AN EXAMINATION ON THE DEVELOPMENT OF VISUOSPATIAL ABILITIES USING HANDS-ON TASKS

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For the most important people in my life, my family.

ABSTRACT

Visuospatial abilities are cognitive processes essential for activities of daily living, they allow us to safely and independently navigate and interact with our environment. These abilities have also shown a strong relationship with academic and professional development, particularly, the sub-ability of mental rotation (MR). However, there is a lack of understanding of the across the lifespan age and sex differences of MR. This is due to the multiple different measures used to assess this ability plus the diversity of age groups which have been assessed. To create a clear understanding on age and sex differences in MR, it is necessary to keep the type of measure consistent across age groups. Therefore, the purpose of this thesis was to investigate the trajectory of visuospatial abilities across the lifespan, using the hands-on brick-building MR task (BBT). The BBT provided the consistency needed to investigate across age and sex differences in visuospatial abilities.

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LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
BBT	Brick Building Hands-on Task
CAH	Congenital Adrenal Hyperplasia
fMRI	functional Magnetic Resonance Imaging
IHH	Idiopathic Hypogonadotropic Hypogonadism
MR	Mental Rotation
MRT	Mental Rotation Test
PMA	Primary Mental Abilities- Spatial Ability Test
PPC	Posterior Parietal Cortex
RH	Right Hemisphere
SES	Socioeconomic Status
STEM	Science, Technology, Engineering and Mathematics
TAMI	Test of Ability in Movement Imagery
TMS	Transcranial Magnetic Stimulation
2D	Two-dimensional
3D	Three-dimensional

CHAPTER 1
Introduction

1.1 Introduction

Visuospatial abilities are cognitive processes essential for everyday life functions. They help us locate ourselves in space based on landmarks or cardinal points, they help us interact with objects; by judging their distances in relationship to ourselves and in relationship to other objects, and by judging their features (i.e. dimension, size, and shape). As well, they allow us to form and manipulate mental representations of these objects. Visuospatial abilities are classified into three main constructs; spatial visualization, spatial perception and mental rotation (Linn & Petersen, 1985). Spatial visualization, defined as the ability to mentally manipulate spatial information that requires a multistep process, is used for example; when imagining the path taken from point A (e.g. your house) to point B (e.g. the grocery store) or to estimate if a car will fit in a certain parking spot. Well-known tests to assess this ability are the Paper Folding (Ekstrom, French, Harman, & Dermen, 1976), Block Design (Weschler, 1955) and Embedded Figures tests (Witkin,Oltman, Raskin, & Karp, 1971). Spatial perception, defined as the ability to interpret body to object or object to object locations in space amidst distracting cues (Linn & Petersen, 1985; Voyer, Voyer, & Bryden, 1995). is particularly important when locating ourselves on a map, or in relationship to landmarks or cardinal points. This ability is assessed by using measures as the Rod and Frame test (Witkin, Dyk, Faterson, Goodenough, & Karp, 1962) and Water Level test (Inhelder & Piaget, 1958). Mental rotation (MR), is defined as the ability to rotate objects in the "mind's eye", that is, mentally imagining how an object would look like when rotated from its original position (Shepard & Metzler, 1971). This ability helps us understand situations in which objects are rotated in space, for example; every time we use a mirror to brush our teeth, comb our hair, or while driving. The Cards Rotation or Cube

Rotation test (French, Ekstrom, & Price, 1963; Ekstrom et al., 1976), Purdue Visualization of Rotations test (Guay, 1977; Bodner & Guay, 1997), Primary Mental Abilities- Spatial Ability (PMA) test (Thurstone, 1938) and particularly the Mental Rotation Test (MRT, Fig 1.) by Vandenberg and Kuse (1978; Peters, Laeng, Latham, Jackson, Zaiyouna, & Richardson 1995) are designed to measure this ability.

Not only are these abilities important for everyday life functions but it has also been well-established across the literature that visuospatial abilities are one of the main contributing factors towards Science, Technology, Engineering and Mathematics (STEM) achievements (Casey, Nuttal, Pezaris, & Benbow, 1995; Wai, Lubinski & Benbow, 2009; Lubinski, 2010; Hegarty, Crookes, Dara-Abrams, & Shipley, 2010; Harlem & Towns, 2011; Uttal & Cohen, 2012; Lauer & Laurenco, 2016, Gold et al. 2018). Throughout formal schooling we are required to constantly interpret numerical symbols or number words regarding their magnitudes, to understand quantities, to visualize, transform, or interpret graphs, geometric shapes, molecular structures, or to solve number/algebraic missing term problems. To succeed at these tasks, it is evident visuospatial abilities are necessary. A great deal of attention from researchers has been placed on studying mental rotation (MR) ability. There are two reasons for this; first, MR has a strong link to STEM in children (Gilligan, Hodgkiss, Thomas, & Farran, 2017) adolescents (Ganley, Vasilyeva, & Dulaney, 2014; Shea, Lubinski, & Benbow, 2001) and young adults (Casey et al., 1995; Wei, Yuan, Chen, & Zhou, 2012), and second, the MRT has shown the largest sex differences (with males outperforming females) amongst all the previously mentioned psychometric tests (Maccoby & Jacklin, 1974; Geiringer & Hyde, 1976; Sanders, Soares, & D'Aquila, 1982; Linn & Petersen, 1985; Voyer et al., 1995; Bodner & Guay, 1997). It is important to note that although, the sex difference seems to be robust at the MRT, there is evidence that has shown cultural backgrounds may be an important factor behind performance on this test (Yang, Hooven, Boynes, Gray, & Pope, 2007). Together, these findings have also led researchers to believe spatial abilities may be an important contributor to the underrepresentation of women in STEM areas (Wang & Degol, 2017), making it a delicate yet intriguing topic. If this is the case, the possibility to diminish the underrepresentation of women in STEM does exist, because these abilities are known to be extremely malleable; which means they are receptive to change, and can be trained towards improvement (Uttal et al., 2013).

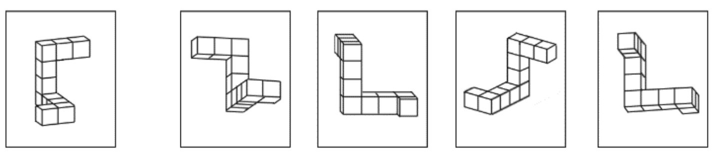


Figure 1. The mental rotation task (MRT). A target stimulus on the left is compared to four stimuli on the right. The participants attempt to identify the two stimuli that match the target stimulus. The second and third stimuli match the target stimulus in this example.

However, there is uncertainty on the developmental progress that visuospatial abilities follow. In particular numerous inconsistent findings have been reported regarding the development of MR ability. The cause of these inconsistency has been considered to be due to two important factors: One, the diversity of measures that have been developed and are used to assess MR ability. Two, the diversity of age groups and age ranges that have been studied. Developed measures vary in type of stimuli (mirrored vs not mirrored or abstract vs animated), dimensions (two- vs three-dimensional), structure (paper-based vs real-world objects) and procedures (time limit vs no time limit) (Lauer, Yhang, & Lourenco, 2019); whereas age groups (i.e. either only young adults or only children) and age ranges (e.g. only pre-school children or only elementary school children) vary on their cognitive maturity, as well, on age-related experience. As a result, the combination of these factors has yielded different results across the literature. The reason different measures are used and different ages are targeted, is mostly because researchers have discovered that well-known measures are not suitable for all ages. For example, multiple studies have had to simplify the MRT because it is too challenging for children but then those simplified versions are found not to be challenging enough for adults. For this reason, the development of MR ability across the lifespan remains unclear.

A novel brick building hands-on task (BBT) was introduced by de Bruin et al. (2016), that required the use of all main visuospatial constructs. The novelty of this task lies in that: 1) it includes varying demands of mental rotation (two-dimensional/low MR demand vs three-dimensional/high MR demand); 2) it does not have a time limit for its completion; 3) it could be suitable for different ages; and 4) that unlike the paper and pencil psychometric tests, it is a highly ecologically valid task. Therefore, the studies presented on this thesis will explore visuospatial abilities using the BBT and the well-stablished MRT in different age groups; with the main purpose being to contribute to this area of research by providing a clearer picture on the developmental progress of such vital cognitive processes. This thesis will begin by acknowledging the brain structures that support visuospatial abilities. It will present behavioural evidence, followed by neuroimaging and neurophysiological evidence. With the objective to convey the numerous inconsistent findings in regards to changes in MR ability across the lifespan, it will review this evidence by separating age groups (infants, children, teenagers, young adults and older adults).

1.2 Behavioral evidence of right-hemisphere involvement in visuospatial abilities

The right-hemisphere (RH) is the dominant hemisphere for visuospatial processes. This was demonstrated by early studies in neurological patients with RH lesions. John Hughlings-Jackson first proposed the idea that the posterior RH had a contribution in spatial-perceptual function (Benton, 1991; Kolb & Whishaw, 2003). However, it was not until later, that work by Oliver Zangwill, Henry Hécanen and their colleagues confirmed his idea. Patterson and Zangwill (1944) identified the parietal lobe as the region of damage that caused the patient to ignore the left-visual field and the left-side of his body (a condition now known as visuospatial neglect). Hécaen, David, van Reeth, and Clement (1953), reported cases of 50 patients with right and left parietal lobe tumors, and found that a greater number of those patients with right parietal damage showed constructional apraxia; previously defined by Kleist (1934) as the inability to assemble, build or draw a replica of a presented item in its correct spatial form (Benton & Fogel, 1962; Benton, 1967). Zangwill and Hécaen and their colleagues provided a vast amount of evidence on the right hemisphere dominance for visuospatial functions (McFie & Zangwill, 1960; Benton, 1991).

Work by Sperry, Bogen, and Gazzaniga (1969) further exemplified the RH contribution for performing visuospatial tasks by studying patients with commisurotomy (or "split brain" patients). These patients had the millions of axons connecting the left- and right-hemisphere cut, preventing their hemispheres to share information with one another. Because of how the brain is organized, each hemisphere controls the contralateral side of the body and also responds to sensory stimuli presented on the contralateral side of the body (Kolb & Whishaw, 2013). Therefore, the RH will control the left side of the body (e.g. the left-hand) and respond to sensory stimuli on this side as well. By cutting the passage of sensory and motor information between the hemispheres patients when presented with a picture of an object on the left-visual field, as the information travelled to the RH were able to accurately locate and identify the object with their left-hand. However, they were not able to accurately name the object; this was due to the disconnection of the two hemispheres, the information did not travel to language dominant hemisphere (the left hemisphere). This example, shows the deficits in transfer of information from one hemisphere to the other, and demonstrates the importance of the right-hemisphere for object location and tactile recognition (Pearce, 2019). From multiple other studies on split-brain patients, the RH was found to play a central role in many spatial related tasks such as, sorting scrambled objects by organizing them based on shape, texture, surface or function, on spatial construction or pattern assembly, and on the capacity to mentally rotate objects (Bogen & Gazzaniga 1965; Sperry, Gazaniga & Bogen, 1969; Corballis & Sergent, 1989; Corballis, Funnel & Gazzaniga, 1999; Farah, 1989; Kolb & Whishaw, 2003).

As noted by Patterson and Zangwill (1944) and later on by Critchley (1953), deficits exhibited in patients with lesions to the parietal cortex demonstrate this is the main structure supporting visuospatial functions. The parietal cortex is part of the "where/how" pathway of information processing in the brain. Milner & Goodale (1992) identified two separate neural-systems for processing information necessary to guide our movements towards objects and to perceive these objects in space. The “where/how” pathway, is known as the dorsal stream. This stream is the one in charge of spatial processing. This includes information about the location of objects in space, information regarding relative position of our limbs and limb movement (Cloutman, 2013). The “what” pathway, the ventral stream, is important for object processing, giving us information about the features (i.e. color, shape, size) of these objects. It has been suggested a third pathway (along the superior temporal sulcus) exists, that is specifically important for visuospatial functions; where exchange or transfer of information between both streams takes place (Kolb & Whishaw, 2003). The rationale behind the existence of a third pathway emerges because visuospatial functions not only process spatial relations among objects (“where/how” pathway) but also must process the features of these objects (“what” pathway). For example, often the features of places or objects (color, shape, size) are used as reference to guide our location or movements.

Within the parietal cortex, the posterior parietal cortex (PPC) plays a major role on processing visuospatial information. In fact, this is where the dorsal stream projects through the parietal cortex (after the visual cortex and before making its way to the frontal cortex). Thus, the PPC is crucial for guiding movements towards objects in the egocentric space. Also, the PPC is an associative region, which means it gets inputs from many sensory systems for their integration. For this reason, it is known to also contribute in higher order cognitive functions such as visuospatial abilities. This is denoted by studies on patients with lesions to this region. Bálint syndrome is caused by a bilateral lesion to the PPC, in which patients are able to recognize objects features (information processed by the ventral stream) but have deficits in eye gaze (inability to fixate the gaze towards an object), have optic ataxia (inaccuracy at visually guiding movements towards objects), have simultagnosia (inability to pay attention to more than one object at a time), and are unable to mentally manipulate objects. A lesion only to the right PPC causes contralateral or visuospatial neglect (briefly described at the beginning of this section). Notably, this condition is highly complex as many sensory systems are known to be disturbed, and although the mechanisms behind it are yet to be fully understood (Halligan, 2012), this is fundamentally a spatial disorder. Right PPC lesions include a variety of other symptoms such as; constructional apraxia (described previously), topographic disorientation (the inability to draw or navigate familiar environments) and object recognition impairment (the inability to recognize objects if these are presented on an unfamiliar position, e.g. rotated). In particular, the inability to mentally manipulate objects has been related to other unexpected symptoms of parietal cortex lesions for example; difficulties in reading and the inability to do geometry or arithmetic problems (Kolb & Whishaw, 2003).

