.72)	51.64 (12.10)
		Post	51.67 (20.10)	59.36 (12.79)
English Digit Span	Forward Total Score	Pre	10.40 (2.00)	9.45 (2.21)
		Post	9.92 (2.04)	9.81 (1.89)
	Reverse Total Score	Pre	8.38 (2.48)	8.00 (2.04)
		Post	8.63 (2.75)	7.81 (1.99)

Task	Measure	Session	Group	
			ASL M (SD)	Control M (SD)
ASL Digit Span	Forward Total Score	Pre	4.04 (2.4)	3.55 (2.07)
		Post	5.52 (2.20)	4.27 (2.32)
	Reverse Total Score	Pre	4.21 (2.36)	2.64 (1.80)
		Post	4.68 (2.59)	3.73 (1.79)
Random Hanshape Digit Span	Forward Total Score	Pre	2.35 (1.58)	2.09 (1.76)
		Post	2.5 (1.44)	3.27 (2.10)
	Reverse Total Score	Pre	2.77 (2.29)	2.91 (2.21)
		Post	2.96 (1.65)	2.82 (2.40)
ASL Naming Test	Accuracy	Pre	0.34 (0.11)	0.05 (0.03)
		Post	0.47 (0.17)	0.04 (0.03)
ASL Recognition Test	Accuracy	Pre	0.67 (0.09)	0.45 (0.08)
		Post	0.75 (0.09)	0.48 (0.10)

ASL Naming (Recall) Test. There were significant effects of session, $F(1,2839) = 33.01$, $p < .001$, $\eta^2 = 0.01$, group, $F(1,2839) = 111.79$, $p < .001$, $\eta^2 = 0.03$, and a significant interaction between session and group, $F(1,2839) = 4.27$, $p < .05$, $\eta^2 = 0.002$. I performed post-hoc *t*-test, with a Bonferroni adjusted *p* value of 0.025, controlling for two tests, either between two groups or two sessions. As shown in Figure 6, the ASL group had higher scores than the control group at the pre-learning session, $p < .001$, and at the post-learning session, $p < .001$. The performance of the ASL group increased from the pre-learning session to the post-learning session, $p < .001$, but the performance of the control group did not significantly change, $p = 0.55$.

Figure 6. Analysis of the ASL Naming test across group and session revealed a significant effect of session, $F(1,2839) = 33.01$, $p < .001$, group, $F(1,2839) = 111.79$, $p < .001$], and interaction, $F(1,2839) = 4.27$, $p < .05$]. ASL group's score increased from the pre-testing session to the post testing session, $p < 0.01$. Error bars are 95% CIs[3].



ASL Recognition Test. There was a significant main effect of session, $F(1,2799) = 14.99$, $\eta^2 = 0.01$ reflected an overall improvement in scores, and a significant effect of group, $F(1,2799) = 89.23$, $p < .001$, $\eta^2 = 0.03$, but no significant interaction between session and group. However, because I predicted a priori that the control group would not improve on the ASL proficiency test, and the ASL group would improve, I did a planned *t*-test for each group across sessions. As shown in Figure 7, the evidence supports the hypothesis that ASL group's score improved from the pre-learning session to the post-learning session, $p < .001$, but the control group did not change, $p = .28$ significantly.

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[3] Confidence intervals for Figure 6 – Figure 15 were produced using the standard error of the mean and used the Morey (2008) correction to the standard error and confidence interval for within subject variables

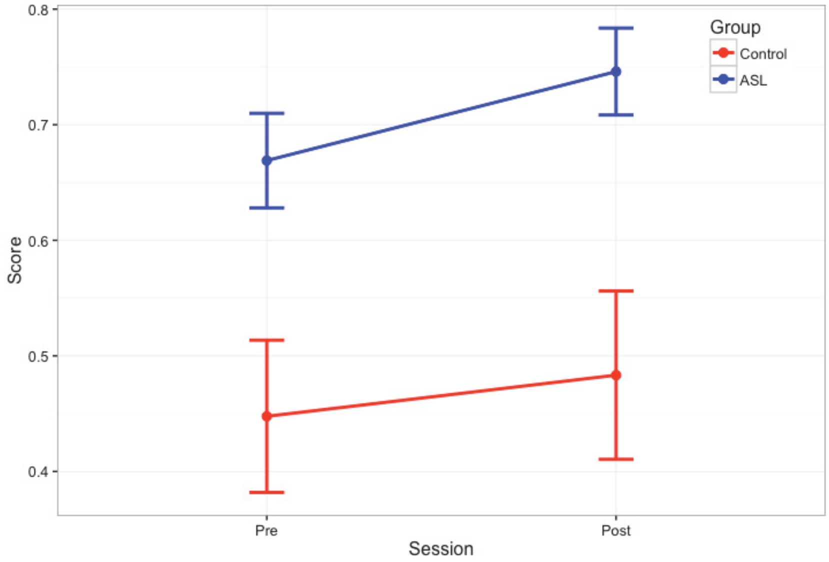


Figure 7. Group by session analysis for the ASL Recognition Test. Effect of session, $F(1,2799) = 14.99$, $p < 0.001$, and effect of group, $F(1,2799) = 89.23$, $p < 0.001$, but no significant interaction. A priori planned *t*-tests revealed that the ASL group improved from the pre-learning to the post learning session, $p < .001$, but the control group did not change significantly, $p = .28$. Error bars are 95% CIs.

Corsi Block-Tapping Task (non-rotated and rotated). I examined the raw score (number of sequences the participant correctly performed) and the span (longest length the participant were able to perform correctly) for both the non-rotated and rotated versions. Figure 8 shows the results of the non-rotated span score. There was a significant interaction between the session and group, $F(1,30) = 5.07$, $p < .05$, $\eta^2 = 0.14$, however post-hoc tests with a Bonferroni adjusted *p* value of 0.025, controlling for two tests, either between two groups or two sessions, revealed no significant differences between groups or across sessions.

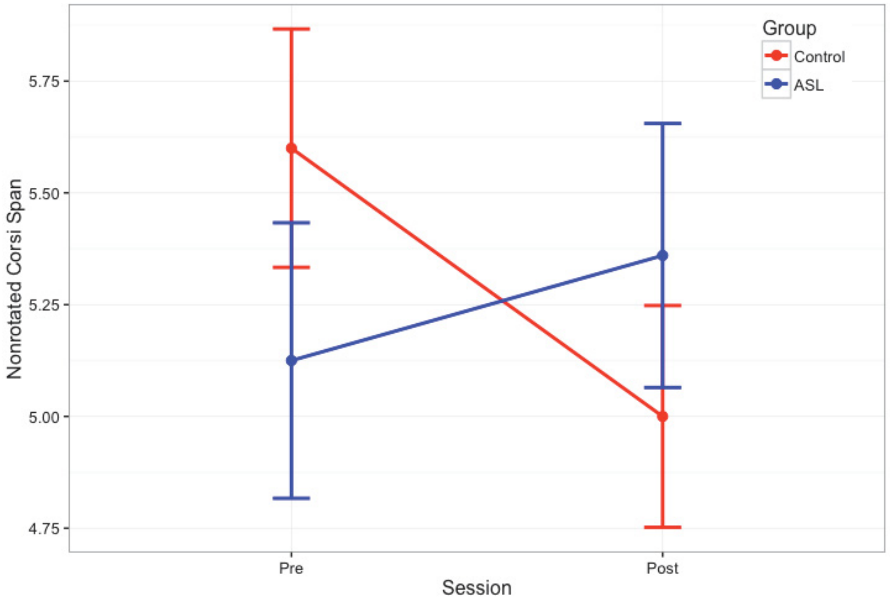


Figure 8. Significant group by session interaction in the span score of non-rotated version of the Corsi block-tapping task, $F(1,30) = 5.07$, $p < .05$], post-hoc tests revealed no group or session difference. Error bars are 95% CIs.

Figure 9 shows that the non-rotated raw score also had a significant interaction between session and group, $F(1,28) = 7.82$, $p < .01$, $\eta^2 = 0.22$. Post-hoc *t*-tests, with a Bonferroni adjusted *p* value of 0.025, controlling for two tests, either between two groups or two sessions, revealed that the ASL group improved from the pre-learning session to the post-learning session, $p < .01$, however the control group's raw score did not change significantly between sessions, $p = .20$. There were no significant effects in the rotated Corsi block-tapping task.