1.3 Neuroimaging and neurophysiological evidence

As a result of the accessibility to non-invasive new technologies, there is vast amount of evidence combining the use of functional Magnetic Resonance Imaging (fMRI) or Transcranial Magnetic Stimulation (TMS) technologies with behavioural visuospatial tasks; with the main purpose to identify the neural substrates that support visuospatial processes. Multiple fMRI studies have revealed a parietal cortex activation when completing spatial cognition tasks (Sacks, 2009; Cona & Scarpazza, 2019). Specifically, the PPC and its regions (superior and inferior parietal lobule) activate when participants solve two-dimensional (2D; Koshino, Carpenter, Keller, Timothy, & Just, 2005; Sack et al., 2008) or three-dimensional (3D) MR tasks (Cohen et al., 1999). It is important to note that an activation of both dorsal and ventral pathways has also been found when performing MR tasks (Koshino et al., 2005), suggesting both pathways play a role in this ability. Furthermore, bilateral activation of the PPC has been found in MR tasks (Everts et al., 2009; Bien & Sack, 2014), mostly when fMRI is used (Sack, 2009). Conversely, when TMS is used, studies have shown a right PPC dominance (Sack et al., 2007). Although, fMRI has proven to be extremely helpful at understanding the neural networks that support visuospatial processes, it has been suggested that this technology does not allow to make direct inferences between the structures being activated and their particular functions (Sack, 2009; Sack et al., 2007), but TMS technology can make these inferences. Thus, by using TMS, the specific area where neural activity is being disrupted can be directly related to the deficits being exhibited on the behavioural task. Göbel, Calabria, Farnè and Rossetti (2006) found that by applying TMS to the right PPC of healthy participants, deficits were exhibited on a spatial line bisection task; deficits that resembled the ones found on this task in contralateral neglect patients. Moreover, Sack et al. (2002), found that, in particular, the disruption of neural activity with TMS on the right PPC caused impaired spatial imagery; and later on, they were able to make use of both technologies at the same time by applying TMS inside the fMRI scanner and finding that visuospatial judgments (i.e. the angle discrimination task) were impaired only when TMS was applied to the right PPC (Sack et al., 2007).

1.4. Visuospatial abilities: Changes throughout the lifespan

1.4.1. Evidence of mental rotation ability in infancy

Research on mental rotation has suggested that the capacity to mentally rotate an object emerges in infancy. Experiments at this young age are based on the habituation-dishabituation technique and use the violation of expectation paradigm. Subjects that are continuously presented with the same stimulus after a prolonged period of time are known to decrease their response (e.g. stop looking at it), which means they have been habituated to that stimulus. When the habituated stimulus is further presented but introduced with a novel characteristic, for example; a different orientation, then the subject becomes dishabituated and their response towards it increases. Baillargeon, Spelke, and Wasserman (1985), used this previously mentioned technique to first introduce the violation of expectation paradigm. This paradigm is based on the fact that infants tend to look for a longer time at events that are impossible or at things they have not encountered before. Rochat and Hespos (1996) used this paradigm to study spatial abilities in infants. They habituated four-month-olds with a real-world rotating object. The object then disappeared from the infants' sight and was later presented either on the corresponding subsequent possible orientation or on an impossible orientation. They found that infants' looking time was longer for the impossible orientation. Although, the previous study used real-world objects, this is often not the case. The study of the development of spatial abilities (including mental rotation) has traditionally used pictures or computerized presented stimuli (2D and 3D). Using printed 2D stimuli (the number 1), Quinn and Liben (2008) found that three- to- four-month-old infants looked at the mirrored stimulus for a longer time than the non-mirrored (previously habituated) stimulus. However, using 3D stimuli

(MRT figures) presented on a computer monitor, Moore and Johnson (2011), found that three-month-olds did not have a preference for the mirrored stimulus but five-month-old infants did (Moore & Johnson, 2008). Although, Quinn and Liben (2008) and Moore and Johnson's (2011) findings in three-month-old infants, seem to contradict each other, this may be the result of the different stimulus they used. 2D stimuli are less complex than 3D stimuli and thus, for younger infants it may be easier to identify changes on a less complex figure. As Moore and Johnson suggested in regards to their findings in three- and five-month-old infants, it could be that it takes more time for younger infants to get fully habituated with a highly complex stimulus. Soska and Johnson (2013) did support the latter idea, as they used more complex 3D stimuli in four- and six-month-old infants, and did not find a preference for the novel versions in the four-months-old but they did in the six-months-old. It is noticeable from the previous studies that depending on the type of stimulus being used, different results are obtained. Thus it becomes a challenge to fully understand when visuospatial abilities first emerge. Although it can be summarized from the previous evidence that the ability to mentally rotate simpler (2D) pictures emerges as young as three-months-old and to mentally rotate more complex (3D) pictures emerges as young as five-months-old, these results may be very different if real objects are used.

Piaget and Inhelder (1971) stated "…the kinetic images become in essence figural imitations of the operations" (Piaget & Inhelder, 1971, p. 100). Since then, a close link between motor and cognitive development has been established across the literature. It has been stated that our ability to mentally rotate objects emerges throughout development due to the constant manipulation of real-world objects. Some studies in infants have explored this idea. Slone, Moore, and Johnson (2018), had four-month-old infants manually explore a real-world version of the 3D MRT figures before and after they were visually habituated with the same stimulus on a computer screen, they found that those infants that were in the group that manipulated the real-world stimulus before and that explored the figure more spontaneously, exhibited a longer looking time for the novel mirrored stimulus. Studies in older six- and nine-month-old infants corroborated this finding: prior manual exploration resulted in higher preference for the 3D mirrored stimulus (Schwarzer, Freitag, & Shum, 2013; Frick, Möhring, & Newcombe, 2014; Gerhard & Gudrun, 2018). Interestingly, longer looking time at the 3D novel stimulus was associated with more developed locomotor abilities (assessed through parent questionnaire) in ten-month-old, but not in eight-month-old infants (Frick & Möhring, 2013). In sum, these findings suggest that manual exploration of an object is necessary to create an appropriate mental representation of it, and more importantly, that motor and mental rotation development may go hand in hand at this young age.

From the preceding evidence, it has been shown that infants increased looking time at the novel (non-previously habituated) stimulus is indicative of them noticing that this stimulus has been modified (i.e. mirrored or rotated) in comparison to the previously habituated stimulus. Numerous studies have reported sex differences in looking times for the novel stimulus. Some studies have found these differences in infants as young as three-months-old: males spent longer time than females looking at the mirrored 2D stimulus than at the same previously habituated non-mirrored stimulus (Quinn & Liben, 2008). In a further study, these researchers failed to replicate this sex difference (Quinn & Liben, 2014). Moore and Johnson (2011), however, did find a sex difference using 3D MRT stimulus in three-month-old infants, but contrary to expected, males looking time was longer than females for the non-mirrored (habituated) stimulus than for the mirrored stimulus. Conversely, using the same 3D MRT stimulus, in five-month-olds, males looking time was longer for the mirrored stimulus than for the non-mirrored stimulus (Moore & Johnson, 2008). Based on their studies, Moore and Johnson suggested that this might be the result of younger (three-month-old) infants still acquiring information from the habituated stimulus due to a slower processing speed than older (five-month-old) infants. Moreover, this may also be the case for four-month-old infants, as other studies using 3D stimulus have also failed to find a sex difference at this age (Soska & Johnson, 2013; Slone, Moore & Johnson, 2018). Sex differences have been more consistently found in six-month-olds. Lauer and Lourenco (2015), found that for males looking time at the mirrored stimulus was longer in a group of six- to thirteen-months-old infants using a 2D stimulus; and other studies using either 2D stimulus (Quinn & Liben, 2014) or 3D stimulus (Soska & Johnson, 2013) in six-month-olds, have supported this finding. An interesting finding from the work by Soska and Johnson (2013) is that the sex difference disappeared by nine months of age; female infants displayed the same behaviour as males (spend more time looking at the rotated figure). Notably, the latter finding, is in line with the age at which Frick and Möhring (2013) reported the association between more developed locomotor abilities and increased looking time for 3D stimuli; supporting the idea that motor development (regardless of sex) may accompany the capacity to mentally represent objects with a higher complexity.

Overall, findings in regards to the development of MR ability and the presence of a sex difference in infancy are unclear. Part of this problem, is the use of many different stimuli and variations in age. It is also important to note, that even when the habituation-dishabituation technique has been well-established across the psychology field; in all the previously mentioned studies, it becomes challenging to ensure that mental rotation is really the mechanism explaining the longer looking times at the mirrored (or novel) stimulus. This is because other perceptual cues could be driving this behaviour, for example; differences in the angle and/or in the location between the habituated stimulus and the test stimulus can cause infants to draw more of their attention towards one of the stimuli (Levine et al., 2016).

1.4.2. Evidence of mental rotation ability in Children

In their cognitive developmental theory, Piaget and Inhelder (1971) first proposed that the ability to mentally rotate objects or what they called: "the modification of kinetic images", emerges at about seven to eight years of age. The previously mentioned evidence from infants and the proceeding studies on children, provide evidence that the ability to mentally rotate may emerge at an even younger age than when Piaget and Inhelder suggested. The concept of mental rotation was first introduced by Shepard and Metzler (1971) in their study; participants were presented with pairs of rotated 3D abstract cube figures. The pair of figures were either the same (simply rotated) or different (one of the figures was the mirror image) of the other. By pressing a button, participants then answered as fast as they could if the figures were the same or different. The results showed that the greater the difference in angular disparity between the pair of figures, the longer time it took for the participants to respond. Since Shepard and Metzler study, MR ability is characterized by the phenomenon of an increase in response time (reaction time) being directly proportional to the increase in angular disparity of the stimulus.

Using the Shepard and Metzler 3D abstract cube figures as stimuli, Vanderberg and Kuse (1978) developed the MRT: a paper and pencil test that consists of a several problems, in which each problem presents a rotated model (the target) and four rotated possible matching options. Only two out of the four options perfectly match the model figure, the other two are different (mirror images). The participant has to pick the two options that correctly match the target figure. To test children, some studies which have specifically used 2D stimuli have looked for the previously mentioned phenomenon to assure MR is happening. Conversely, most studies in children using 3D stimuli have not specifically looked at this phenomenon but have used an experimental paradigm as the one described to complete the MRT. In other words, some studies have changed the stimuli but have kept a paper and pencil test that consists of different problems with one targeted figure and multiple choices to pick the matching figures from. It is important to consider that for studies with children, not only having different dimensionalities (2D or 3D stimuli), but also different types of stimuli (i.e. abstract vs animated/familiar) have been shown to aid their ability to mentally rotate it (Kail, Pellegrinno & Phillip,1980; Rosser, Stevens Ensing, Glider, & Lane; 1984; Rosser, Stevens Ensing, & Mazzeo, 1985; Krüger & Ebersbach; 2017).

Although, it may be true that MR ability emerges in infancy, to measure infants' reaction time in a similar way as it has been done in older children or in adults (e.g. pressing a button or picking the matching option) is rather challenging if not impossible. Therefore, it is questionable if infants are indeed performing mental rotation using the violation of expectation paradigm. In fact, three-year-olds tested by Krüger, Kaiser, Mahler, Bartels, and Krist (2014), scored above chance at a computerized mental rotation test using 2D animated stimuli; but in a follow up study this finding was not replicated (Kruger, 2018). In four-year-olds evidence of MR ability is inconsistent. Also using 2D animated stimuli, Marmor (1977) found similar behaviour in four-year-olds and in adults suggesting that MR skill was in place by age four. In further studies, however, researchers were unable to replicate this finding even in five-year-olds (Dean & Harvey, 1979; Platt & Cohen. 1981). This undermines the possibility of MR ability being mature in four-year-olds. A study by Estes (1998), combined a 2D animated computerized stimuli and a questionnaire on "mental activity", in a group of four- and five-year-old children. It was found that the minority of four-year olds but the majority of five-year olds were able to give an explicit verbal description of MR taking place or what the investigators considered evidence of "mental activity". Importantly, this phenomenon was only associated with those that were able to formulate the verbal description. Taken together, this evidence suggests that MR ability is consistently present somewhere around five years of age. For example, Frick, Hansen, and Newcombe (2013) used 2D animated stimuli (although presented in a real-world setting), and found a dramatic increase in performance between three- and five-year-olds, from a 54% accuracy to an 83%, respectively. Individual analyses revealed that only a few of the three-year-olds, less than half of the four-year-olds, and most five-year-olds performed above chance at the task. The latter finding shows evidence of why the MR phenomenon is not found in three-year-olds, is inconsistently found in four-year-olds, and is more consistently found in five-year-olds (Marmor, 1975; Kosslyn, Margolis, Barrett, Goldknopf, & Daly, 1990; Frick, Daum, Walser, & Mast, 2009; Quasier Pohl, M. Rohe, & Amberger, 2010; Frick et al., 2013; Frick, Ferrara, & Newcombe, 2013).

Other studies investigating the developmental trajectory of MR ability have included further improvement in MR between five and seven years of age. The Lehman, Quaiser-Pohl, and Jansen (2014) study also exemplifies an improvement specifically during these ages; they grouped five- and six-year old children and three- and four-year-old children and tested them on the same 2D animated stimuli mental rotation task, and found that the older group significantly outperformed the younger group. Lastly, in five-year-olds and in older children (eight- and eleven-year-olds) MR skill has been found regardless of using 2D animated (Platt & Cohen, 1981) or 2D abstract (Frick et al., 2009; Kosslyn et al., 1990) stimuli.

In line with age-related cognitive development, most evidence using 3D stimuli instead of 2D stimuli, suggests that the age at which children are capable of completing 3D computations is later than for 2D. This is not surprising because 3D stimuli require a higher demand of MR ability than 2D stimuli do. It is important to note, however, that MRT stimuli are abstract and do not depict familiar or real world objects as the studies using 2D stimuli. Although several studies in children have modified the presentation (e.g. displaying real-world stimuli) of the MRT or have a simplified version of it (e.g. only displaying one pair of stimuli) results are also inconsistent in the literature. Without any modifications, the MRT has proven challenging for elementary school children (mean age= 7.8; Hoyek, Collet, Fargier, & Guillot, 2012) and some researches have even considered it unreliable as a test for children younger than ten-years of age (Johnson & Meade, 1987).

Even when the MRT is presented with real blocks (i.e. not paper- or computer-based), it appears to be challenging. Hawes, LeFevre, Xu, and Bruce (2015) developed a test that displayed the figures as real-world objects. They found that four-year-old children performed below chance, and although five-year-olds performed above chance, eight-year olds doubled their scores. This suggests that 3D MR ability continues to develop during the first decade. It also suggests that even when the MRT stimuli are modified in their presentation their configuration seems to be challenging for younger children to comprehend thus, making the MRT unsuitable for assessing MR abilities in the young. Acknowledging this limitation, Lütke and Lange-Küttner (2015), developed a simplified version of the MRT. Instead of having multiple cube aggregates they just presented children with single rotated cube, and multiple choices from which the children had to pick the correct matching cube. Although, they did not test children younger than seven, the ten-year-olds significantly outperformed the seven- and eight-year-old children. In sum, it may in fact be that Piaget and Inhelder (1971) were correct when suggested that seven years of age was when the capacity for the "modification of kinetic images" first appears.