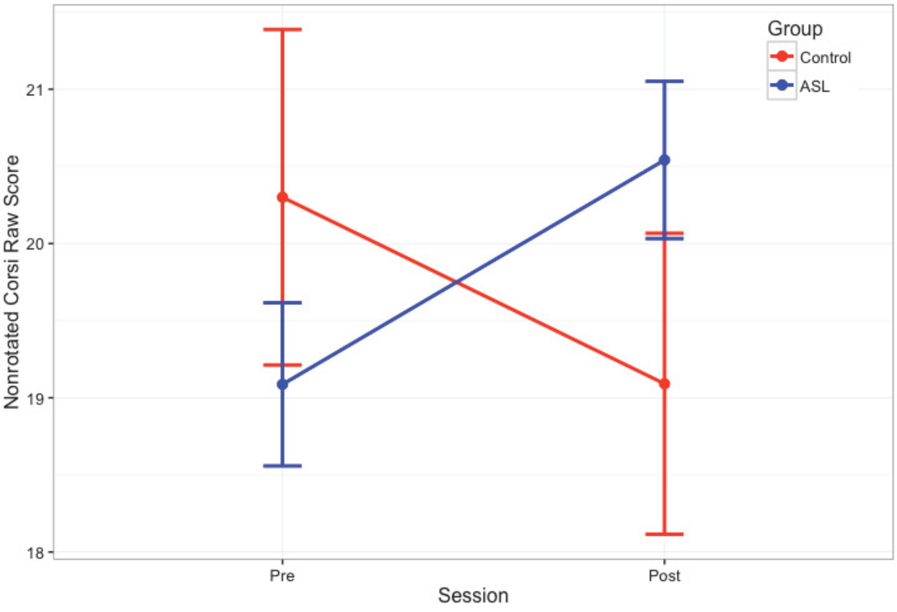


Figure 9. Significant group by session interaction for the raw score of the non-rotated version of the Corsi block-tapping task, $F(1,30) = 5.07$, $p < .05$. ASL group's score increased from pre to post session, $p < .01$. Control group did not change significantly, $p = .20$. Error bars are 95% CIs.

MoveSpan. I examined the span (highest length of actions remembered), the raw score (number of actions correctly remembered), and the number of completed blocks. There was a significant effect of session for all three measures: the span, $F(1,32) = 7.46$, $p < .05$, $\eta^2 = 0.19$ the raw score, $F(1,32) = 7.59$, $p < .01$, $\eta^2 = 0.19$ number of completed blocks, $F(1,32) = 4.46$, $p < .05$, $\eta^2 = 0.12$ respectively. There were no significant effects of group or significant interactions between group and session for any of the scores. However, because I predicted a priori that the ASL group would improve more than the control group I performed a planned *t*-test for each group across session, for each score. As shown in Figure 10, Figure 11, and Figure 12, there were overall higher scores in the post-learning session. The *t*-test results supports the hypothesis that ASL group would improve but the control group would not improve. The ASL group's span score, $p < .01$, raw score, $p < .05$, and number of completed blocks, $p < .05$ increased from the pre-learning session to the post-learning session but the control group's span score, $p = 0.5$, raw score, $p = .1$, and number of completed blocks, $p = .37$, did not change significantly.

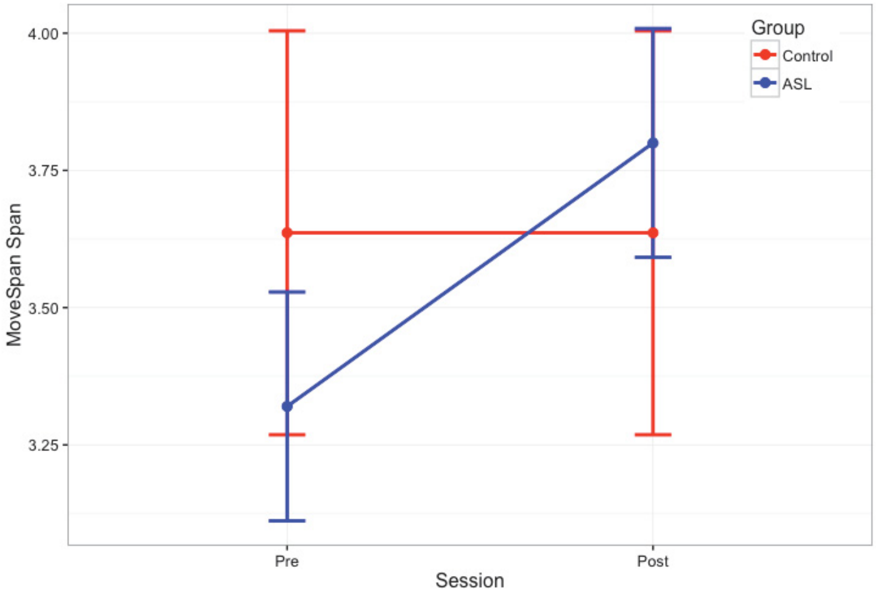
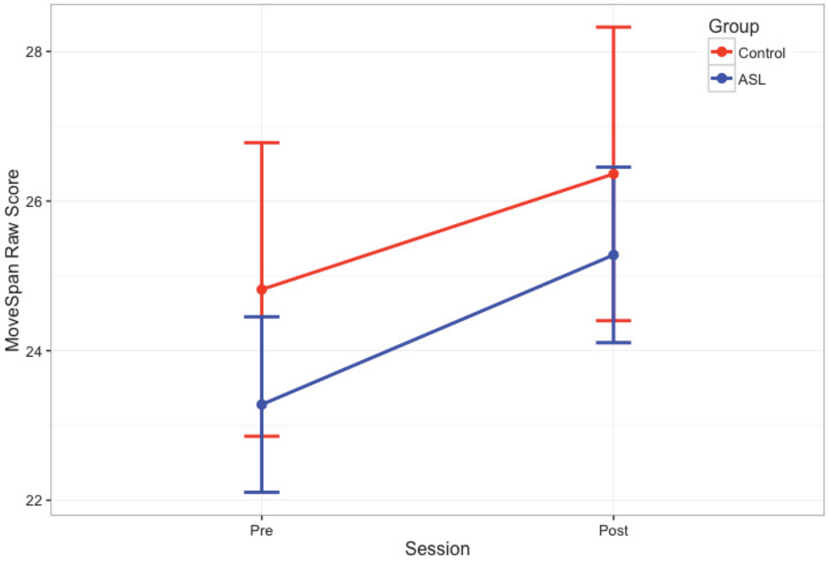


Figure 10. There was a significant effect of session in the MoveSpan span score, $F(1,32) = 7.46$, $p < .05$. Planned contrasts revealed that the ASL group increased from the pre-learning session to the post learning session, $p < .01$, but the control group did not change significantly, $p = .50$.

Figure 11. There was a significant effect of session in the MoveSpan raw score, $F(1,32) = 7.59$, $p < .01$. Planned contrasts revealed that the ASL group increased from the pre-learning session to the post learning session, $p < .05$, but the control group did not change significantly, $p = .10$.



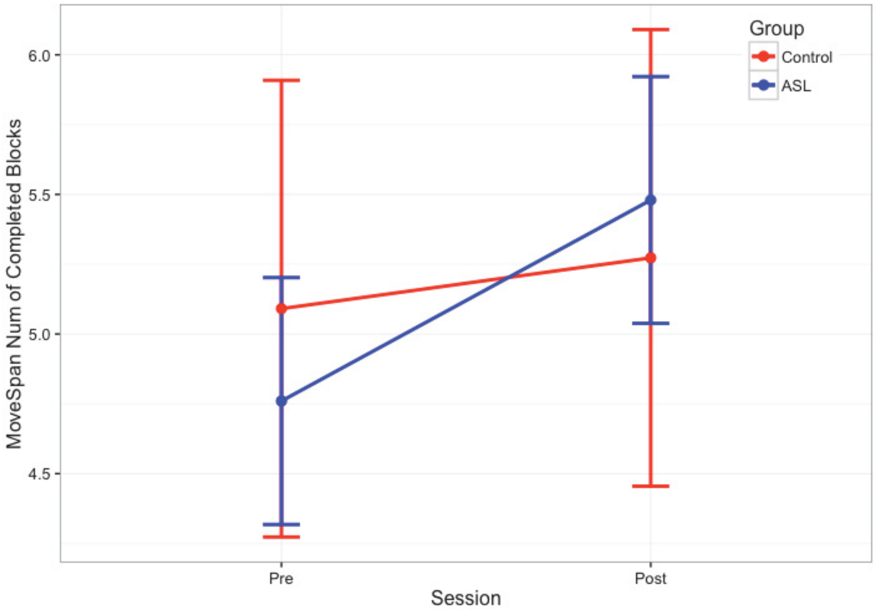


Figure 12. There was a significant effect of session in the MoveSpan number of completed blocks, $F(1,32) = 4.46$, $p < .05$. Planned contrasts revealed that the ASL group increased from the pre-learning session to the post learning session, $p < .05$, but the control group did not significantly change, $p = .37$.