Numerous researchers have investigated sex differences in young children using 2D stimuli (abstract or animated) or 3D stimuli (the MRT or simplified versions of it) (Tetering, van der Donk, de Groot, & Jolles, 2019; Titze, Jansen, & Heil, 2010; Neuburger, Jansen, Heil, & Quaiser-Pohl, 2011; Hoyek et al., 2012). Levine, Huttenlocher, Taylor, and Langrock (1999), developed the Children Mental Transformation Task (CMTT), that required children to put together the split rotated components of an abstract 2D figure to recreate its unified version. Using this task, researchers found a male advantage in children as young as 4.6 years that remained in their older group (seven-year-olds). Also, using 2D abstract stimuli Tzuriel, and Egozi (2010), confirmed the male advantage in 6-7 year olds. However, there are numerous studies on MR ability (using 2D stimuli) that have failed to find sex differences in four-year-olds (Marmor, 1977; Estes, 1998; Fernández, Contreras, & Elosúa, 2018), five-year-olds (Marmor, 1977; Estes, 1998; Marmor, 1975; Frick et al., 2013; Frick et al., 2009; Fernández et al., 2018), six-year-olds (Estes, 1998; Frick et al., 2009; Lehman et al., 2014), eight-year-olds (Marmor, 1975; Kosslyn et al., 1990; Roberts & Bell, 2000; Rodán, Gimeno, Elosúa, Montoro, & Contreras, 2019) and even in eleven-year-olds (Frick et al., 2009; Barel & Tzischinsky, 2018).

With respect to the MRT either as a simplified version or the regular test, sex differences have been reported but they appear to be consistent only in older children. Boys tested in the simplified version of the MRT showed an advantage over girls at seven (Tetering et al., 2019) and at nine-years of age (Vederhus & Krekling, 1996; Tetering et al., 2019). Using the regular MRT, it has been suggested the male advantage does not appear reliably until ten years of age (Johnson & Meade, 1987) and several studies confirm this finding. Children in the 2nd grade (6.83 - 9.92 years old; mean age = 7.94) and the 4th grade (8.25 -12.17 years old; mean age= 10.06) completed the MRT, but only males in 4th grade outperformed females. There were no sex differences in 2nd grade children (Neuburger et al., 2011). Barel and Tzischinsky (2018) tested children in elementary and middle school and found that males outperformed females starting in grade four (mean age= 10.4) but not before. Titze et al. (2010) explored the sex difference on the MRT in a narrowed age gap (8-11 years). Authors found that males between the ages of 9.9-11.0 years of age significantly outperformed females but younger males between the ages of 8.3-9.6 years did not. Lastly, Kerns and Berenbaum (1991) provided evidence that the male advantage in 4th to 7th grade children (mean age= 10.2) can be present using 3D abstract stimuli that are not necessarily the MRT. In sum, sex differences in MR ability particularly using the MRT seem to appear at age ten.

Overall from this evidence, it is clear that the use of different stimuli dimensionality and stimuli type play a very significant role in the study of MR, particularly its development and the presence/emergence of sex differences. For example, some evidence has suggested that females tested at the MRT during childhood do not significantly show improvement with age, but males do and thus the sex difference (Titze et al., 2010; Neuburger et al., 2011). This finding is important if we are to develop programs that enhance MR abilities particularly in young females.

1.4.3. Evidence of mental rotation ability in teenagers

Research on the development of mental rotation ability has historically presented evidence of improvement during the teenage years (Wilson et al., 1975). Piaget and Inhelder (1958) proposed that at this age abstract, logical, and systematic ways of thinking were possible. Following researchers tested the idea that on a given mental rotation task, teenagers must then perform significantly better compared to children. Waber, Carlson, and Mann (1982) tested 5th grade children (11-year-olds) and 7th grade teenagers (13-year-olds) on a mental rotation task using 2D familiar stimuli (letters) and argued that although the children were capable of mentally rotating the stimuli, teenagers significantly outperformed them. Others have not only compared children and teenagers on their ability to mentally rotate, but they have also compared adolescents with young adults. Using 2D familiar stimuli (letters) Kail et al., (1985) compared teenagers in grades 8th and 9th (Mean age= 14) to children in grades 4th and 5th (Mean age= 11) and to young adults (Mean age= 19). The results showed that teenagers' and adults' response time was comparable to each other and that both of these groups were significantly faster than children. This suggests that the ability to rotate 2D familiar stimuli in teenagers may already be developed to the same level of adults. In a previous study, using the same stimuli, Kail (1980) did not directly test teenagers, but did find that the response time to abstract 2D stimuli (MRT) was significantly higher in children (grades 3^{rd} ,4^{th}, and 6^{th}) than in young adults. Kail suggested that the time in between childhood and adulthood (which are the teenage years), is critical for the improvement of MR ability. Findings of Kail (1980) and (1985) were confirmed later by Kosslyn et al. (1990). Kosslyn and colleagues, found a faster response time with increasing age between children (two groups; 4.5- to 6-years-old and 7.6 to 9-years-old), teenagers (13- to 15-years-old) and young adults (18- to 57- years-old), using abstract 2D (MRT) figures as stimuli. Moreover, a large difference was only found between the youngest (children) groups and the oldest (adolescents and young adults) groups. Together, this evidence suggests that the ability to mentally rotate 2D stimuli regardless of being familiar or abstract reaches adult-like levels during the teenage years.

In the teenage years, a sex difference in psychometric tests for mental rotation has been well-established across the literature. Early studies even suggested that the male advantage emerges at this time of development (Waber, 1976; Maccoby & Jacklin, 1974), and some researchers argue that sex differences in MR ability increases during the teen years (Linn & Petersen, 1985; Voyer et al., 1995; Herlitz, Reuterskiöld, Lovén, Thilers, & Rehnman, 2013). The majority of research exploring sex differences in MR have utilized the MRT (involving 3D abstract stimuli) perhaps because as it has been previously stated that this test is suitable for this age group (Linn & Petersen, 1985). Using this test, numerous studies have found sex differences beginning with thirteen-years-old and up until seventeen-years-old (Wilson, 1975; Johnson & Meade, 1987; Kosslyn, 1990; Masters & Sanders, 1993; Codorniu-Raga & Vigil-Colet, 2003; Neubauer, Bergner, & Schatz, 2010; Moé, 2016; Jansen, Ellinger, Jehmann, 2018). However, as it is the case from the evidence on infants and children, other research in adolescents has failed to find a sex difference, especially using abstract or familiar 2D stimuli (Kosslyn et al., 1990; Kail,1980; Waber et al., 1982; Kail et al., 1985). It is possible that the absence of a sex difference is due to the fact that mentally rotating 2D stimuli is less demanding than rotating 3D stimuli. Thus teenagers, regardless of sex, can easily rotate 2D figures making the sex difference disappear. Interestingly, Neubauer et al. (2010) presented teenagers (15-year-olds) with the MRT but as if it was presented in "real life" (through using a projector and special glasses), in this case they did not find a male advantage. This result suggests that females may have benefited from a "real life" presentation of the stimuli. Experimenters should be careful in choosing the type of stimuli and presentation when exploring sex differences in MR as these can significantly affect the outcome.

1.4.4. Evidence of mental rotation ability in young adults

Although some studies have shown no differences in MR between teenagers and young adults, overall it is well accepted that young adults typically outperform all other age groups. Specifically, adults between 20-28 years of age show the best performance (Wilson, 1975; Borella et al., 2014; Iachini, Ruggiero, Bartolo, Rapuano, & Ruotolo, 2019) suggesting that this is the time when mental rotation ability peaks. Young adults' performance in mental rotation tasks has been compared to children, teenagers and older adults finding that regardless of stimuli dimensionalities (2D or 3D), or stimuli types (abstract or familiar), their response time was the fastest and their accuracy was the highest (Kail, 1980; Herman & Bruce, 1983; Kosslyn et al.,1990; Jansen & Heil, 2009; Titze et al., 2010; Borella et al., 2014; Iachini et al., 2019). For this reason, when investigating the progress of MR across the lifespan young adulthood has served as the differentiating point between ongoing developmental improvements and normal age-related declines.

With respect to sex differences in MR, research in young adults has shown the most consistent results. Meta-analyses across the years have confirmed a male advantage using the MRT (Linn & Petersen, 1985; Masters & Sanders, 1993; Voyer et al., 1995; Voyer, 2010). This advantage has also been found on studies using tests such as the Purdue Visualization test (Bodner & Guay, 1997) which uses 3D abstract stimuli, the Cards Rotation Test (Petrusic, Varro, & Jamieson, 1978; Sanders, Soares, & D'Aquila, 1982; Geary, Gilger, & Elliott-Miller, 1992) which uses 2D abstract stimuli, and also in tests that use 2D stimuli that are familiar (e.g. human faces, human features, or animals; Roberts & Bell, 2000; Jansen & Heil, 2009). Using the MRT or its abstract 3D stimuli, sex differences have been found across young adulthood with varying mean age. Some of this mean ages studied are: 22.8 years (Jansen & Heil, 2009), 23.1 years (Titze et al., 2010), 23.2 years (Heil, Krüger, Krist, Johnson, & Moore, 2018), 23.6 years (Voyer & Jansen 2016), 25.3 years (Herman & Bruce, 1983), 27.4 years (Debarnot, Piolino, Baron, & Guillot, 2013) and 27.9 years (Parsons et al., 2004). Sex differences in MR have also been described in undergraduate students in general with unspecified mean age (Geary et al., 1992; Delisi & Cammarano, 1996).

Very few studies have reported no sex differences in MR in young adults. However, it is impossible to know if this is because journals are rarely interested in publishing null results, or if because the sex difference is robust and universal. Although this might be a matter of debate, interestingly when the MRT was presented differently, that is, instead of using the paper and pencil set up but in a more real-world manner (using virtual reality), a male advantage was not found (Larson et al., 1999; Parsons et al., 2004). It has been suggested that females significantly improve more than males when the stimuli are human figures (Doyle & Voyer, 2018); suggesting that female and male performance may differ depending on the type of stimuli used for the MR task. For example, no male advantage was found using a test (TAMI- Test of Ability in Movement Imagery) that requires mental rotation but that is presented in an egocentrically based manner using human-like stimuli. On the TAMI, the participant is given a certain initial body position, then a set of instructions (e.g. "step your left foot forward, turn your torso 60 degrees to the right, etc") and then they are required to choose a final body position from a set of drawings. It is possible that utilizing body parts particularly when egocentric frames of reference are needed for the MR computation (Madan & Singhal, 2015) simplifies the task. Using a clever design, Voyer and Jansen (2016), modified the 3D MRT stimuli in two ways: they added heads to the top of the abstract cubes, and they made them look more like human bodies. The authors found that performance was better in the human-like MRT figures when compared to the regular abstract stimuli. They also found sex differences (male advantage) for accuracy but not for reaction time. The results suggest that the type of stimuli, its presentation, and the frame of reference (egocentric versus allocentric) may partly contribute to the large sex effect found in young adults. Some studies have specifically explored this idea, for example; Voyer, Jansen, and Kaltner (2017) used 2D egocentric- or allocentric-based (object-based) stimuli to investigate sex differences. The authors found that in general, participants were better on the egocentric-based task and that there was male advantage but this was smaller than for the allocentric-based task. Finally, some studies have investigated if the sex of the human-like stimuli affects MR abilities. Alexander and Evardone (2008), used the MRT or human figures (male and female) in different orientations to assess MR ability. The results showed that males were better when using human figures but only if these depicted a male. Female performance using the human figures (regardless of the sex of the figure) was better than for the MRT. This suggests that the item properties, specifically the sex of human-like stimuli influences MR ability. From this evidence, it appears that males outperform females in some tests of MR but importantly, it is clear that the type of stimuli and its presentation can greatly impact the magnitude of the sex differences, thus, these factors must be taken into account when studying sex differences.

1.4.5. Evidence of mental rotation ability in older adults

Mental rotation ability is among the cognitive functions that have been demonstrated to show consistent and linear age-related declines. Studies have shown that younger adults significantly outperform older adults regardless of the mental rotation task. Several studies have focused on exploring response time differences between younger and older adults. This consisted of asking participants to identify if the pair of rotated stimuli presented in front of them were the same or different (one was a mirror image); the time taken for the participant to respond was then recorded. A slower response time in older adults using 2D familiar (letters) stimuli has been frequently found (Cerella, Poon, &

Fozard, 1981; Dror & Kosslyn, 1994; Jansen & Kaltner, 2014; Zhao, Della Sala, & Gherri, 2019), and some authors have even suggested a 95% age-related decline in MR skill in seniors (Cerella et al., 1981). This slow response time is also found when using 2D or 3D abstract stimuli (Berg, Hertzog, & Hunt, 1982). Using the MRT Gay Lord and Marsh (1975) concluded that older adults' mental rotation processing was significantly slower than in younger adults (precisely 84% slower). The slower response time in older adults has also been found using 3D familiar (human or object toy pictures) stimuli (Puglisi & Morrell, 1986; Rahe, Ruthsatz, Jansen, & Quaiser-Pohl, 2018).

Although some studies have found differences between younger and older adults in reaction time using 2D letters as stimuli, others have not found differences in accuracy between these groups (Cerella et al., 1981; Berg et al., 1982). However, using other types of stimuli, for example; abstract 2D stimuli (Jansen & Heil, 2009; Iachini et al., 2019), familiar 3D stimuli (Rahe et al., 2018) or abstract 3D (MRT) stimuli (Hermann & Bruce, 1983; Jansen & Heil, 2009; Borella et al., 2014) differences in accuracy have been found. Response time seems to also be affected even within the same dimensionality. For example, 2D human figures were rotated faster than 2D letters (Jansen & Kaltner, 2014). Notably, it has been suggested that differences in reaction time are much larger than differences in accuracy when comparing young and older-adults. In their meta-analysis Techentin, Voyer, and Voyer (2014), found that although older adults' performance in psychometric tests including 2D or 3D stimuli (e.g. MRT) was significantly below that of young adults, they also found that measures that recorded response time produced larger age-related effects than those that recorded accuracy.

As can be noted from the previously presented evidence in this section, it is important to acknowledge that different types of stimuli (familiar versus abstract) may be easier or more challenging to rotate for older adults. Iachini et al. (2019) found that although young adults outperformed older adults in 2D abstract (lines) or familiar (human, animal faces) stimuli, the older adults' performance significantly improved when the familiar stimuli were used. Similarly, older adults are significantly faster at mentally rotating 3D familiar (human bodies) stimuli that displayed anatomically possible rotations (egocentric-based), in comparison to human bodies that displayed impossible rotations (object-based) and those two were faster than rotations of 2D letter stimuli (Jansen, & Kaltner, 2014). This suggests that even within familiar stimuli (human features and letters), differences in the ability to mentally rotate them exist. In a unique study, de Bruin et al. (2016), used a real-world hands-on brick building visuospatial task (BBT) which varied in mental rotation demand (2D-low mental rotation demand versus 3D-high mental rotation demand) of objects constructed with bricks. Time to complete was recorded and the results showed that although young adults outperformed older adults on the test, the differences in time expressed as a percentage change between the low- and high-mental rotation demand objects were comparable between groups. This suggests that the ability to mentally rotate was preserved in older adults. The use of a real-world task instead of paper and pencil tests, to assess MR may make it less challenging for older adults to complete. Lastly, another important aspect to take into account is the procedural differences between MR tasks; older adults performance may be impacted as a result of the type of instructions to complete the task and specially as a result of having a set time limit (Hertzog, Vernon, & Rypma, 1993).

Sex differences have been reported in older adulthood regardless of the use of 2D or 3D stimuli. The male advantage has been found on the Cards Rotation Test, which uses 2D abstract stimuli (Willis & Schaie, 1986). The advantage in this test was confirmed in a further longitudinal study (McCarrey, An, Kitner-Triolo, Ferrucci, & Resnick, 2016). Interestingly, some evidence has suggested that visuospatial abilities decline faster in males than in females. Two longitudinal studies that investigated overall age-related cognitive changes (in language, learning, memory, attention, motor speed, and visuospatial function) both reported less rapid decline in women in most (including visuospatial skill) cognitive functions (McCarrey et al., 2016; Caskie, Schaie, & Willis, 1999). When using the MRT or its simplified version, some research has found sex differences in older adults. Males outperformed females in a simplified version of the MRT (Herman & Bruce, 1983) and in the standard MRT (Jansen & Heil, 2009). The simplified version consists of simultaneously presenting two 3D abstract cube figures. The participant's job is to decide if they are the same or different. There are only a few studies that have reported no sex differences in older adults (again, perhaps researchers have found null results but have failed to publish them). The studies that have found similar performance by females and males also happen to use different stimuli than the frequently used MRT. Males did not outperform females when 3D familiar objects (Rahe et al., 2018) or when real-world objects were used (de Bruin et al., 2016).

Collectively, it is evident from this section and previous sections that there are numerous tasks used to measure MR ability. These tests differ in dimensionality (2D versus 3D), familiarity (familiar versus abstract), frame of reference (egocentric versus allocentric), and structure (paper-based versus hands-on) and these different characteristics can significantly affect performance at any age including the presence or absence of a male advantage. Moreover, even a small age difference can impact performance on MR tasks as shown in the studies with young children. Perhaps using (or developing) tools that do not need to be modified to be appropriate for the different age groups would bring some consistency to the results and would prove valuable when investigating the developmental trajectory of spatial ability (including its decline).

1.5 Factors known to influence the development of visuospatial abilities

1.5.1. Sex hormones

Sex hormones (i.e. steroid hormones, gonadal hormones) are responsible for sexual differentiation and reproductive development of males and females. The male sex hormones are androgens (e.g. testosterone) and the female sex hormones are estrogens (e.g. estradiol) and progesterone. A classic and prominent study that clarified the relationship between sex hormones and behaviour was documented by Phoenix, Goy, Gerral, and Young (1959). They found that prenatal androgen treatment in female guinea pigs, masculinized behaviour on the later adult guinea pig, demonstrating that altering sex steroid levels during this time in development caused permanent changes on the adult brain. Phoenix et al., (1959) also put forward the idea that sex hormones had differential effects on the brain. Guinea pigs that were treated with androgens prenatally, during adulthood were defeminized and more masculinized in their coupling behaviour thus exhibiting permanent effects that they called, organizational effects. They also observed that those adult female guinea pigs with higher levels of estrogens and progesterone displayed feminine coupling behaviour that was not exhibited when these hormones were absent

(Phoenix et al., 1959). Coupling behaviour is also affected by transient hormonal changes. These have been called activational effects (Arnold & Breedlove, 1985; Arnold, 2009). In sum, organizational effects cause permanent and irreversible changes to brain structures, while activational effects are reversible and can happen at any point in time. Since the study by Phoenix et al., (1959), research in humans and other animals have used the organizational-activational concept as a theoretical framework to understand brain and behavioural changes (Hampson, 2018). This research has demonstrated that sex hormones affect brain cells' structure and function (Kolb & Whishaw, 2003; Kolb & Gibb, 2011; Wierenga et al., 2018) including regions that support visuospatial cognition (Kolb & Whishaw, 2003; Sisk & Zehr, 2005; Becker et al., 2008; Schulz, Molenda-Figueira, & Sisk, 2009; Thornton, Zehr, & Loose, 2009; Beltz & Berenbaum, 2013).

Researchers have demonstrated that performance in MR tasks is affected by the organizational and activational effects of sex hormones. Two natural occurring prenatal hormonal disorders that substantiate organizational effects of sex hormones are: Congenital Adrenal Hyperplasia (CAH) and Idiopathic Hypogonadrotopic Hypogonadism (IHH). CAH, is a mostly female hormonal disorder; characterized by abnormally high androgen levels in utero. During childhood, CAH females display a better performance on mental rotation ability tests when compared to their sisters without the disorder (Puts, McDaniel, Jordan, & Breedlove, 2007; Berenbaum, Bryk, & Beltz, 2012; Hampson & Rovet, 2015). IHH, is a male hormonal disorder characterized by low levels of androgens in utero. Males with IHH later in life show poor performance on mental rotation tests compared to control males (Hier & Crowley, 1982). There is also supporting evidence that prenatal exposure to sex hormones contributes to performance in MR tests in people without a hormonal disorder. A study measured testosterone levels in utero and found a positive relationship between the levels of this hormone and mental rotation performance at seven-years of age (the higher the testosterone levels the better the performance; Grimshaw, Sitarenios, & Finegan, 1995). Another study measured testosterone levels in 1-2 month old infants and found positive associations with performance in a mental rotation task at 5-6 months of age (Constantinescu, Moore, Johnson, & Hines, 2018). Having a male co-twin has also been related to better performance by the female twin on a mental rotation task. This is because testosterone levels in utero are higher (Vuoksimaa et al., 2010). Although organizational changes have been mostly considered to happen prenatally; some studies support the idea that puberty places another window on which sex hormones can produce organizational effects on the brain (Sisk & Zehr, 2005; Schulz, Molenda-Figueira, & Blakemore, 2009; Blakemore, Berenbaum & Liben, 2013). It has been found that timing of puberty mediates sex-typical behaviour. For example; females who mature earlier have better verbal abilities than those who mature later; and those who mature later have better spatial abilities. Conversely, in males, those who mature earlier have better spatial abilities than those who mature later, and those who mature later, have better verbal abilities (Waber, 1976; Beltz & Berenbaum, 2013). Similarly, Sanders and Soares (1986) found that young adults females who were late-maturers scored significantly higher in a mental rotation test than early-maturers. In general, levels of testosterone (in both males and females) have been related to better performance on mental rotation tests during puberty (Davison, & Susman, 2001). There is some evidence however, that high levels of testosterone in males either in utero (Grimshaw et al., 1995), during puberty (Vuoksimaa, Kaprio, Eriksson, & Rose, 2012), or during adulthood (Yonker, Eriksson, Nilsson, & Herlitz, 2006) could lead to poorer spatial ability. For example; Yonker et al. (2006), measured the amount of free testosterone in a large sample (N= 450) of adult men (ages 35 to 80). These men were first placed into their corresponding age groups (35,40,45,50.. etc) and the median amount of free testosterone was calculated for each group. Participants were then divided according to their amount of free testosterone. Those that were below the median were placed on the "low testosterone" group and those above the median on the "high testosterone" group. Yonker and colleagues found that those with low testosterone levels performed better at a spatial ability task than those with high levels of this hormone. Thus it appears that the effects of testosterone on MR ability follow an inverted U shape curve. Very low or very high levels of testosterone result in low MR ability. Together these studies suggest that levels of testosterone during critical developmental periods influence spatial ability in very significant ways.

There is also evidence of changes in performance on MR tasks due to the activational effects of sex hormones. These changes have been particularly studied in young adults. In adulthood, sex hormone levels vary in both females and males but due to the menstrual cycle, sex hormone variations are more evident in females. Menstrual cycle phases are characterized by changing levels of these hormones. For example, the luteal phase is characterized by high estrogen and progesterone levels, while the ovulatory phase, is characterized by low levels of estrogen and high levels of testosterone. A particular strong link has been found between varying levels of estrogen and performance in MR tasks. A poor performance has been recorded when estrogen and progesterone levels are high and a favorable performance when estrogen levels are low and testosterone levels are high (Hampson, 1990; Hausmann, Slabbekoorn, Van Goozen, Cohen-Kettenis, & Gunturkun, 2000; Hampson, Levy-Cooperman, & Korman, 2014). In addition, external hormonal influences have also shown to affect MR. Principally, females are constant users of hormonal medications (e.g. oral or injection birth control, hormonal intrauterine device, etc). These medications prevent the peak of estrogen that characterizes a typical menstrual cycle keeping hormonal levels stable. Some research has shown that female users of oral birth control outperform non-users in MR tasks (Beltz, Hampson, & Berenbaum, 2015). Importantly, testosterone levels in males or females have also been related to better performance in MR tasks. In young adult females, the increase of testosterone results in improvements in spatial ability (Pintzka, Evensmoen, Lehn, & Håberg, 2016) and in young adult males, very low levels of this hormone have been related to a poor performance in MR tasks (Yang et al., 2007). In older adulthood, testosterone has also shown to mediate performance in spatial tasks. Older males on hormonal replacement therapy display improvements on these tasks (Janowsky, 2006). Notably, it has been suggested the persistent male advantage (up until older adulthood) in spatial abilities is related to circulating levels of testosterone (Driscoll, Hamilton, Yeo, Brooks, & Sutherland, 2005). Interestingly, males with very high levels of this hormone show a poor performance in spatial tasks (Kolb & Whishaw, 2003), suggesting again, that there is an optimal level of this hormone for optimal MR performance.

In sum, several studies support the organizational and activational effects that sex hormones exert in MR for both, females and males. In addition, although there is some evidence supporting the idea that estrogen levels affect performance in MR tasks; testosterone seems to play a bigger role in mediating improvement of performance on MR tasks. Therefore, because for males the dominant sex hormone is testosterone, the male advantage may emerge from this biological factor. However, because experiments on sex hormones are challenging to accomplish in humans, there are inconclusive results on how and why these hormones affect brain structures supporting visuospatial functioning. Moreover, there are also inconclusive results on how the effects of sex hormones may be accompanied or influenced by genetics or environmental factors and further, how together these factors could potentially interact with one another to cause the sex differences in MR.

1.5.2. Training

Not only biological factors influence the development of visuospatial abilities but so do environmental factors. Visuospatial abilities are known to be malleable (Uttal et al., 2013) meaning that they can be easily enhanced through exposure to spatially stimulating activities. The meta-analysis by Uttal and colleagues was the first to investigate the effects of training on spatial abilities. They included research from 1984-2009 that used various psychometric tests covering multiple different aspects of visuospatial abilities. The main finding was that spatial training significantly improved performance in this type of task (in the case of MR training improved both reaction time and accuracy). Importantly, the effects of training were: 1) long-lasting (no differences between performance immediately after training, a week later or a month later were found); 2) all types of training were comparable (no type of training was more beneficial); 3) females and males both benefited equally from training (although the sex gap did not diminish after training); 4) training benefited people of all ages; 5) those subjects displaying lower spatial ability levels before training benefited the most from training; and 6) the effects of training were not only transferable within ability but they were also transferable to other types of spatial abilities (tapping on the interconnection of these abilities).

Following the meta-analysis by Uttal et al. (2013), several studies have confirmed their findings. Beginning with infants, studies using the habituation-dishabituation technique and the violation of expectation paradigm (see section 1.4.1 for descriptions of this technique and paradigm) have demonstrated improvement on MR tasks with training. Using real-objects, Frick and Wang (2014) found that infants who during the training phase manipulated and rotated the object located in front of them increased their looking time to the rotated object during the testing phase. Likewise, Slone et al. (2018) allowed infants to first physically manipulate the figures (3D MRT) that were later presented in their computer version during the testing phase. The results showed that infants also increased their looking time to the mirrored stimulus. Significant improvements in MR through training have also been found in children (older children benefit more) and adolescents. For example, 4-5 year olds improved in a 2D mental rotation task after training for three consecutive days (15 min sessions). This was not the case, however, for 3-4 year olds (Fernández-Méndez et al., 2018). Similarly, another study showed that 6-8 year olds performed better in the post-testing phase of a 2D picture rotation task after they had played games with digitized 2D rotation figures (that were different from the testing stimuli; Hawes, Moss, Caswell, & Poliszczuk, 2015). A recent study also investigated the effects of training in MR in 6-8 year olds (Rodán et al., 2019). They used a computer-based program for training that consisted of rotating the stimuli (two available options) and picking the one that correctly matched the mold. For the testing, children were asked to pick the rotated stimulus that matched the mold in order to complete a puzzle. To make it more challenging, authors included four options instead of only two. Significant improvements were found in the children that participated in the training while no improvements were seen in the children that did not receive any training. Of note, is that all previous studies used 2D stimuli for the pre-testing, training, and post-testing phases. Lin-Heng and Chien-Min (2016) used 3D stimuli (MRT figures) and a unique training with digital puzzle games in primary school children and found that training was beneficial. Using the same training, pre- and post-tests described previously by Rodán and colleagues, teenagers also demonstrated improvements in MR (Rodán, Contreras, Elosúa, & Gimeno, 2016). Moreau (2013) used video game training in young adults to investigate if MR ability could be improved. Two video game set ups were used; one was a 2D block video game (Tetris) and the other one was a 3D block video game (Blockout). Half of the young adults were trained with the 2D video game and half with the 3D video game. All young adults were assessed pre- and post-training using MR tasks which varied in the dimensionality of the stimuli (2D vs 3D). Interestingly, results demonstrated that 3D training was favorable for both 2D and 3D post training, but 2D training did not lead to improvements on 3D tasks. This result suggests that the use of higher complexity activities in training may be more beneficial at enhancing MR. Lastly, not only is training is favorable during development and young adulthood but also in older adults (Meneghetti, Cardillo, Mammarella, Caviola, & Borella, 2018).