Ospan. There was a significant effect of session, $F(1,30) = 5.44$, $p < .05$, $\eta^2 = 0.15$, but no significant effect of group. Figure 13 shows an overall increased in scores. I did not have any specific a priori predictions about the groups change in score so I did not perform any planned *t*-tests.

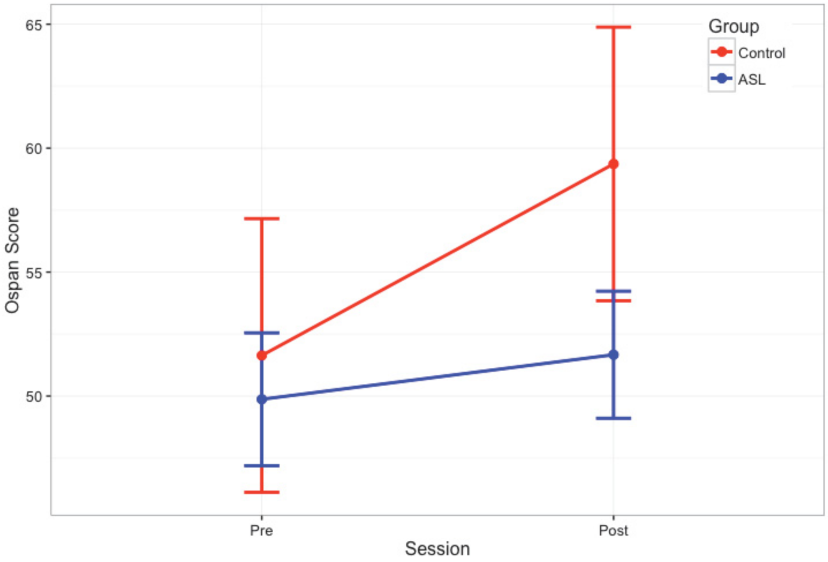


Figure 13. There was a significant effect of session in the Ospan final score, $F(1, 30) = 5.44$, $p < .05$].

Digit Span Tasks. There were no significant effects in any of the digit span tasks, English, ASL, non-ASL (forward or reverse).

Three-dimensional Mental Rotation Task. There were no significant effects in the accuracy data. There was an effect of session for the reaction time data, $F(1,3300) = 79.60$, $p < .001$, $\eta^2 = 0.02$, but no significant effect of group or significant interaction between group and session. As shown in Figure 14, the main effect of session revealed overall faster reaction times in the post-learning session. Furthermore, because I predicted that the ASL group would change more than the control group, I did a planned *t*-test contrast between sessions for both groups. The evidence failed to support the hypothesis that the ASL experience enhances mental rotation abilities as both the ASL group, $p < .001$, and the control group, $p < .001$, had faster reaction times in the second session.

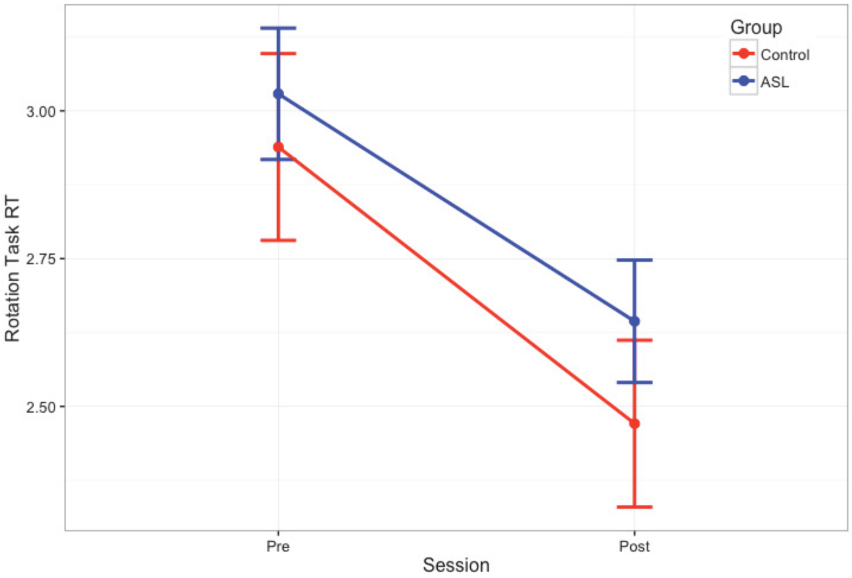


Figure 14. There was a significant effect of session in reaction time (RT) of the Mental Rotation task, $F(1,3300) = 79.60$, $p < .001$]. Planned contrasts revealed that both the ASL group, $p < .001$, and the control group, $p < .001$, decreased their RTs. Error bars are 95% CIs.

Mental Clock Task. There were no significant effects in the accuracy data. As shown in Figure 15, the main effect of session reflected the fact that both groups had faster reaction times in the post-learning session, $F(1,2203) = 46.00$, $p < .001$, $\eta^2 = 0.02$ and the group and the session significantly interacted, $F(1,2203) = 33.40$, $p < .001$, $\eta^2 = 0.01$. Post-hoc *t*-tests, with a Bonferroni adjusted *p* value of 0.025, controlling for two tests, either between two groups or two sessions, revealed that the control group's reaction times decreased, $p < .001$, and the ASL group's reaction times also decreased, p = .015, although the magnitude of change was somewhat less than the controls.

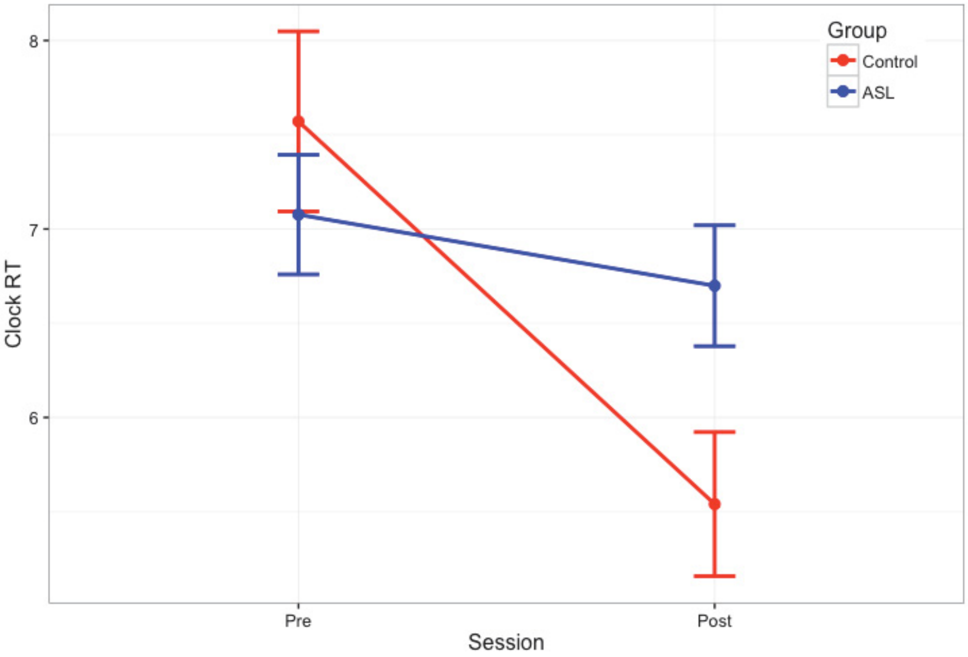


Figure 15. There was a significant effect of session in reaction time (RT) of the Mental Clock task, $F(1,3300) = 79.60$, $p < .001$, and a significant interaction, $F(1,2203) = 33.40$, $p < .001$], were the RT both the control group, $p < .001$ and the ASL group decreased, $p < .05$. Error bars are 95% CIs

Question 2 – Can visual-spatial cognition predict ASL proficiency?

To examine if pre-existing visual-spatial skills could predict ASL proficiency, I analyzed the relationship between the ASL participants' pre-learning performance on a subset of the cognitive tasks, and their change in accuracy on the ASL Recognition and ASL Naming tests. The interaction between session and each of four pre-learning cognitive scores — non-rotated Corsi raw, MoveSpan raw, average reaction time of the rotation task, and Ospan — were combined in 15 GAMM models. Table 5 and Table 6 gives the delta AIC, Akaike weights (w_i,) and weight ratio (which reflects much more likely the model with the lowest AIC is to be the best model, compared to other models), for the ASL Naming and ASL recognition task respectively. The tables are arranged from the model with the lowest AIC, or most likely model, to the model with the highest AIC, or least likely model.

Table 5. Using AIC to compare models predicting ASL participants' change in ASL naming test scores.