With respect to sex differences, some evidence suggests that regardless of age training can fill in the gap between male and female MR ability. A large sample of children between six and seven years old (mean age= 6.7 years old) were divided into two groups: an experimental group, which underwent an in school three-month intervention program, and a control group, which did not take part in the program. The intervention consisted on presenting children with 2D drawing of perspective images (e.g. geometrical figures that could take a concave or convex perspective) and then ask them to draw the figures. The experimenter, then spent some time showing the children how the images could be seen one way or the other. The results demonstrated that the male advantage which was present at baseline; disappeared in the experimental group (Tzuriel & Egozi, 2010). Similarly, teenagers involved in a two-week computer based training program displayed comparable performance between female and males in the post-test even though female teens were below male performance during baseline (Neubauer, Bergner, & Schatz, 2010). In the Moreau study, (described previously), the sex differences present on the 3D pre-training tasks in young adults disappeared, but, only in the group that was involved on the 3D (Blockout) video game. The benefit of training and its impact on males and females is not restricted to childhood. A fourteen-year long longitudinal study by Willis and Schaie (1988) in a large sample of older adults demonstrated that sex differences present at baseline disappeared after training. Notably, they also found that females significantly improved more than males between the pre- and the post-test phase. The fact that all of the studies mentioned before found sex differences at base-line that disappeared or diminished after training, suggests that training is specifically beneficial for females. Although, this evidence does not support the overall finding by Uttal et al. (2013) of the prevalence of sex differences in MR, it is in line with their finding that those who show low mental rotation before training (e.g. females) benefit the most from training. Importantly, a link between higher spatial skills has been found with STEM domains (Wai et al., 2009). Particularly MR has been linked to success in STEM in all age groups (Gilligan et al., 2017; Ganley et al., 2014; Shea et al., 2001; Casey et al., 1995; Wei et al., 2012); and the underrepresentation of women in STEM professions has been partly suggested to be the result of the female disadvantage in spatial abilities (Wang & Degol, 2017). Training MR thus may not only help both males and females consider STEM paths (Lubinski, 2010;

Uttal & Cohen, 2012; Uttal et al., 2013) but it can also potentially help close the sex gap present on these areas. Some studies in children (Cheng & Mix, 2014; Gilligan et al., 2017) and in young adults (Hoyek et al., 2009; Sorby, Casey, Veurink, & Dulaney, 2013; Miller & Halpern, 2013) have already found that the skills acquired through MR training are transferable to STEM domains.

1.5.3 Stereotype

Human (Berenbaum & Hines, 1992; Pasterski et al., 2005) and non-human primate studies (Hines et al., 2002; Hasset, Siebert, & Wallen, 2008) have shown a biological predisposition for females and males to prefer "feminine" or "masculine" types of play behaviour and toys, (e.g. human females are more attracted to dolls and males are more attracted to cars). Differences in toy (Berenbaum & Hines, 1992; Servin, Nordenström, Larsson, Bohlin, 2003; Pasterski et al., 2005) and activity preferences between males and females have also been related to prenatal hormonal levels (Wallen, 2005; Constantinescu & Hines, 2012; Hines, Constantinescu, & Spencer, 2015). Recent evidence suggests that especially toy preferences appear early in development (without parental influence; Todd, Barry, & Thommesssen, 2016). Although, there is undoubtedly evidence that supports a biological influence that can explain the sex differences in the preference for toys or activities, it is crucial to acknowledge that societal influences such as gender stereotypes can certainly have an impact towards these preferences. Bandura and Bussey (2004) state that "gender identity emerges from cognitive processing of correlative experiences in which physical characteristics, objects, and activities are differentially linked to the sexes" (p. 696). Thus, gender is a societal construct built from a combination of biological and environmental factors for which gender-stereotypes have been created, and females and males have been differentiated from each other. Some examples are females and males are expected to play with different types of toys (doll vs car) and be involved on different types of activities (cooking vs building).

Gender stereotypical masculine toys such as construction toys and video or computer games, in particular, have been shown to encourage mental rotation, spatial visualization, spatial manipulation, and the understanding of movement in space. A study by Nazareth, Herrera, and Pruden, (2013), in fact found that the degree of exposure to masculine spatial activities was correlated with MRT scores. On the contrary, feminine stereotypical toys for the most part do not encourage visuospatial computations. For example, dressing up, playing with dolls, or tea sets, (Tracy, 1987) are not particularly spatially challenging. In an earlier study, Bussey and Bandura (1999) also suggested that another factor that promotes gender stereotypes is parental engagement on gender-stereotypical activities. As a matter of fact, parental gender-stereotypical attitudes have shown to impact their children's performance in MR tasks, especially in females, where the more traditional the parents were in regards to gender-stereotype toys, the lower the performance of their daughters at MR tasks (Constantinescu et al., 2018). In addition, the language used by parents (i.e. frequent use of spatial words (e.g. under, above etc)) has been shown to positively correlate to the amount of spatial language used by their children and importantly, to better performance on spatial tasks (Pruden, Levine, & Huttenlocher, 2011). Lastly, even in young adulthood, when experimenters notify female participants before completing the MRT that males were better than females on the test, this had an negative effect on their performance (McGlone & Aronson, 2006; Campbell & Collaer, 2009; Sanchis-Segura, Aguirre, Cruz-Gómez, Solozano, & Forn, 2018).

Overall it is clear that gender stereotypes can have a significant impact on the development of visuospatial abilities and that together biological predisposition and societal factors can be contributing to the sex differences in visuospatial abilities. It is important to note that these stereotypes greatly affect the possibility for females to participate in spatially stimulating activities, as well as to make use of the malleability of visuospatial abilities to enhance them. Further, if more attention is given to these gender-stereotypes and societal beliefs, perhaps more females would be involved on STEM related areas.

1.6. Rationale for this thesis

As discussed in the previous sections, the development of MR abilities in humans has been studied using numerous types of tests. A problem when trying to unify the results is that the measures to evaluate the different age groups are not consistent with each other nor do they, in a lot of cases, measure the same function. This is because these tests vary on their characteristics; for example: dimensionality (2D versus 3D), familiarity (familiar versus abstract), frame of reference (egocentric versus allocentric), and structure (paper-based versus hands-on). Undeniably, there are also procedural differences and sample differences between studies. Variations between measures and studies have led to multiple inconsistent findings in regards to age and sex differences on visuospatial abilities. As it is noted from the previously presented evidence (see section 1.4), many results in the area of

MR are at best inconsistent and at worst contradictory. It is not clear the age at which this ability emerges, the age differences on this ability (between or within age groups), the age at which sex differences emerge, and if the sex difference remains or fluctuates across the lifespan. Furthermore, to my knowledge there has been only one study that assessed three-different age groups (children, young adults, and elderly people) using the same task (Iachini et al., 2019). However, they only used a 2D paper-based test in their assessment, did not include adolescents and did not find sex differences in any of the age groups. We have therefore, no information on how 3D MR abilities mature and/or decay throughout the lifespan, nor how sex influences 3D MR functioning. To create a clear understanding of age and sex differences in MR it is necessary to keep the type of measure consistent across age groups. Therefore, the purpose of this thesis is to contribute to our understanding of the trajectory that visuospatial abilities follow across the lifespan using the hands-on 3D mental rotation task developed in the Brain in Action lab (the BBT [brick-building task]; de Bruin et al., 2016). This thesis thus aims to answer the question: Are there age and sex differences in MR abilities when this is assessed by the same visuospatial task? To answer this question, first, the relationship between the brick-building task and the well-established spatial abilities test (the MRT) was investigated. This was followed by two studies that utilized the brick-building task to investigate MR ability in: 1) children and adolescents and 2) in older adults (60-80 year olds). The thesis ends with a brief discussion and integration of the results from the three studies.

1.7. Theory, Hypotheses and Predictions

Theory: All the studies were based on the theory that cognitive functions start to develop early in childhood, they stabilize in young adulthood and then they suffer a decline with normal aging. Additionally, sex differences emerge from the effects of sex hormones on structures that support visuospatial functions and this can be assessed behaviourally. The hypotheses and predictions are listed below.

Hypotheses and Predictions:

Study 1: Validation of the 3D- brick building task

Hypothesis 1a: There are shared MR mechanisms used to solve the MRT and the 3D brick building task.

Prediction 1a: If the brick-building task also measures MR, then a relationship between this task and the MRT will be found in young adults.

Hypothesis 1b: There is a male advantage in MR ability.

Prediction 1b: If males have an advantage on MR tasks, then males will outperform females in the BBT.

Study 2: Mental rotation ability in children and adolescents

Hypothesis 2a: Performance on MR tasks improves throughout childhood and adolescence.

Prediction 2a: If MR ability improves during the first two decades, performance on the BBT will be better in adolescents than in children. Older children will outperform young children.

Hypothesis 2b: There is a male advantage in MR ability that emerges in late childhood.

Prediction 2b: If there is a male advantage in late childhood, then boys will outperform girls in late childhood and adolescence.

Study 3: Mental rotation ability in older adults

Hypothesis 3a: MR ability declines with normal aging.

Prediction 3a: If MR declines with aging then older participants should demonstrate worse performance in the BBT than younger participants.

Hypothesis 3b: The male advantage on MR disappears in older adulthood due to the decrease of circulating sex hormones.

Prediction 3b: If the male advantage is due to circulating sex hormones, then no sex differences should appear in older adults.

CHAPTER 2
Study 1: Validation of the 3D- brick building task

2.1. Abstract

The purpose of this study was to investigate spatial skills using hands-on tasks. Three tasks using toy bricks were devised: A task with low mental rotation requirements (2D condition brick building task- BBT); a task with high mental rotation requirements (3D condition brick building task- BBT); and a visual search task. These hands-on tasks were compared to a variant of the well-known paper-based Shepard and Metzler (1971) mental rotation task (MRT). This variant and others have shown consistent sex differences on mental rotation ability (males outperform females). With this knowledge in mind, we tested young adult females (n= 59) and males (n=26). The results showed high correlations between the hands-on tasks, particularly the 3D BBT, and the MRT. Furthermore, it was found that males consistently outperformed females but only in the 3D BBT and the MRT. We propose that there are common underlying visuospatial neural-mechanisms for the 3D BBT and the MRT, and that sex differences might only exist in mental rotation and not in other aspects of visuospatial abilities. The BBT has several advantages over the MRT. It requires real-world object manipulation and features a "game" structure. These characteristics may make this task more suitable and appealing for young children, seniors, and people with mental disabilities. The BBT might also be used to enhance, detect, or remediate spatial skills.

2.2. Introduction

Spatial ability "refers to the skill in representing, transforming, generating, and recalling symbolic, nonlinguistic information" (Linn & Petersen, 1985, p. 1482). Spatial skill is not a solitary function but rather an assemblage of specific skills (Voyer et al., 1995). These skills are divided into three main constructs; spatial visualization, spatial perception and mental rotation. Spatial visualization, is defined as the ability to mentally manipulate spatial information that requires a multistep, analytical process (Linn & Petersen, 1985). This ability, for example, allows us to meticulously pack the trunk of a car or a suitcase; through analyzing the different object properties (i.e. size and shape) we are capable to know how and if an object may or may not fit in a particular space. Spatial perception is described as the ability to navigate our environment and orient our bodies accordingly, regardless of the variety of distractors situated around us (Linn & Petersen, 1985; Voyer et al., 1995). This ability plays a role in the capacity to reach for objects presented in the visual field and to adjust our gaze accordingly (Kolb & Whishaw, 2003). When driving, for example, spatial perception helps us stay in our lane amidst traffic and safely park in a small space. Lastly, mental rotation is the ability to imagine what a two- or three-dimensional figure would look like when rotated (Kolb & Whishaw, 2003). Also useful when driving; by simply looking through the rear view mirror, this ability helps us make sense of how the objects behind us are located in space. Mental rotation has been extensively assessed by the Shepard & Metzler test (1971; Peters & Battista, 2008). This test uses perspective views of three-dimensional objects and measures the time to determine which two out of four simultaneously presented objects with different orientations are of the same three-dimensional shape (Shepard & Metzler, 1988). Figure 1 shows the mental rotation task (MRT) by Vandenberg and Kuse (1978; Peters et al., 1995), a variant of the Shepard and Metzler test. The MRT is the most well-documented test to assess mental rotation skill.

The largest sex differences in cognitive functions are seen in visuospatial skills (Linn & Petersen, 1985), with mental rotation skill showing the largest sex effect. Using the MRT, researchers have consistently found sex differences in humans (Vandenberg & Kuse, 1978; Peters, 2005). A meta-analysis supported that males are better than females at mental rotation tests (mean weighted Cohen's d = 0.56; Voyer et al., 1995). A well investigated theory put forward by researchers for many years to explain the origin of the sex differences, is the exposure to sex hormones theory. Experiments on natural occurring hormonal disorders, happening during sensitive developmental periods, such as Congenital Adrenal Hyperplasia-CAH (predominantly exhibited in females) and Hypogonadotropic Hypogonadism- IHH, (exhibited in males), show strong evidence to support this theory. Males and females differ in their dominant sex hormones; for females these are estrogen and progesterone and for males it is testosterone. CAH is characterized by abnormally high levels of testosterone. Females with this disorder perform better at spatial abilities tasks than females without the disorder (Puts et al., 2008). Correspondingly, IHH is characterized by abnormally low levels of testosterone, and males with this disorder perform poorly on spatial ability tasks (Hier & Crowley, 1982). Researchers have also found normally varying levels of sex hormones impact males and females' visuospatial abilities. For example, the phase of the menstrual cycle a woman is in may benefit or hinder their performance on spatial ability tests. Females with low estrogen levels display better accuracy on mental rotation tests than females with high estrogen levels (Hampson et al., 2014). Similarly, males with high testosterone levels, responded faster to items on mental rotation tests than males with low levels of this hormone (Yang et al., 2007). Moreover, Hausmann et al. (2000) tested women during the menstrual phase (low estrogen levels, high testosterone levels) where they performed better at the task than during the midluteal phase (high estrogen and progesterone levels). They suggested it is the combination of high testosterone and low estradiol hormones that caused an increase in mental rotation scores. It is important to note, however, that females are common users of hormonal medications (e.g. oral or injection birth control, hormonal intrauterine devices). These medications are synthetic hormones that help maintain estrogen and progesterone hormones at consistent levels. As a consequence, there will not be a peak in estrogen levels during the menstrual cycle of a woman, which has shown to decrease performance on mental rotation tests (Hausmann et al., 2000; Hampson et al., 2014). Overall, it is evident sex hormones are sources of between-sex and within-sex variations on cognitive functioning (Hampson, 2018).

In the Brain in Action Laboratory we have developed hands-on tasks using Lego® to assess spatial skills (brick building test-BBT; de Bruin et al., 2016). The BBT combines spatial visualization, spatial perception and mental rotation abilities. This novel visuomotor test requires the participant to duplicate a brick model from an assortment of bricks. Spatial visualization is used to identify the matching bricks (i.e. shape and size), spatial perception is used when searching for the correct brick among a multitude of distractors and mental rotation is used to determine how each brick should be placed. All the skills work together simultaneously to accurately duplicate the model. The models from the test vary in spatial complexity, with a low spatial demand condition (2D models- constructed in one plane) and a high spatial demand condition (3D models- constructed in two planes). All participants from the study took longer to replicate the 3D models, even when models were built with exactly the same brick pieces as the 2D models (de Bruin et al., 2016). This finding indicates that the increase in time shown in the 3D models was exclusively a consequence of the higher level of spatial complexity (higher demands on mental rotation). Another finding of de Bruin et al. (2016) was the presence of sex differences with the 3D brick building task in a small sample (n=12) of young adults.