Model	Variable * Session Interaction included	delta AIC	*wi* (AIC)	Weight Ratio
M5	Rotation RT, Non-rotated Corsi Raw	0.00	0.31	1.00
M11	Rotation RT	2.18	0.11	2.98
M2	Rotation RT, Non-rotated Corsi Raw, Ospan	2.24	0.10	3.06
M1	Rotation RT, Non-rotated Corsi Raw, Movespan Raw	2.39	0.09	3.30
M6	Rotation RT, Movespan Raw	2.63	0.08	3.72
M7	Rotation RT, Ospan	2.92	0.07	4.30
M12	Non-rotated Corsi Raw	3.19	0.06	4.94
M0	Rotation RT, Non-rotated Corsi Raw, Movespan Raw, Ospan	4.43	0.03	9.17
M3	Rotation RT, Movespan Raw, Ospan	4.59	0.03	9.92
M8	Non-rotated Corsi Raw, Movespan Raw	4.75	0.03	10.76
M9	Non-rotated Corsi Raw, Ospan	5.37	0.02	14.62
M15	No variables (main effect of session)	6.01	0.02	20.16
M4	Non-rotated Corsi Raw, Movespan Raw, Ospan	6.41	0.01	24.65
M14	Ospan	6.76	0.01	29.36
M13	Movespan Raw	7.66	0.01	46.15
M10	Movespan Raw, Ospan	8.88	0.00	84.90

Table 6. Using AIC to compare models predicting ASL participants' change in ASL Recognition test scores.

Model	Variable * Session Interaction included	delta AIC	*wi* (AIC)	Weight Ratio
M11	Rotation RT	0.00	0.19	1.00
M15	No variables (main effect of session)	0.61	0.14	1.36
M8	Non-rotated Corsi Raw, Movespan Raw	1.15	0.11	1.78
M6	Rotation RT, Movespan Raw	1.97	0.07	2.68
M1	Rotation RT, Non-rotated Corsi Raw, Movespan Raw	2.03	0.07	2.75
M13	Movespan Raw	2.29	0.06	3.14
M5	Rotation RT, Non-rotated Corsi Raw	2.38	0.06	3.29
M12	Non-rotated Corsi Raw	2.41	0.06	3.34
M7	Rotation RT, Ospan	2.44	0.06	3.38
M14	Ospan	2.89	0.05	4.24
M9	Non-rotated Corsi Raw, Ospan	3.59	0.03	6.02
M2	Rotation RT, Non-rotated Corsi Raw, Ospan	3.95	0.03	7.21
M4	Non-rotated Corsi Raw, Movespan Raw, Ospan	3.96	0.03	7.25
M3	Rotation RT, Movespan Raw, Ospan	4.94	0.02	11.83
M0	Rotation RT, Non-rotated Corsi Raw, Movespan Raw, Ospan	4.95	0.02	11.88
M10	Movespan Raw, Ospan	5.15	0.01	13.12

As shown in Table 5, the most likely model (M5) contained the interaction between sessions and reaction times of the mental rotation task, which was significant in this model, χ^2 (1, N=2000) = 4.32, $p < 0.05$, and the interaction between sessions and the non-rotated Corsi raw scores, χ^2 (1, N=2000) = 3.60, p = 0.06. Figure 16 shows the partial effect of the interaction between session and mental rotation task reaction times in M5. The longer the participants took on the mental rotation task, the larger the improvements between the participants' ASL Naming test scores. Figure 17 shows the partial effect of the interaction between session and the non-rotated Corsi raw scores in M5. The ASL participants' raw scores show a positive relationship with the ASL participants' change in ASL Naming test scores.

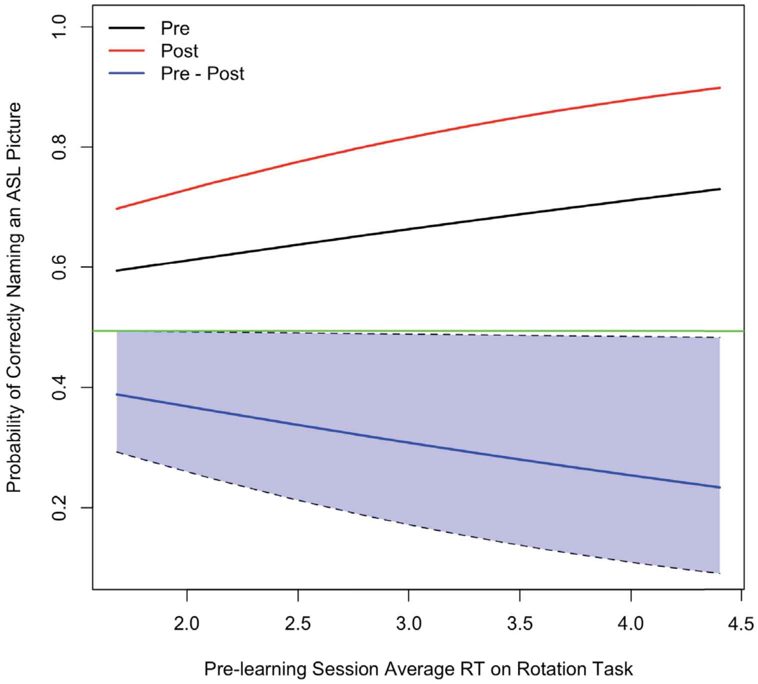


Figure 16. The relationship between the ASL participants' pre-learning session average reaction time (RT) on the mental rotation task and the change in their performance on the ASL Naming test. The shaded blue area represents 95% CI's of the relationship between the RTs and the difference in ASL naming scores between the pre-learning and post-learning sessions. The green line represents the slope of the null hypothesis, or no relationship between the RT and session.

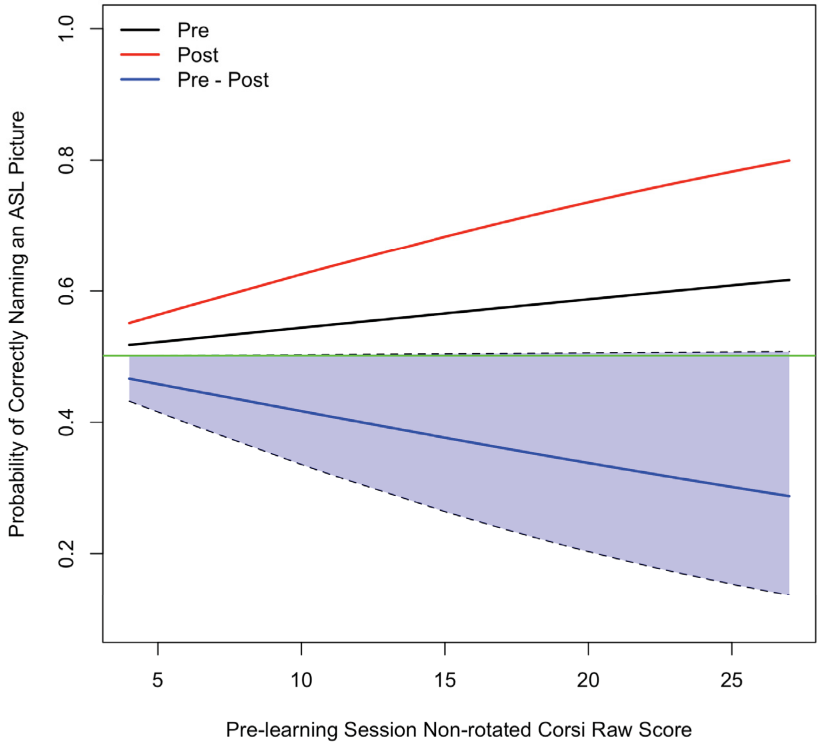


Figure 17. The relationship between the ASL participants' pre-learning session non-rotated Corsi raw score and the change in their performance on the ASL Naming test. The shaded blue area represents 95% CI's of the relationship between the Corsi scores and the difference in ASL naming scores between the pre-learning and post-learning sessions. The green line represents the slope of the null hypothesis, or no relationship between the Corsi score and session.

Turning to the ASL recognition test, Table 6 shows that the most likely model (M11) contained the interaction between sessions and the participants' average reaction times on the mental rotation task. Just as in the ASL Naming test, Figure 18 shows that the longer the participants took on the mental rotation task, the larger the improvements between the participants' ASL Naming recognition scores. This interaction, however, was not significant, χ^2 (1, N=2000) = 1.44, p = 0.23. The next best model in Table 6 is (M15) contained only the main effect of session and no predictor variables.