The first purpose of the present study was to investigate whether the hands-on tasks (2D BBT, 3D BBT and visuospatial search) shared commonalities with the well-established MRT. This would be relevant to researchers, as the BBT offers unique advantages over the paper-based tests. The BBT requires real-world manipulation of objects, making it more comparable to our everyday environment where we are not only mentally rotating objects but also physically manipulating them in order to position them in our environment. The test features a game structure that may be more appealing and/or less intimidating to children, seniors, or people with mental disabilities. The second purpose of the current study was to investigate if the hands-on tasks were sensitive enough to demonstrate sex differences. Participants were tested on the 2D condition and 3D condition of the BBT (as in de Bruin et al., 2016), a hands-on purely visuospatial search task, and on the MRT (Vandenberg & Kuse, 1978; Peters et al., 1995). Based on previous literature we made two specific predictions: 1) of the three hands-on tasks, the 3D condition of the BBT would show the highest correlation with the MRT; and 2) men would outperform women in the 3D condition of the BBT and in the MRT.

2.3. Methods

Participants

Eighty-five participants were divided into three groups; females on hormonal medication (females-ON; n = 29), females not on hormonal medication (females-OFF; n = 30), and males (n = 26). Participants were healthy students from the University of Lethbridge, who received course credits for their participation. They were recruited through the Psychology Department, using participant management software (Sona Systems). The experiment was approved by the University of Lethbridge Human Subject Research Committee.

Tasks

Participants were asked to read and sign an information consent form. They then completed four tasks: the 2D and 3D conditions of the BBT (low- and high-mental rotation demands, respectively; Fig. 2, a and b), a visuospatial search task, and the MRT (Fig. 1). The 2D and 3D conditions of the BBT consisted of three trials each. Each trial involved duplicating a 12-brick model. At the start of each of the brick tasks, sixty unique bricks were pseudo-randomly placed in front of the participant with thirty bricks on the left side of the participant and thirty bricks on the right side (Fig. 3). The 2D and 3D models consisted of identical number and type of bricks, the only difference was in the configuration of the model (Fig 2, a and b). The visual search task used the same set up and models as the brick building tasks. The difference was that participants looked on the table for the 12 bricks that composed a 2D model and placed those pieces into a bowl [without duplicating (i.e. building) the model]. The MRT consisted of two sets of 12 problems each. Each problem had five stimuli (Fig. 1). Within each problem there was a target stimulus and the participant's job was to find the *two* of the four stimuli that matched the target (for a total of 48 possible correct answers). The order of the four tasks was counterbalanced for each participant, and the order of the trials within each task was randomized.

a.

b.

Figure 2. a) 2D condition BBT models (low mental rotation requirements). b) 3D condition BBT models (high mental rotation requirements). Note that both sets of models contained identical bricks.

Procedure

For the BBT participants were seated in front of a table facing the middle of the brick display (Fig. 3). The participants were instructed to build an exact replica of the models (2D or 3D) located in front of them using the bricks placed on the table as quickly and accurately as possible. They were told they could move or rotate the model as needed to investigate it. Additionally, they were told to start at the "go" signal and to say "done" when they were finished. For the visual search task, the participants were instructed to look for the blocks that made up the 2D model and place them in the container located in front of them as quickly and accurately as possible. For the MRT, the participants were instructed to choose the two out of the four options that matched the target stimuli. They were also told they had a three-minute time limit for each set (12 problems) with a three-minute rest in between sets. At the end of the tasks, the participants were asked to fill out two questionnaires: a questionnaire that documented their frequency and comfort using bricks for building (e.g. “how many times you manipulate Lego (or similar) in a week”) on a scale of 1-10 (1 being no comfort or continuous manipulation and 10 being complete comfort and continuous manipulation) and the Waterloo-Edinburgh handedness questionnaire (Stone, Bryant, & Gonzalez, 2013).

Figure 3. Set up of the bricks at the start of the first trial. Sixty unique bricks were pseudo-randomly placed on the table with thirty to the left of the participant and thirty to the right. A model is placed in front of the participant and they are asked to replicate it (2D or 3D model), or find the bricks in the model (visual search task) as quickly and accurately as possible. One of the 2D models is shown in front of the participant. Consent was obtained from the participant for use of this image for publication.

Data analysis

For the 2D-, 3D-models, and visual search task, the total amount of time taken to build or collect the bricks for each trial was registered from the “go” signal of the experimenter to the “done” signal of the participant. The mean time for the three trials was calculated for each task (2D BBT, 3D BBT, visual search). The number of correct responses for the MR scored was the sum of only the problems where the *two* answers were correct (24 points total) (Vandenberg & Kuse, 1978; Peters et al., 1995). The relationships between all the tasks were examined with correlations (Pearson’s r). Specifically, the participants’ performance (time and/or score) on each task were correlated with all the other tasks. Differences between the groups were investigated with a one-way ANOVA for each task. Significant main effects were analyzed with post-hoc comparisons, and the familywise error rate was controlled with the Bonferroni correction. The alpha level for all comparisons was .05.

2.4. Results

We considered it important to control for hormonal medication intake (i.e. birth control) with their high prevalence in female university students. As the intake of hormonal medication affects sex hormone levels, this could influence their performance on our hands-on tasks. However, there were no significant differences between the two groups at any of the tasks (females-ON and females-OFF hormonal medication). Therefore, the two groups were collapsed into a single group of females (n=59) and were then compared to the male group.

Correlation Analysis

Significant correlations were found between all dependent variables (Table 1). The largest correlations, unsurprisingly, were between the 2D times and 3D times (r = .63). The smallest correlation had a medium effect size and was between the visual search times and MRT score (r = -.25). Importantly, the correlation between 3D time and MRT score (r= -.46) was higher than for 2D time (r= -.35).

Table 1

Correlation table for the dependent variables

	2D time	3D time	Visual Search	MRT
2D time	1.00	.63**	.54**	-.35**
3D time		1.00	.51**	-.46**
Visual Search			1.00	-.25*
MRT score (strict)				1.00

* p < .05, ** p < .01

Group Comparisons

The grand mean scores and group mean scores are shown in Table 2. There was a significant main effect of sex for 2D times ($F_{(2,84)} = 5.8$, $p < .05$, $n^2 = .06$), 3D times ($F_{(2,84)} = 13.8$, $p < .001$, $n^2 = .14$), and MRT score ($F_{(2,84)} = 12.1$, $p < .01$, $n^2 = .13$). Males had shorter 2D and 3D times than females, they also scored significantly better at the MRT. There was not a main effect of sex for visual search time ($F_{(2,84)} = 2.6$, $p > .1$, $n^2 = .03$).

Table 2

Means and standard errors for the dependent variables

Dependent variable	Grand mean	Males	Females
2D time (s)	39.7 ± 1.1	35.9 ± 1.9	41.4 ± 1.2
3D time (s)	69.6 ± 1.9	59.6 ± 2.9	74.1± 2.24
Visual search time (s)	24.9 ± 0.6	23.3 ± 1.3	25.5 ± 0.7
MRT score	9.68 ± 0.5	12.4 ± 1.0	8.5 ± 0.6

The Waterloo-Edinburgh handedness questionnaire was used to determine whether participants were right handed (n = 74), left handed (n = 8), or ambidextrous (n = 3). There was no significant difference between the groups with respect to handedness $F_{(2,84)} = .12$, $p > 0.1$, $\eta^2 = .003$. The questionnaire documenting the frequency manipulating bricks (Lego or similar) showed that males and females had low continuous manipulation (1.4 ± 0.09) and were not different from each other, $F_{(2,84)} = 1.1$, $p = .3$, $\eta^2 = .01$. However, there was a main effect of comfort with bricks $F_{(2,84)} = 5.1$, $p = .03$, $\eta^2 = .06$. Males (8.2 ± 0.29) were significantly more comfortable with bricks than females (7.2 ± 0.25).

2.5. Discussion

This study validated real-world, hands-on tasks to assess spatial skills. Both conditions of the BBT were significantly correlated with the well-known MRT. They required participants to use the three main spatial skills; spatial visualization, spatial perception and mental rotation. These new tasks also highlighted the previously known sex differences in spatial skills, specifically in mental rotation skill (Linn & Petersen, 1985; Voyer et al., 1995; Peters, 2005). The present study found that males were faster than females on the 3D brick building task and had higher scores on MRT; confirming the male advantage on visuospatial skills. Overall, the brick building tasks had commonalities with the MRT but, in contrast, the brick building tasks required real world manipulation, which makes it a more ecologically valid task than the paper-based test.

The performance on the tasks in the present study were significantly correlated with each other. Participants who had a fast time on the 2D brick building task also had a fast time on the 3D brick building task, the visual search task, and had high scores on the MRT. Thus, participants who had good performance on one of the tasks also had good performance on the others. This relationship found between all the different tasks demonstrates the interdependence among the various spatial skills. This interdependence could suggest that spatial skill is one function. However, the correlations between the hands-on and the MRT tasks explained only 6 to 39% of the variability ($r = -.25$, $R^2 = .06$; $r = .63$, $R^2 = .39$). Furthermore, some of the correlations were stronger than others. Of note were the low correlations between the visual search task and the MRT score ($r = -.25$), which suggest these tasks require somewhat different spatial skills. Stronger correlations were found between the time to complete the 2D brick building task and the MRT scores (r = -.35) suggesting more commonalties between these two tasks. Finally, and as predicted, the 3D brick building task showed the most overlap with the MRT (r = -.47) as the 3D task features high mental rotation demands. Together, these results reinforce the notion that spatial skill is not a monolithic construct but rather it is an association of interrelated subskills that contribute to its proper functioning.

The male advantage seen in most visuospatial tasks, especially in mental rotation ability (as measured by the MRT), was supported. This advantage was also evident in the brick building tasks, particularly in the 3D task (high-mental rotation demands task). The higher the demand for mental rotation skill the more evident the sex differences were. This supports previous evidence on the large sex effect exhibited in mental rotation tasks (Voyer et al., 1995). The presence of sex differences in young adulthood could suggest permanent changes in cognitive functioning during sensitive developmental periods (where sex hormone levels change abruptly) indeed happened. However, it could also suggest an influence of current varying levels of circulating sex hormones in young adult males (high testosterone levels) and females (varying estrogen and progesterone levels as a function of their menstrual cycle phase; Hampson, 2018). Importantly, the brick building task demonstrated its sensitivity to sex differences opening up a great number of possibilities for researchers interested in investigating the role and/or the extent to which sex differences are impacted by sex hormones (e.g. testing the brick building task in pubertal children or paring it with saliva hormone analysis). Lastly, simply controlling for hormonal medication in females did not reveal any difference. This can be useful information for researchers investigating the effects of these medications on cognitive functioning.

With respect to the tasks used in this study, it will be important to test them in different populations. We believe the brick building task offers several advantages over other spatial tests. The MRT variant of the Shepard and Metzler [based on Vandenberg and Kuse (1978; Peters et al., 1995)] used in this study, although effective for healthy adult participants, has been considered too difficult (Jansen et al., 2013) for young children (Hoyek et al., 2012), for seniors [as mental rotation performance decreases with age (Jansen & Heil, 2009)], and people with sensory deficits [i.e. dyslexic children (Winner et al., 2001)]. The hands-on tasks employ a real-world manipulation and a "game" structure. These exclusive attributes may make the test more appealing and suitable for these populations.

We have started exploring the brick building test in a group of 5- to 8-year-old children, not only as an evaluating tool, but as well as a tool to enhance visuospatial abilities. There is evidence suggesting that having good visuospatial skills can strongly influence achievement in science, technology, engineering and mathematics (i.e. STEM programs; Wai et al., 2009; Lubinski, 2010; Uttal et al., 2013). Additionally, studies have shown that children's early performance on visuospatial tasks is related to later aptitude on spatial and mathematical concepts (Lauer & Lourenco, 2016), along with a stronger arithmetical development (Zhang et al., 2014). Certainly, the development of visuospatial skills has proven to be important for an individual's overall intelligence. As a consequence, we consider it of great importance to enhance, detect and, if difficulties exist, remediate the progress of spatial skills at an early stage, as this will affect the overall development of the person. We believe the brick building task would be an easy and engaging means to enrich visuospatial functioning.

The present study carries certain limitations important to note. First, we only compared the 2D-3D brick building task against the MRT. Considering the Shepard and Metzler (1971) test has served as the foundation for the development of other mental rotation tests such as the Rotated Color Cube Test (Lütke & Lange-Küttner, 2015), the Three-dimensional Human Figures Test (Alexander & Evardone, 2008), the BiRT (Bilder Rotations Test; Quasier-Pohl, 2003; Rüsseler, Scholz, Jordan, & Quaiser-Pohl, 2006), and the Clock Rotation Test (Collins & Kimura, 1997), we feel confident that the relationship found for our hands-on tasks would also hold against these other tests. This, however, remains to be shown. Second, we did not account for the participants' specific undergraduate program (e.g. Sciences, Social Sciences, Humanities, Fine Arts, Education, and Management). Even though, the population recruited was exclusively through the Psychology department (i.e. students enrolled in Psychology courses), no specific undergraduate program was recorded. Because previous research has shown that spatial abilities performance is a predictor of learning and involvement of STEM programs (Uttal & Cohen, 2012), knowing this information would have allowed us to make inferences about biases in spatial abilities due to the participant's undergraduate major. Third, we did not record the specific age of the participants. Despite the fact that we know the age range of the specific population recruited (i.e. undergraduate university students 18-25 years old) we cannot confirm an exact age population average. Lastly, although all groups reported similar rates of frequency playing with blocks, males did report more comfort playing with them. This could be one factor influencing the better performance in the mental rotation tasks exhibited by the males.

CHAPTER 3:

Study 2: Mental rotation ability in children and adolescents

3.1. Abstract

Spatial abilities are not only fundamental for daily living activities but they are also markers of academic and professional success. In particular, mental rotation ability has shown a strong link with STEM (science, technology, engineering and mathematics) achievements. Therefore, understanding its development across childhood and adolescence is extremely important. However, this has remained a challenge. Part of this challenge lies on the lack of tasks that can be applicable to different age groups, particularly for young children. The well-established test for paper-based mental rotation test (MRT; Shepard & Metzler, 1971) has proven extremely difficult for children under 13 years old. Therefore, in the present study, we used the brick-building task (BBT), a visuospatial hands-on task that differed in mental rotation demand (low versus high) to investigate age and sex differences in a sample divided into three age groups: younger children (5-8 years-old), older children (9-12 years –old) and teenagers (13 to 17 years old). Age and sex differences were found using the BBT. In addition, although the BBT only showed a strong relationship with the MRT in adolescents and not in older or younger children, we suggest this was the result of the difficulty for both groups of children to complete the MRT. Contrarily, the BBT was easily completed by children as young as 5-years old. Due to the unique characteristics of the BBT, the advantage for its use as an assessment or intervention tool for younger age groups is discussed.