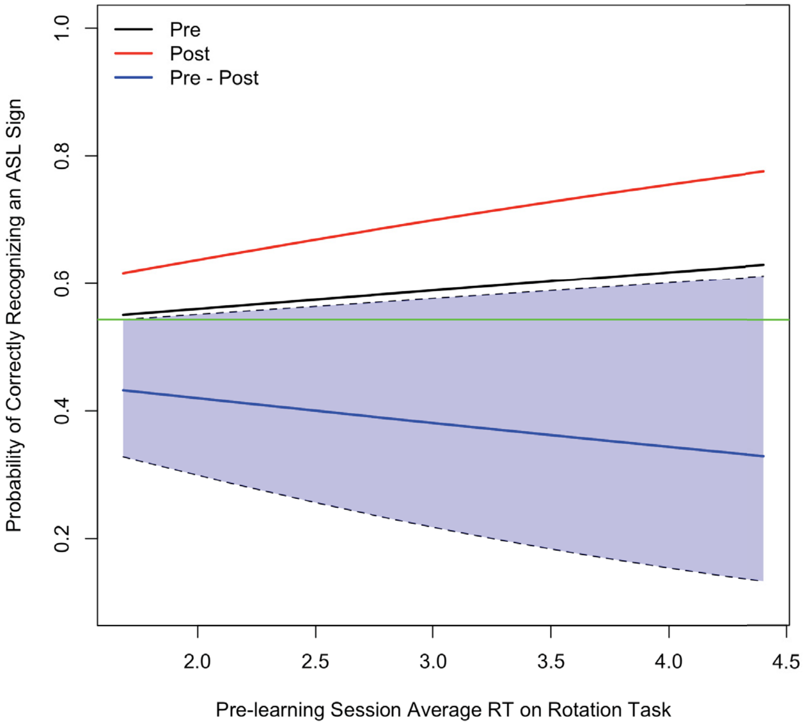


Figure 18. The relationship between the ASL participants' pre-learning session average reaction time (RT) on the mental rotation task and the change in their performance on the ASL Recognition test. The shaded blue area represents 95% CI's of the relationship between the RTs and the difference in ASL recognition scores between the pre-learning and post-learning sessions. The green line represents the slope of the null hypothesis, or no relationship between the RT and session.

Chapter 4: Discussion

This study was one of the first to investigate visual-spatial cognition in adults as they began to learn ASL. There were two main research questions. First, I asked if ASL training could improve the visual-spatial cognition in adult learners. Second, I explored whether pre-existing visual-spatial cognitive abilities could predict how well the adult learners learned ASL.

Question 1 - Does ASL instruction improve visual-spatial cognition?

To answer the first research question, I examined two groups of students. One group of students, the ASL group, were enrolled in a first level ASL course, and the other group of students, the control group, were enrolled in a comparable level spoken language course (e.g., Beginner French or Spanish). Both groups performed several visual-spatial cognitive tasks, a verbal working memory task, verbal STM tasks, and ASL proficiency tests, at their beginning and the end of their course. Using generalized linear mixed effect modeling we compared the cognitive tasks' scores, and the ASL proficiency scores, between groups and across the pre-learning and the post-learning session.

It was predicted that the ASL group would improve on the ASL proficiency tests and the control group would not. I also predicted that the ASL group would improve in the tasks that assess visual-spatial STM/working memory (Corsi block-tapping, MoveSpan), mental imagery (3D mental rotation, mental clock) and the ASL Digit span tasks, and would improve more than the control group.

ASL proficiency test. As predicted, the ASL group improved significantly on both the ASL naming and recognition tests. This shows that the participants did learn basic ASL vocabulary in their one semester of ASL training. While these results are not surprising, given that students were enrolled in an academic class to learn ASL, they nevertheless provide confirmation that ASL learning occurred, which is a prerequisite for determining whether ASL learning affected changes in spatial cognition. These results are consistent with other sign language L2 studies where adults were able to learn sign vocabulary with relatively little training (Ortega & Morgan, 2015b; Williams, Darcy, & Newman, 2016)

The ASL group had significantly higher scores than the control group at both the pre-learning session and the post-learning session, on both ASL proficiency tests. This suggests that the ASL group started off with more ASL knowledge than the control group prior to the experiment. I did attempt to control for prior ASL knowledge in the pre-screening questionnaire, and exclude anyone who reported taking an ASL course previously. However, due to the fact that the ASL participants were presumably more interested in learning ASL than control participants, they may have had prior exposure to ASL in some form, leading to familiarity with the meanings of some signs. The ASL participants may also have put more effort on the tests due to their interest in the subject. An additional factor that may have contributed to better performance at the pre-learning session among ASL learners is the fact that the ASL group had, on average, about fourteen hours of ASL instruction before their pre-learning session. So, some learning may have occurred prior to the initial assessment in this study, contributing to higher “pre-learning” scores in this group. Nevertheless, the ASL group’s proficiency did significantly improve between testing sessions. However, on average the ASL group were only approximately 10%

more accurate in the post-learning session compared to the pre-learning session. Larger improvement in proficiency may have been seen if the ASL participants were tested closer to the start of their course.

The significant interaction between group and session in the ASL naming test revealed, as expected, that the experimental group improved significantly but the control group did not improve significantly. For the ASL recognition test, as expected, the ASL group had higher scores than the control group. Planned contrasts showed that only the ASL learners improved significantly on this test. It should be noted though, that the control group were still approximately 50% accurate on the ASL recognition test. The control group's better than chance performance on the recognition test suggests that even with no ASL training, the control participants were able to guess the meaning of some signs. This is likely due to the iconicity of some of the signs used in the ASL recognition test. Iconic signs are when the gesture of that sign resembles the meaning (e.g., the verb DRINK resembles the pantomime of drinking from a cup). Prior work has shown that signs rated as more iconic are easier to guess by both learners of BSL and sign-naïve participants (Campbell, Martin, & White, 1992). Future work should consider attempting to design a test without iconic signs, although this might prove difficult given the limited vocabulary that is taught in a first semester of ASL.

The ASL group, on average, were approximately 75% accurate on the recognition test, and only reached 50% accuracy on the naming test. Therefore the ASL participants did not know every single sign in the tests, which is to be expected, however the ASL learners' performance on the ASL naming test was relatively low.

This could be due to the fact that the Carleton University's ASL instructors do not teach from a standard curriculum. The tests were designed using signs from the widely-used *Signing Naturally* curriculum. The Carleton ASL instructors do not use standardize materials or textbook. Therefore, there may have been some variability in what individual students learned, even though the instructors confirmed that their material was very similar to the material in the *Signing Naturally* curriculum.

Both ASL proficiency tests were able to detect improvements in ASL vocabulary in the ASL group, and both are valuable in measuring ASL knowledge. It is important the note, that even though I termed these "ASL proficiency tests", they only examined the ASL participants' changes in ASL vocabulary. However, since the ASL students are enrolled in a course, which has a focus on learning ASL vocabulary, and are not simply being trained on the vocabulary stimuli in the tests, I am inferring that these vocabulary tests measure proficiency and their overall ASL performance. In the future, I will consider other proficiency measures like self-rated proficiency and obtaining the students' grades.

Visual-spatial STM/working memory tasks. The ASL group improved significantly in some of the scores of both visual-spatial memory tasks — Corsi block-tapping and MoveSpan — while the control group did not improve significantly on any of these tests. This suggests that, compared to learning a spoken language, learning a signed language can improve visual-spatial STM and working memory. There were, however, some inconsistencies and the relationship between the groups and the sessions was not always clear.

Corsi block-tapping task. For the non-rotated version, all participants in both groups obtained scores in the normal range (Kessels et al., 2010), and had a higher span than 3.50, which is the cut off for pathological performance (Orsini et al., 1987). To my knowledge, the non-rotated version has never been standardized.

The ASL group improved on their non-rotated raw score — the total number of sequences performed correctly. This is consistent with the learning study performed with children, whose Corsi scores increased after a year of sign language instruction (Capirci et al., 1998). However, although the raw scores increased, the ASL group's non-rotated Corsi span did not increase. This implied one semester of sign language might affect the participants' visual-spatial memory but it did not increase the participants' capacity for remembering spatial items. In previous studies, Deaf native signers had a higher span than hearing non-signers (Lauro et al., 2014; Wilson et al, 1997), however the participants in those studies had native experience, while the ASL group in the present study only had one semester of experience. Compared to the span score, the raw score has more room for variability and has a larger scale. Two participants may have the same span score but different raw scores. Therefore, the raw score may be more sensitive in detecting small improvements in visual-spatial STM than the span score. Improvements in the span might only come with additional sign language training. Furthermore, there were no differences between the groups or the sessions in the rotated version. In a previous study, interpreters, who learned sign language in adulthood, performed better on the rotated version than non-signers (Keehner & Gathercole, 2007). However, these interpreters had, on average, 6 years of experience and were working in the sign language field, while our participants were just beginning to learn ASL. The rotated version of the Corsi task is harder because it requires the participants to use their mental rotation abilities. So, it is reasonable to expect improvements in the non-rotated version earlier in ASL learning and before improvements in the rotated version.