3.2. Introduction

Spatial abilities are important for the activities of daily living. They allow us to navigate the environment, to locate landmarks, and to interact with objects. Additionally, these abilities can be crucial for academic and professional development. Much of the curriculum in primary and secondary education requires spatial abilities to visualize, transform, or interpret graphs, geometric shapes, or word/number problems. There is, for example, a relationship between spatial abilities and mathematical reasoning in elementary school for word problems, fractions, and algebra (Mix et al., 2016). Particularly, mental rotation ability is related to science and mathematical performance in children (Ganley et al., 2014). Mental rotation is defined as the ability to imagine what a two- or three-dimensional object or image would look like when rotated (Linn & Petersen, 1985). This ability has been extensively assessed with the paper-based mental rotation task (MRT; see Fig. 1) by Vandenberg and Kuse (1978; Peters et al., 1995). Performance on the MRT predicts success in science, technology, engineering, and mathematic (STEM) disciplines, and MRT scores are strongly correlated with Scholastic Aptitude Test-Math (SAT-M) scores (Hegarty et al., 2010; Harlem & Towns, 2011; Uttal & Cohen, 2012; Cromley et al., 2017). For these reasons, the development of spatial abilities in early education has received attention, and some countries have added activities with spatial stimulation to their early childhood curriculum (e.g. Australian curriculum, 2015; Finish National Board of Education, 2004). Hence, it is extremely important to develop tools that can assess the developmental progress of mental rotation ability. Part of the challenge in measuring mental rotation ability lies on the lack of mental rotation tasks that are appropriate for different age groups and abilities. The commonly used MRT is more appropriate for young adults than for children as it has proven challenging for elementary school children (mean age= 7.8; Hoyek et al., 2012; Jansen et al., 2013) and some researches have even considered it an unreliable test for children younger than ten-years of age (Johnson & Meade, 1987). However, a novel tool for assessing visuospatial abilities and in particular mental rotation ability was introduced by de Bruin et al. (2016) and compared to the MRT (Aguilar et al., in press). The assessment is a brick building task (BBT), which involves duplicating two- and three-dimensional brick models. The BBT requires real-world manipulation of bricks, and it feels more like a game than a test. In the current experiment, we investigated whether these characteristics make the BBT a more suitable assessment tool than the MRT for school-aged children, specifically younger children, older children, and teenagers.

Mental rotation assessment measures have shown one of the largest sex differences across all cognitive processes (Voyer et al., 1995; Levine et al., 2005; Wai et al., 2009) a medium effect size is already present by age 9, which increases with age, and by age 23 becomes a large effect size (Voyer et al, 1995; Geiser, Lehmann, & Eid, 2008). Males have consistently shown an advantage over females from preschool-aged children to young adulthood on some spatial tasks. In preschool children, Levine et al. (1999) found a sex difference in a two-dimensional Mental Transformation Task (CMTT) in children between four and five years of age (M= 4.6. years old); the task required mental rotation and mental translation. Moreover, Frick et al. (2013) found five-year-old boys outperformed five-year-old girls using a two-dimensional figure matching task but there was no sex difference for three- or four-year-old children. However, using three-dimensional stimuli, like the MRT, sex differences are consistently found in school-aged children but not younger children (Neubauer et al., 2010; Neuburger et al., 2011; Titze et al., 2010). Titze et al. (2010) found males outperformed females between the ages of 9.9-11.0 years but younger males between the ages of 8.3-9.6 years did not. Similarly, Neuburger et al. (2011) found sex differences in 10 year olds (M=9.9, 8.8 to 12.1 years old) but not in 8 year olds (M=7.8, 6.6 to 9.5 years old). For young adults the sex difference on the MRT is certainly consistent (e.g. Vandenberg & Kuse, 1978; Peters, 2005; Madan & Singhal, 2015; Voyer & Jansen, 2016). The BBT has reproduced this sex difference (de Bruin et al., 2016; Aguilar et al., in press) specifically in the high spatial demand condition (3D; three-dimensional models).

Changes in sex hormone levels are strongly associated with brain organization and cognition (Sisk & Zehr, 2005; Piekarski et al., 2017; Wierenga et al., 2018). Organizational effects of sex hormones, cause permanent effects and irreversible changes to brain structures, while activational effects happen at any point in time and can be reversible (Arnold & Breedlove, 1985; Arnold, 2009). Organizational effects have been shown to affect the effect size of the sex difference in mental rotation. These effects take place during sensitive developmental periods, when the developing brain is susceptible to changes in gonadal hormones. This has been shown by investigating changes in sex hormones with genetic conditions and by comparing across developmental stages. Congenital adrenal hyperplasia (CAH) and hypogonadotropic hypogonadism (IHH) are genetic conditions that have helped to understand the relationship of prenatal steroid hormones on spatial abilities in females and males. CAH is a condition characterized by the overproduction of testosterone, the predominant male sex hormone in females, and IHH is characterized by its deficiency in males. A meta-analysis revealed that females with CAH have significantly better spatial abilities compared to females without CAH (Puts et al., 2008). Berenbaum et al. (2012) also showed that females with CAH score better in three-dimensional mental rotation tests than their sisters without the condition. Males with IHH have impaired spatial abilities. The onset of IHH also affects its impact on spatial abilities. Males that acquire IHH before puberty have impaired spatial abilities, whereas males that acquire it in adulthood do not (Hier & Crowley, 1982). CAH and IHH suggest that sex hormones, particularly testosterone, affect the sex difference in spatial abilities. Moreover, testosterone is crucial for the development of spatial abilities during puberty (Davidson & Susman, 2001). Puberty is characterized by elevated levels of male sex hormones (androgens, e.g. testosterone) and female sex hormones (estrogens and progestogens; Nussey & Whitehead, 2001). The elevated levels of the sex hormones lead to the maturation of the reproductive system, the development of secondary sex characteristics, and menarche for females. The timing at which puberty maturation takes place has also shown to mediate cognition differences in males and females, with early-maturers presenting more sex-typed characteristics and late-maturers presenting less or even opposite sex-typed characteristics. Females with an early pubertal maturation, for example, have better verbal abilities than those with a later maturation, and those with a later maturation have better spatial abilities and even a higher likelihood of choosing a STEM major (Brenner-Shuman & Waren, 2013). Conversely, in males, early-maturers have better spatial abilities and late-maturers have better verbal abilities (Waber., 1976; Beltz & Berenbaum, 2013).

Spatial abilities are also sensitive to environmental factors. Nazareth et al., (2013) found that the degree of exposure during childhood to traditionally masculine spatial activities was correlated with MRT scores. Boys are more likely than girls to play with construction toys, building blocks, puzzles, video or computer games. These stereotypical masculine activities encourage spatial manipulation, spatial visualization, and the understanding of movements in space. Stereotypical girl toys, like dolls, costumes, and tea sets, in contrary, do not encourage the development of spatial abilities (Tracy, 1987). Encouragement towards activities requiring more, or less, spatial manipulation can also be influenced by parental preferences and gender stereotypes (Pruden et al., 2011). Children learn to avoid opposite sex-activities by the time they enter preschool, which is when their involvement in same-sex activities tends to increase (Connor & Serbin, 1977). In addition, when gender was primed in undergraduate students prior to completing the MRT, the sex difference was larger than when their student status (i.e selective college student) was primed (McGlone & Aronson, 2006). Lastly, evidence of the malleability of spatial abilities (Uttal D.H. et al., 2013) confirms they are sensitive to environmental factors. Studies have shown that training with spatial activities (i.e. mental rotation tasks) produces improvements on spatial cognition (Adams, Stull, & Hegarty, 2014; Meneghetti, Cardillo, Mammarella, Caviola, & Borella, 2017; Cheng & Mix, 2014); and overall engagement in spatial play in the classroom also results in better performance on spatial tasks (Vander Heyden, Huizinga, & Jolles, 2017).

In sum, there is evidence that spatial abilities are affected by biological and environmental factors and by their potential interaction (Levine et al., 2016). The degree to which these factors affect spatial abilities across the lifespan remains an intriguing and challenging question. Part of the challenge is the lack of spatial ability assessment tools that are appropriate across most of the lifespan. The most commonly used tool to assess mental rotation ability is the MRT. It, however, has shown to be challenging for children younger than 13 years old (Linn & Petersen, 1985; Hoyek, et al., 2012) and even suggested to be unreliable for measuring mental rotation ability in children younger than ten-years of age (Johnson & Meade, 1987). Easier versions of the MRT have been developed for children that involve two-dimensional figures of animal or letters (Titze, et al., 2010). The problem with these tasks is that they only account for mental rotation of two-dimensional stimuli and may also be too easy for teenagers and adults. This prevents critical comparisons across the lifespan. The BBT, in contrast to the MRT, may be sensitive to changes in mental rotation ability throughout childhood and adulthood. It may be a better test, particularly for children, because it involves real-world manipulation of bricks with a game-like structure. We have already shown that the BBT can be used to assess the mental rotation ability of young adults and seniors (de Bruin et al., 2016; Aguilar et al., in press). If the BBT is also appropriate throughout childhood, then it could be a powerful new tool to investigate the role of biological and environmental factors throughout the lifespan.

The current study had two goals. The first goal was to assess the ability of the BBT and the MRT to quantify mental rotation ability of three different age groups of children from 5 to 17 years old; specifically, younger children (ages 5 to 8), older children (ages 9 to 12) and teenagers (ages 13 to 17). We predicted that scores on both tasks would improve across age groups. Better mental rotation ability with age could be caused by biological factors (brain development), environmental factors (experience with mental rotation tasks), or both. Furthermore, we hypothesized that the MRT would be too difficult for younger children and insensitive to changes in mental rotation ability at that age. The BBT, in contrast, should be sensitive to mental rotation ability across all age groups. The second goal was to test for sex differences across age groups on both tasks. We predicted there would be no sex difference in either task for the younger children because they were prepubescent. In contrast, there should be a sex effect for older children and teenagers.

3.3. Methods

Participants

One hundred and nineteen participants took part in the experiment, separated into three groups: younger children (ages 5 to 8; M=6.58; N=43; 23 females and 20 males), older Children (ages 9 to 12; M=10.29; N=42; 20 females and 22 males), teenagers (ages 13 to 17; M=14.85; N=34; 19 females and 15 males). They were all healthy participants recruited through poster advertisement around the University of Lethbridge. The experiment was approved by the University of Lethbridge Human Subject Research Committee.

Tasks

The parents or guardians of the participants were asked to read and sign an informed consent form. The participants then completed two tasks: the BBT, 2D and 3D conditions (low- and high-spatial demand, respectively; Fig. 2, a and b), and the MRT (Fig. 1). The 2D and 3D conditions of the BBT consisted of three trials each. Each trial involved duplicating a 12-brick model. For the younger and older children, 36 unique bricks were pseudo-randomly placed in front of the participant with 18 bricks on the left side of the participant and 18 bricks on the right side. The pseudo-randomization ensured that half of the pieces for each model were on the left side and the other half on the right side. For the teenagers, 60 unique bricks were pseudo-randomly placed in front of the participant, 30 pieces on the left side of the participant and 30 pieces on the right side. The MRT consisted of 12 problems for the younger and older children and 24 problems for the teenagers. The order of the tasks was counterbalanced for each participant, and the order of the conditions and trials within each task was randomized.

Procedure

For the BBT, participants were seated in front of a table facing the middle of the brick display (Fig. 3). The participants were instructed to build an exact replica of the model located in front of them using the bricks placed on the table as quickly and accurately as possible. They were told they could move or rotate the model as needed to investigate it. Additionally, they were told to start at the "go" signal and to say "done" when they were finished. For the MRT, participants were instructed to choose the two out of the four options that matched the target stimuli. The younger and older children were told they had a three-minute time limit for one set of 12 problems. The teenagers were told they had a time limit of three-minutes for each of two sets with a three-minute break between sets. At the end of the tasks, the parents or guardians of the younger and older children were asked to complete a questionnaire that documented the frequency of using bricks (e.g. "how many times do you manipulate Lego [or similar] in a week on a scale from 1 [no manipulation] to 10 [continuous manipulation]") was completed by a sample of younger and older children (n=23) and teenagers (n=34).

Data analysis

For the BBT 2D- and 3D-conditions, the time taken to replicate the models in each trial was recorded from the "go" signal of the experimenter to the "done" signal of the participant. Two types of errors during the BBT were recorded: when the participant placed a brick in the wrong position and when the participant grasped the wrong brick. The MRT was scored by giving one correct point if and only if both answers were correct (perfect score; younger and older children = 12 points and teenagers = 24 points). Additionally, an MRT percent score was calculated to allow for across age comparisons. It was determined by dividing the number of correct problems by the total number of problems (12 total problems for younger and older children and 24 total problems for teenagers). A mixed-design ANOVA was used to analyze the BBT task, and a univariate analysis was used to analyze the MRT task. The relationships between tasks were examined with correlations (Pearson's r). Significant main effects were analyzed with post-hoc comparisons, and the familywise error rate was controlled with the Bonferroni correction. The alpha level for all comparisons was .05.

3.4. Results

BBT- Brick Building Task

Performance on the BBT was analyzed with Condition (2D, 3D) by Trial (1, 2, 3) by Sex (female, male) by Group (younger children, older children, teenagers) mixed-design ANOVAs, with Sex and Group as a between-participant factors.

Regarding task time (Fig. 4), all of the main effects were significant: Condition, $F_{(1,113)} = 206.61$, $p<0.001$, $\eta^2 = 0.65$, Trial, $F_{(2,112)} = 5.39$, $p < 0.01$, $\eta^2 = 0.08$, Sex, $F_{(1,113)} = 7.68$, $p < 0.01$, $\eta^2 = 0.06$, and Group, $F_{(2,113)} = 34.81$, $p < 0.001$, $\eta^2 = 0.38$. These results indicated that the 2D condition was faster than the 3D condition and the third trial was faster than the first and second trials. Furthermore, males were faster than females, and teenagers were faster than the younger children ($p < .001$) but comparable to the older children ($p > 0.1$). Significant Condition by Sex and Condition by Group interactions were also found: $F_{(1,113)} = 6.23$, $p < 0.05$, $\eta^2 = 0.05$, $F_{(2,113)} = 12.37$, $p < 0.001$, $\eta^2 = 0.18$. Males were significantly faster than females in the 3D condition ($p < .05$), but males and females were comparable in the 2D condition ($p > .1$). For the younger children, the time difference between the 3D and the 2D conditions was far greater compared to this difference in the older children and teenagers (see Figure 4).