Inconsistencies between studies on this Corsi block-tapping task already exist in the literature. For example, the hearing non-native signers in Keehner and Gathercole (2007) and non-native Deaf signers (Marschark et al., 2013) did not outperform the hearing non-signers on the non-rotated version. Even though the Corsi block-tapping task has been widely used to measure non-verbal memory, a review of this literature revealed inconsistencies, including administration and scoring (Berch et al., 1998). Indeed, there were some scoring and procedure differences in this study compared to the other sign language studies. For example, Keehner and Gathercole (2007) used direct serial recall — scoring every item in a sequence, whereas the present study took the total number of correct sequences. Wilson et al. (1997) only recorded the span, and stopped after reaching a length of 5, whereas the present study went up to eight. Nevertheless, the ASL participants did improve, albeit only on one out of four scores, and the control group did not. This supports the hypothesis that ASL instruction can improve visual-spatial memory.

MoveSpan. The overall main effect of session for all three of the MoveSpan scores (span, raw score, number of completed blocks) and no significant interaction between groups and sessions, suggested that both groups improved on this task.

However, planned *t*-tests showed that the ASL group improved significantly on all three scores, while the control group did not. This suggests that sign language experience might enhance people's visual-spatial working memory for observed actions (Wood, 2007). The MoveSpan has never been used in sign language research prior to this study, so there is no literature to compare these results to. However, the results are consistent with my predictions: learning a visual-manual language appears to improve memory for even non-sign human actions. Sign language researchers who are interested in visual-spatial cognition or action observation should consider adding this task to their repertoire.

Verbal working memory — Ospan. Verbal working memory has previously been shown to be an important predictor of spoken L2 learning. Therefore, this task was mainly included to address the second research question, however comparing the groups' changes in the visual-spatial working memory tasks and this verbal working memory task could lead to some interesting insights. I did not anticipate sign language experience would improve verbal working memory, so no group differences were expected. Consistent with this prediction, the groups did not differ at either session, although both groups improved. The improvement of both groups could indicate that learning an L2 does improve verbal working memory capacity in one's native language, regardless of whether the language is spoken or signed. Alternatively, this improvement could reflect practice effects; a study testing the reliability of the Ospan, Klein and Fiss (1999), found improvements from the first to second administration of the test. The fact that the control group improved on this verbal working memory task, but not on the other visual-spatial working memory tasks, implies their lack of improvement on the visual-spatial memory tasks were not due to impairment in working memory.

Mental imagery tasks. There were significant improvements in reaction times, but not accuracy, in both mental imagery tasks — mental rotation and mental clock. The lack of differences in accuracy suggests that people did get faster as there was no speed-accuracy trade off. These results are comparable to the results of prior studies that also found differences in reaction time but not accuracy between groups in a mental rotation task (Emmorey et al., 1993), an image generation task (Emmorey et al. 1993; Emmorey & Kosslyn, 1996) and a mental clock task (Paivio, 1978). However, in the present study, reaction times improved significantly in both groups, with no between-group differences. Since, to my knowledge, there is no evidence indicating improvements on mental imagery tasks with (spoken) L2 learning, this improvement in reaction times seems most likely to be a practice effect, rather than the improvement predicted due to learning a visual-manual language.

Three-dimensional Mental Rotation Task. As previously stated, the ASL group's reaction times were comparable to the control group's reaction times. These results coincided with the results in Talbot and Haude (1993), which showed that students with less than one year ASL experience did not perform better on a mental rotation task compared to students with no ASL experience. Only students with an average of six years experience showed significant enhancements in their accuracy.

The results from Talbot and Haude (1993) suggest that it would take more than one year of sign language experience to improve mental rotational abilities.

However, Talbot and Haude used a paper and pencil version of the mental rotation task, and therefore did not record reaction times, only accuracy. So, they were unable to detect any changes in speed of performance, if such changes occurred; these may occur earlier than one year. According to the present study however, one semester of sign language instructions does not improve how fast the ASL learners mentally rotate objects.

STM – ASL Digit Span. I expected that the ASL group would improve in the ASL Digit span task, while the control group would not. In the pre-learning session, the ASL participants would not know the ASL digits. Once the ASL participants learned the ASL digits in their course, they would have two advantages: they would be able to recognize and remember the digits as meaningful signs, rather than meaningless hand shapes, and they would be able to translate the ASL digits and phonologically rehearse them in English.

There were no significant effects in this task. The ASL learners may not have been skilled enough to recognize the ASL digits and translate them into English for rehearsal — or at least not at the rate the digits were presented in this task. As well, previous studies that have used the ASL digit span either had a signer sign the digits in person or in video (Bavelier et al., 2008; Logan, Maybery, & Fletcher, 1996; Wilson et al., 1997). This study used line drawings of hand shapes (which looked very similar to each other), and the images flashed on the screen relatively quickly. This might have made it difficult for the participants to recognize the digits. I only recorded and analyzed changes in accuracy — the number of trials performed correctly, and not the span length. Future work should include calculating and analyzing the span scores on this task. The span scores will be easier to compare to the previous literature, and may detect changes that the total scores did not.

Question 1 – Overall conclusions and interpretations

The first research question asked if ASL training could enhance visual-spatial cognition in adults. The results of the Corsi block-tapping task and the MoveSpan task suggest that one academic semester of ASL instruction enhanced visual-spatial STM and working memory, particularly memory for observed actions. This supports my hypothesis that visual-spatial STM and working memory are enhanced by sign language experience. However the results were not found for all measures. The results of the mental rotation task and the mental clock task suggested that one semester of ASL experience does not enhance mental imagery.

A possible explanation for the results is that one semester of ASL training is not enough to see clear changes in visual-spatial memory and mental imagery abilities in adults, especially at the group level — as the variability in ASL proficiency scores post-training indicates, not all students showed equal gains in ASL knowledge. The ASL group significantly improved from the pre-learning session and the post learning on both ASL proficiency test, however only by approximately 10%. This indicates that on average, the ASL group improved by four questions. This is a relatively minimal gain, and is probably because some ASL participants did not show improvement, lowering the post-learning average. Future analysis could examine the changes in visual-spatial cognition in ASL participants that only showed clear improvements in the ASL proficiency tests. However, this would reduce the relatively small sample size of 25 participants.

Another possible explanation for not seeing clear improvements in visual-spatial cognition is what is taught in the beginner ASL course. In any first-level L2 course, the focus of the curriculum is learning vocabulary and basic grammar. The *Signing Naturally* first level curriculum also has this focus. Even though students are exposed to all the facets of ASL in their first course by watching their instructor, they are not explicitly taught the complexities of using space for grammatical purposes until second-level courses. Emmorey (2002) suggested that mental imagery skills are enhanced in signers because of the cognitive demands when conversing in sign — having to imagine referents and scene descriptions, and having to mentally reverse the narrator's signing space to understand the narrator's perspective. First level students do practice conversing, but given their limited knowledge of the language these conversations are very limited in their content and length, and do not utilize the spatial grammar taught in the upper level courses. First-level ASL students therefore have little experience with imagining referents and rotating the signing space.

The present results suggested that improvements in visual-spatial STM and working memory might be seen in the early stages of learning. It is conceivable that visual-spatial memory, particularly memory for observed actions, is enhanced earlier on in learners than mental imagery skills. Students in a first-level ASL courses have to adapt to using the visual-manual modality, something that is difficult for first time learners (McKee & McKee, 1992). Therefore, students' visual-spatial working memory skills are needed to view and process the actions of their instructor and their fellow classmates. Additionally, because first-level courses are focused on learning vocabulary, students are focused on their instructor's actions, and remembering the signs and their translation. This could in turn enhance their memory for observed actions. As the students gain more experience, and more explicit knowledge about using space in a conversation, their mental imagery abilities will probably also improve.

Question 2 – Can visual-spatial cognition predict ASL proficiency?

To investigate the second research question, I examined the relationship between the ASL learners' visual-spatial cognitive task scores as measured at the start of the study, and the change in their ASL proficiency tests scores. I only examined the ASL group, as I did not expect the control group to learn ASL, and I was only interested in what scores predicted ASL learning. Four pre-learning scores were incorporated into the GAMM models: 1) non-rotated Corsi Raw score, 2) MoveSpan raw score, 3) average reaction time in the mental rotation task, and 4) Ospan score. I only selected four measures to simplify the models and to decrease the amount of correlations between the variables. Table 1 in the Appendix shows the correlations between the pre-learning cognitive tasks scores in the ASL participants. Many of the tasks are moderately or highly correlated. Therefore, rather than choosing a measurement from each task, I chose one measurement to be a representative of a specific skill. I chose the non-rotated Corsi raw score to represent visual-spatial memory instead of the span score because, a previously mentioned, the raw score is more sensitive at detecting difference in participants. The MoveSpan also represents visual-memory but it is specific to observed actions, which may predict ASL scores differently than the Corsi tasks. Therefore I included the MoveSpan task. I decided to choose the raw score, to be consistent with the Corsi raw score. To represent mental imagery ability, I chose the mental rotation task, instead of the clock task. I made this decision because the mental rotation task has been used previously in sign language literature, but the clock task has not, therefore the relationship between sign language and the mental rotation task is already established. To represent verbal memory, I chose the Ospan score.

Previous literature has emphasized a positive relationship between individuals STM and verbal working memory and their L2 proficiency (Linck et al., 2014; Martin & Ellis, 2012; Nicolay & Poncelet, 2013; Wen, 2012; Williams, 2011). Therefore, I expected that there would be a positive relationship between the participants' pre-learning cognitive tasks scores, particiularly the visual-spatial STM/working memory tasks — Corsi and MoveSpan raw score — and the participants change on the ASL proficiency tests.

In the ASL Naming test, as shown in Table 5, the model with the lowest AIC contained the reaction times for the rotation task and the non-rotated Corsi raw score (M5). The interaction between the rotation task reaction time and session was signficant, but the interaction between session and the non-rotrated Corsi raw score was not (*p* = .06), suggesting that the Corsi raw score is at best only weakly related to improvements in ASL test scores. However, the Akaike weight of M5 is realtively large and, according to the weight ratio, M5 is 3 times more likley to fit the data compared to the next best model (M11) which only contains the rotation reaction time parameter. Therefore, even though the interaction between session and non-rotated Corsi raw score was not signficant in the model, there is evidence to suggest that the non-rotated Corsi raw score may be a good predictor of the changes in the ASL Naming test. Further investigation is needed to establish whether there is a real relationship between the participants pre-learning Corsi scores and their change in ASL proficiency.

When examining the next best models, the rotation reaction time parameter in included in the next 7 top models, and the Corsi is in the third and fourth best models. The weight ratio of M5 compared to other models increases drastically after the top seven models, suggesting that models after the top seven are unlikley to to fit the data. Within the top 7 models, all of them contain the rotation reaction times and four models contains non-rotated Corsi score, while only two contain the MoveSpan score and only one contains the Ospan score. This supports the idea that the reaction times on the rotation task and the non-rotated Corsi raw score are good predictors of the ASL participants' change in ASL Naming test scores. It also suggest that the Ospan score and the MoveSpan score are not good predictors.

In the ASL Recognition test, the model that had the lowest AIC contained only the interaction between the average reaction time on the rotation task and session (M11). This interaction, however, was not significant. Furthermore, this model (M11) is only 1.36 times more likley to fit the data compared to the next best model, which only contains the main effect of session and no predictors (M15). AIC scores balance for the accuracy of the model and the complexity of the model — number of paramters the model contains. When two models have similar AIC scores, the simplest model is usually the best model. M15 is the simplest model, and is the second lowest AIC value and is close to the lowest AIC value. This suggests that the best model is probably the model with no predictors. Therefore, as opposed to the ASL Naming test, it seems that no variables predict the ASL participants' change in the ASL Recognition test. This might be because the ASL Recognition test was easier than the ASL Naming test, and thus perhaps less sensitive as a measure of ASL learning.

The participants' average reaction time on mental rotation task showed a negative relationship with the participants' change in proficiency — the longer the participants took on these tasks, the more the ASL participants improved on their ASL scores. This was opposite to what I expected. I predicted that participants who were better, and therefore faster, at mental imagery would be better at acquiring ASL. Slower reaction times, with no differences in accuracy, may reflect taking greater care with the task, and/or giving it greater attention. This general approach may lead to better outcomes in ASL learning.

As expected, the non-rotated Corsi block-tapping raw score showed a positive relationship with the ASL naming test: the higher the participants' pre-learning raw score, the larger the improvements in the participants' change in proficiency. These results correspond to my hypothesis that visual-spatial STM is important in acquiring a visual second language. The verbal working memory Ospan task, was not a good predictor in ASL learning. As expected, this suggests that specifically visual-spatial STM memory, compared to verbal working memory, is predictive of sign language acquisition.

Unexpectedly, the MoveSpan tasks was also not a good predictor ASL learning. I expected that memory for observed actions would be important in acquiring a sign language. The Corsi task, which did show a relationship, involves remembering a visual-spatial sequence, while the MoveSpan task involes remembering a sequences of actions while performing distractor movements, and then performing the to-be remembered actions at the end of sequence. While the Movespan task in the visual-spatial domain, it is specific to action obervation. This suggests memory for visual-spatial sequences may be more predictive of proficiency than visual memory for observed actions.

A limitation to having models with mutiple predictors is the correlation between thoses predictors. Predictors that are correlated with each other create issues in the model as they may explain the same variance in the data. This means that the effects of one individal variable can not be isolated. Furthermore, the AIC scores do not account for correlation between the variables. As previously stated, many of the ASL participants' pre-learning scores were moderately or highly correlated (Appendix 1). I tried to control for this by only using four parameters instead of a measurment from every cognitive task. However these scores are still correlated with eachother. For example the non-rotated Corsi raw score is moderatley correlated with the Ospan score, $r = 0.36$, and the MoveSpan raw score is strongly correlated with the Ospan score, $r = 0.66$. Future analysis could include principal component analysis to control for the correlation between the parameters.

General Limitations and Future Directions

One limitation in this study is the small sample size of the control group. Due to the smaller size of the control group (n = 11) compared to the ASL group (n = 25), it is possible that the same magnitude of change could have been significant in the

ASL group, but not the control group. However, examination of the confidence intervals of the plots shown in the Results section suggest approximately equivalent variance in each group, and as well significant improvements were found for the control group on several measures, suggesting that the study did in fact have the sensitivity to detect between-session changes in this group.

Another limitation is the timeline. All the participants already had some language instruction prior to the first session. Students were identified by virtue of being in a language class, so, they had some exposure to the language between starting the class and coming to their first experimental session. Therefore, I was not measuring true "baseline" knowledge prior to any exposure to the new language. As previously stated, the ASL group performed better than the control group on both ASL proficiency tests in the pre-learning session, suggesting that ASL learning occurred prior to the first testing session. This might also suggest that changes in visual-spatial cognition may have also occurred in the ASL participants prior to the first testing session. Therefore, the resulting changes in visual-spatial cognition might have been larger, or I may have found additional effects, if I measured the ASL group closer to the start of their class. That being said, however, there were no significant differences between the ASL group and the control group in any of the cognitive tasks at the pre-learning session, suggesting that the ASL group started with similar visual-spatial cognitive abilities to the control group. Based on the presumption that learning a spoken L2 language does not affect visual-spatial cognition, the prior ASL language experience in the ASL group probably did not affect their visual-spatial cognition greatly and the participants' visual-spatial cognition were probably very close to "baseline".

Another limitation in the timeline is that the control group had signifcantly more days in between the two testing sessions than the ASL group. Consequently, the ASL group may have experienced more practice effects than the control group, as they had less time between sessions. The ASL participants could have remembered the tasks better than the control group resulting in greater improvements. Additionally, the ASL group had their sessions at a different location than the control group, and they performed them at different times in the year. The sessions for the ASL group were conducted at Carleton University, and their post-learning session was at the end of the year, during exams. The sessions for the control group, on the other hand, were conducted at Dalhousie Unversity. The spoken second language courses the control participants were enrolled in were two semesters long and the control participants' pre-learning and post-learning session were more variable depending on when they were recrutied. Since the ASL group's post-learning session was conducted during final exams, and the many of the control group's post-learning session were not, the ASL learners were possibly under a lot more stress than the control group at the time of the post-learning session. This could have lead the ASL group to experience more fatigue, and could have lessened the predicited improvements on the visual-spatial cognitive tasks, and the ASL proficiency tests.

I also did not measure the proficiency of the control groups' second languages, as their were a number of different languages and equating the difficulty and scales of these tests across different languages (and compared to ASL) would have been very challenging. Therefore it is possible that the factors that predicted ASL proficiency in this study might also predict spoken language proficiency — future studies could investigate this question. A future study should include three groups: 1) ASL group; 2) Control group only learning one second language (e.g., Spanish); 3) Control group not learning any second languages, and I would then measure both ASL and spoken L2 proficiency. Additonally, I would track the learners over a year and half, and have several testing sessions. This would allow me to track the ASL participants changes as they enter second year and begin to learn about spatial grammar.

Conclusion

This was one of the first studies that investigated in adults who were beginning to learn ASL as a second language, both which visual-spatial cognitive abilities predict sign language aquistion, and which visual-spatial cognitive abilities may change during learning. Visual-spatial STM and visual-spatial working memory, particularly memory for observed actions, were enhanced after a sememster of ASL training. Visual-spatial STM and working memory are most likley enhanced at the early stages of learning due to the learners having to adapt to using a visual-manual modality, and having to focus on their instructor's actions to learn and remember vocabularly. More ASL experience — gaining knowledge about spatial grammar, and practicing imagining referents and using space for grammatical purposes, is likely needed for improvements in mental imagery abilities, including mental rotation and image generation. Another finding was that visual-spatial STM can predict how well adults learn ASL as a second language. Verbal working memory was not predicitive of sign language L2 aquistion. Therefore, visual-spatial memory appears more important than verbal memory in acquiring a visual-manual language.

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Appendix One — Correlation Tables

Appendix Table 1. Correlations (Pearson) between ASL participants pre-learning scores

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Corsi Nonrotated Span (A)	1.00	0.97	0.30	0.18	0.25	0.57	0.40	-0.09	0.15	0.36	0.04	-0.26	0.54	0.17
Corsi Nonrotated Raw (B)		1.00	0.28	0.21	0.23	0.51	0.39	-0.02	0.17	0.40	0.05	-0.33	0.52	0.23
Corsi Rotated Span (C)			1.00	0.89	0.54	0.50	0.56	-0.18	0.25	0.30	-0.26	-0.04	0.37	0.33
Corsi Rotated Raw (D)				1.00	0.47	0.38	0.48	-0.16	0.20	0.21	-0.39	-0.07	0.25	0.25
MoveSpan Span (E)					1.00	0.64	0.74	-0.31	0.19	0.56	-0.13	0.29	0.01	0.20
MoveSpan Raw (F)						1.00	0.90	-0.42	0.06	0.66	-0.43	0.15	0.62	0.41
MoveSpan Completed Blocks (G)							1.00	-0.39	0.20	0.69	-0.38	0.25	0.50	0.43
Clock Average RT (H)								1.00	-0.14	-0.02	0.55	-0.28	-0.50	-0.11
Clock Total Score (I)									1.00	0.10	0.00	0.05	0.17	0.18
OSPAN Score (J)										1.00	-0.08	0.00	0.38	0.62
Rotation Average RT (K)											1.00	-0.12	-0.48	-0.17
Rotated Total Score (L)												1.00	-0.15	-0.08
Forward English Digit Total Score (M)													1.00	0.41
Reverse English Digit Total Score (N)														1.00

*Correlations were obtained from R cor function (Becker, Chambers, & Wilks, 1998)

Appendix Table 2. Correlations (Pearson) between the pre-learning scores collapsed across ASL group and the control group

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
Corsi Nonrotated Span (A)	1	0.96	0.36	0.27	0.34	0.42	0.43	-0.09	0.26	0.32	-0.04	0.09	-0.01	0.23	0.24	0.27	0.26	0.22	0.27	0.03
Corsi Nonrotated Raw (B)		1	0.39	0.34	0.34	0.44	0.48	-0.01	0.27	0.41	-0.02	0.07	-0.02	0.31	0.28	0.35	0.3	0.22	0.34	0.03
Corsi Rotated Span (C)			1	0.87	0.34	0.43	0.44	0.02	0.27	0.19	-0.06	0.24	0.02	0.31	0.31	0.25	0.06	0.18	0.36	0.03
Corsi Rotated Raw (D)				1	0.38	0.41	0.46	0.04	0.2	0.18	-0.1	0.13	-0.22	0.24	0.21	0.23	0.08	0.02	0.31	-0.28
MoveSpan Span (E)					1	0.66	0.8	-0.15	0.1	0.5	-0.14	0.23	-0.16	-0.01	0.19	0.36	-0.01	0.38	0.36	-0.15
MoveSpan Raw (F)						1	0.88	-0.004	-0.1	0.65	-0.09	0.15	-0.05	0.57	0.38	0.49	0.36	0.41	0.49	-0.09
MoveSpan Completed Blocks (G)							1	-0.12	0.1	0.61	-0.21	0.22	0.001	0.38	0.37	0.53	0.41	0.39	0.55	-0.05
Clock Aveage RT (H)								1	-0.14	0.1	0.67	-0.11	-0.15	0.01	-0.17	-0.07	-0.14	-0.24	-0.1	-0.1
Clock Total Score (I)									1	0.07	-0.06	0.14	-0.04	0.13	0.13	-0.02	-0.15	-0.03	0.27	-0.72
OSPAN Score (J)										1	-0.06	0.04	0.02	0.48	0.64	0.54	0.37	0.23	0.52	-0.1
Rotation Average RT (K)											1	-0.06	0.12	-0.04	-0.2	-0.24	-0.07	-0.16	-0.25	0.2
Rotated Total Score (L)												1	-0.06	-0.1	-0.09	0.1	-0.1	0.27	0.26	-0.18
ASL Recognition Test (M)													1	0.28	0.13	0.09	0.42	0.19	-0.04	0.85
Forward English Digit Total Score (N)														1	0.5	0.34	0.52	0.13	0.35	0.2
Reverse English Digit Total Score (O)															1	0.44	0.45	0.22	0.41	-0.02
Forward ASL Digit Total Score (P)																1	0.35	0.51	0.56	0.09
Reverse ASL Digit Total Score (Q)																	1	0.15	0.25	0.29
Forward Random Handshape Total Score (R)																		1	0.45	0.18
Reverse Random Handshape Total Score (S)																			1	-0.05
ASL Naming Test (T)																				1

Appendix Table 3. Correlations (Pearson) between the post-learning scores collapsed across ASL group and the control group

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
Corsi Nonrotated Span (A)	1.00	0.95	0.34	0.32	0.45	0.29	0.25	0.25	0.28	0.61	0.04	0.13	0.13	0.57	0.47	0.36	0.23	0.20	0.10	0.36
Corsi Nonrotated Raw (B)		1.00	0.27	0.25	0.48	0.30	0.28	0.20	0.24	0.59	-0.06	0.16	0.07	0.56	0.43	0.32	0.18	0.19	0.11	0.29
Corsi Rotated Span (C)			1.00	0.92	0.30	0.15	0.19	-0.08	0.16	0.39	-0.28	0.14	-0.19	0.14	0.34	0.23	0.38	0.11	0.10	-0.13
Corsi Rotated Raw (D)				1.00	0.34	0.17	0.15	-0.02	0.25	0.40	-0.21	0.06	-0.17	0.16	0.30	0.30	0.46	0.11	0.16	-0.09
MoveSpan Span (E)					1.00	0.65	0.53	0.07	0.41	0.77	-0.12	0.08	0.11	0.50	0.26	0.42	0.38	0.42	0.47	0.28
MoveSpan Raw (F)						1.00	0.85	-0.10	-0.01	0.57	-0.18	0.27	0.03	0.36	0.22	0.36	0.20	0.27	0.23	0.04
MoveSpan Completed Blocks (G)							1.00	0.03	-0.09	0.45	-0.15	0.36	-0.01	0.19	0.26	0.14	0.23	0.18	0.18	0.05
Clock Aveage RT (H)								1.00	0.15	0.15	0.42	0.00	0.29	-0.08	0.26	-0.03	0.15	0.02	0.00	0.30
Clock Total Score (I)									1.00	0.45	0.06	-0.04	0.03	0.24	-0.07	0.13	0.35	0.25	0.32	0.15
OSPAN Score (J)										1.00	-0.03	0.26	-0.01	0.69	0.52	0.43	0.39	0.43	0.37	0.22
Rotation Average RT (K)											1.00	-0.36	0.20	0.16	0.03	-0.20	0.02	-0.17	-0.26	0.22
Rotated Total Score (L)												1.00	-0.20	0.24	0.11	0.11	0.15	0.17	0.05	-0.04
ASL Recognition Test (M)													1.00	-0.07	0.11	0.30	0.17	-0.28	-0.09	0.83
Forward English Digit Total Score (N)														1.00	0.43	0.54	0.37	0.43	0.28	0.18
Reverse English Digit Total Score (O)															1.00	0.22	0.16	0.25	0.30	0.15
Forward ASL Digit Total Score (P)																1.00	0.65	0.27	0.26	0.44
Reverse ASL Digit Total Score (Q)																	1.00	0.06	0.23	0.31
Forward Random Handshape Total Score (R)																		1.00	0.69	-0.05
Reverse Random Handshape Total Score (S)																			1.00	0.02
ASL Naming Test (T)																				1.00