Regarding task errors (Fig. 5), there were significant main effects of Condition, ($F_{(1,113)} = 65.86$, $p < 0.001$, $\eta^2 = 0.67$), Trial, ($F_{(2,112)} = 6.27$, $p < 0.01$, $\eta^2 = 0.05$), and Group ($F_{(2,113)} = 3.69$, $p < 0.05$, $\eta^2 = 0.06$). However, there was no significant main effect of Sex ($p > 0.1$). These results indicated that in the 2D condition participants made fewer errors than on the 3D condition, and they also made fewer errors on the third trial than on the second and first trials. Moreover, teenagers and older children made fewer errors than younger children ($p < 0.05$), but teenagers were comparable to older children ($p > 0.1$). A significant Condition by Group interaction was found: ($F_{(2,113)} = 4.92$, $p < 0.01$, $\eta^2 = 0.8$). The younger children made significantly more errors than older children and teenagers ($p < 0.05$, for both) in the 3D condition. In the 2D condition, however, none of the groups were significantly different from each other ($p > 0.1$).

We were curious whether the *relative* increase in difficulty from the 2D condition to the 3D condition was comparable for all three groups. This was determined by calculating the percent increase in the mean time to build the models in the 3D condition compared to the 2D condition; specifically, mean time in the 3D condition divided by the 2D condition and then multiplied by 100. This relative increase in difficulty for the 3D condition was analyzed with a one-way between-participants' ANOVA on the three groups, which was significant, $F_{(2,118)} = 3.32$, $p < 0.05$, $\eta^2 = 0.05$. The younger children took longer to complete the 3D condition when expressed as a percentage of the 2D condition than teenagers' $p < 0.05$. However, older children and the teenagers were comparable to each other $p > 0.1$.

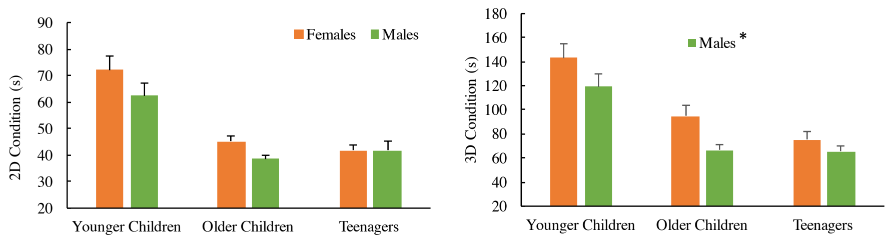


Figure 4. Brick Building Task (BBT) times for each Condition (2D and 3D), Sex (Females and Males), and Group (younger children, older children and teenagers).

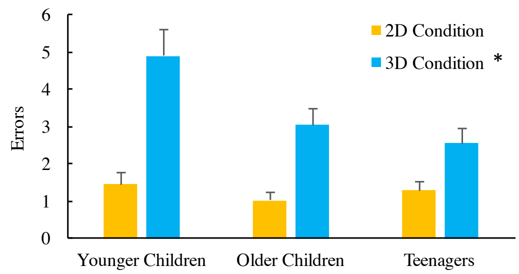


Figure 5. Brick Building Task (BBT) errors for each Condition (2D and 3D) and Group (younger children, older children and teenagers).

<u>MRT - Mental Rotation Task</u>

MRT score for younger children, older children, and teenagers was analyzed with univariate analysis: MRT percent score as the dependent variable with Sex and Group as fixed factors. The analysis revealed significant main effects of Group, $F_{(2,117)} = 23.01$, $p < 0.001$, $\eta^2 = 0.29$, and Sex, $F_{(1,117)} = 14131$, $p < 0.001$, $\eta^2 = 0.11$. The results suggested that males had better scores than females ($p < .001$). Furthermore, teenagers outperformed older children who outperformed younger children ($p < .01$).

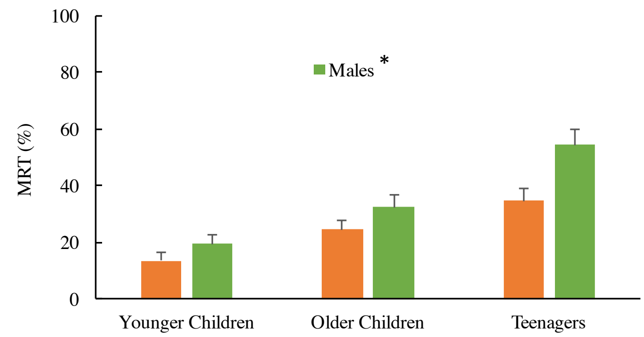
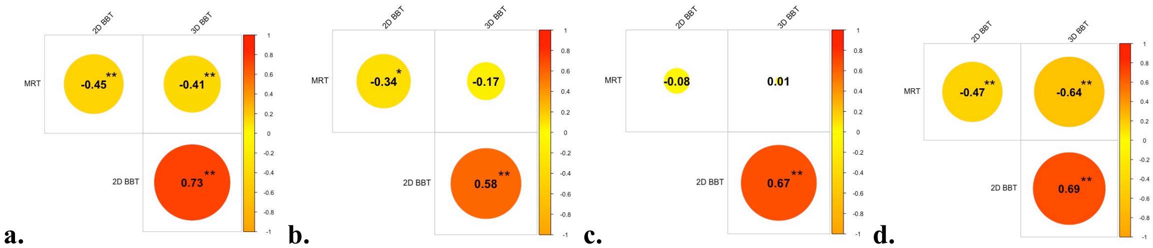


Figure 6. Mental Rotation Task (MRT) scores for each Sex (female, male) and Group (younger children, older children, teenagers).

BBT and MRT comparisons

Bivariate correlational analyses were run to investigate whether there were relationships between the tasks. Correlations are shown in Figure 7. When collapsed across groups, there were medium to large correlations between BBT scores (2D and 3D conditions) and MRT scores (r= -.45 and -.41, respectively). The negative correlations suggested that the longer the time on the BBT, the lower the MRT score. In the younger children, a significant medium correlation was found between the BBT 2D condition and the MRT task (r= -.34). There was also a negative correlation for the BBT 3D condition (r= -.17), but it was not significant. No significant correlations were found in the older children. In the teenagers, there were medium to large correlations between the BBT (2D and 3D conditions) and the MRT in the expected direction: the longer the time on the BBT, the lower the MRT score. Between the 2D and 3D conditions of the BBT, significant large correlations were found in all age groups. These increased with age for younger children (r= .58), older children (r= .67) and teenagers (r= .69), the longer the time taken on one of the conditions the longer the time on the other one. These relationships may suggest similarities in the mechanisms being used to complete both conditions.



* p < .05, ** p < .01

***Figure** 7*. Correlation plots for the dependent variables: MRT scores and BBT times (2D and 3D conditions time) **a.** All groups combined, **b.** Younger children, **c.** Older children, and **d.** Teenagers.

<u>Brick Manipulation Questionnaire Analysis</u>

Fifty-seven participants completed the Brick manipulation questionnaire (29 females and 28 males; 23 younger and older children and 34 teenagers). A univariate analysis revealed a significant main effect of Group, $F_{(1,56)} = 20.91$, $p < 0.001$, $\eta^2 = 0.28$. The main effect of Sex was not significant, $F_{(1,56)} = 2.05$, $p > 0.1$, $\eta^2 = 0.04$. These results suggested that teenagers manipulated blocks more than children but not more than older children and males did not manipulate blocks more than females.

3.6. Discussion

Spatial abilities are crucial for academic and professional development. There is a strong relationship between performance on measures of spatial abilities and achievements in STEM training from childhood to young adulthood. Results from the MRT have consistently supported this relationship. The MRT also has shown the largest sex effect of all psychometric tests measuring visuospatial abilities (Maccoby & Jacklin, 1974; Geiringer & Hyde, 1976; Sanders et al., 1982; Linn & Petersen, 1985; Voyer et al., 1995;

Bodner & Guay, 1997) and even one of the largest sex effects across all cognitive processes (Voyer et al., 1995; Levine et al., 2005; Wai et al., 2009). The problem with the MRT is that it has been suggested to be unreliable when used in children younger than ten years of age (Johnson & Meade, 1987) and not suitable even for children younger than 13 years of age (Linn & Petersen, 1985). It is, therefore, not the most appropriate tool to be used to investigate the development of mental rotation ability in children. The main aim of the present study was to assess whether the BBT was an appropriate measure of mental rotation ability for younger children, older children, and teenagers. The overall results of the current study suggested that the BBT was appropriate for all age groups examined, and it was sensitive to the development of mental rotation ability. The ability to use the BBT to track the mental rotation ability progress in children and up to teenage years is yet another advantage for this test over others like the MRT.

The BBT was sensitive to the developmental changes in mental rotation ability from younger children, to older children, to teenagers. The younger children had the worst performance on the BBT; the older children and teenagers had comparable performance (result also shown by the *relative* increase in difficulty - the 3D condition when expressed as a percentage of the 2D condition). It is worth noting, however, that teenagers were given a more difficult version of the BBT with 60 bricks to choose from instead of 36. The teenagers were, therefore, better than the older children because they completed a more difficult BBT with the same performance as the older children. The large improvement in performance from younger children, 5 to 8 years old, to older children, 9 to 12 years old, may be caused by the onset of puberty for the older children. The increase in sex hormones that accompanies puberty, could indeed be another sensitive window where sex hormones cause changes in brain structure and improvements in cognition (Sisk & Zehr, 2005; Wierenga et al., 2018). Performance on the MRT also improved with age, but the MRT was far too difficult for younger children (5-8 years old). The group scored 16.5%, which is below the chance level of 16.7%. This finding confirms Johnson and Meade (1987), study that suggested that the test was unreliable for children younger than ten years of age.

There was a sex difference in the 3D condition of the BBT: males outperformed females across all age groups. Interestingly, there was no sex difference in the 2D condition. These results suggest that a sex difference occurs only with high processing demands on mental rotation ability, that is 3D mental rotation and not 2D. Many other 2D mental rotation tasks also have failed to find a sex difference for younger children, older children (Marmor, 1975; Marmor, 1977; Kosslyn et al., 1990; Estes, 1998; Roberts & Bell, 2000; Frick et al., 2009; Frick et al., 2013; Lehman et al., 2014; Fernández et al., 2018; Barel & Tzischinsky, 2018; Rodán et al., 2019) and teenagers (Kosslyn et al., 1990; Kail,1980; Waber et al., 1982; Kail et al., 1985). The reason why there is not a male advantage in the 2D condition may be because is not demanding enough to manifest sex differences as the 3D condition is. Thus, both females and males can easily rotate 2D figures which would make the sex difference disappear. If this is the case, then appropriate tools for children using three-dimensional stimuli may display a male advantage, as it was the case for the BBT in the present study. Although, sex differences were found in the MRT, they must be taken with caution, especially because (as mentioned previously) the younger children performed very poorly on this test.

Importantly, there was a large, positive relationship between the BBT and the MRT: participants who completed the BBT quickly also had high scores on the MRT. This relationship was strongest between the 3D condition of the BBT and the MRT, which is consistent with previous results by Aguilar et al., in press. These two tasks likely had the strongest relationship because they both require 3D mental rotation. In the teenager group, there was a strong relationship found between the 2D condition and the MRT as well as between the 3D condition and the MRT; similar to the one found in young adults (Aguilar et al., in press). However, there was not a strong relationship between the BBT conditions and the MRT in younger or older children. For younger children, this result could be due to their great difficulty demonstrated in the MRT. For older children, this could in part still be difficulty with the MRT (since the mean age of this group is just above the age that has been suggested for this test to be reliable for M=10.29) and/or large variability as a result of individual and impactful puberty related sex hormonal changes (Davidson & Susman, 2010). Nonetheless, for the younger children group, there was a medium correlation with the 2D condition, suggesting similar cognitive mechanisms may have been used to do both tasks.

Numerous mental rotation tasks have been developed for children, some of them use two-dimensional stimuli, such as animal stimuli or letter stimuli (Quasier-Pohl, 2003; Titze, et al., 2010), and some use three-dimensional stimuli such as the Rotated Color Cube Test; Lütke, & Lange-Küttner, 2015). However, within these measures there are factors that can influence children's performance. For example, some of these factors are: number of dimensions (two-dimensional stimuli demand less mental rotation ability than three-dimensional stimuli), type of stimuli (easier to rotate familiar [animal or letters], than unfamiliar [abstract cubes] stimuli) structure (paper-based vs real-world; Alexander & Evardone, 2008; Krüger, & Ebersbach, 2017; Lauer et al., 2019). These factors affect performance and as a consequence they are likely to yield inconsistent results. The BBT is unique compared to the previously mentioned developed tasks. It integrates two different conditions with varying demands of mental rotation (two and three dimensions). Both conditions are also made up with the same type of stimuli (same shape and color of building bricks). Lastly, it involves real-world object manipulation. Taken together, these characteristics of the BBT make it suitable for children and allow for across age comparisons.

Last but not least, the BBT can also serve as an intervention tool for children. Because it has been suggested from early cognitive developmental theories (Piaget & Inhelder, 1971) that sensorimotor experiences are crucial for developing higher cognitive functions as visuospatial abilities, the real manipulation of objects in combination with the simultaneous use of different visuospatial abilities (spatial perception, spatial visualization and mental rotation) including varying demands of mental rotation, can make the BBT an extremely valuable tool for the enhancing these abilities starting at a young age. The individual can benefit from the enhancement of these abilities at a young age by later academic and professional achievements. Specifically, enhancing these abilities in females may help close the sex gap.

CHAPTER 4
Study 3: Mental rotation ability in older adults

4.1. Abstract

Visuospatial abilities are a cognitive process essential to perform activities of daily living. One example is navigating the environment. This process has shown the largest aging effect (young adults outperforming older adults) and sex difference effect (males outperforming females). Age-related cognitive decline affects visuospatial abilities. As a result, our capacity to safely and independently interact with the environment gets compromised. The purpose of the present study was to evaluate visuospatial abilities functioning in a group of older adults (M= 66), males (n=14) and females (n=18), with our developed battery of hands-on visuospatial tasks (two-, three-dimensional mental rotation brick building tasks (BBT) and a visual search task). The well-documented visuospatial test, the paper-based mental rotation task (MRT) was also assessed. A strong relationship was found between the BBT and the MRT. Sex differences were persistent in older adults; the male advantage was found on the MRT and interestingly, a female advantage was found on the visual search task. However, no sex differences were found on the BBT. Based on biological or environmental influential factors, we discuss possible reasons on why sex differences are persistent in older adulthood in some visuospatial tasks. Additionally, we suggest, the hands-on tasks may serve as a more ecologically valid tool to enhance visuospatial abilities on this age group, where functional independence is critical.

4.2. Introduction

Aging involves a gradual decline in physiological systems, which affects the brain and its cognitive functions. Particularly, visuospatial functions are vulnerable to aging effects (Klencklenn, Després, & Dufour, 2012). With a decrement in visuospatial skills, our capacity to safely and independently navigate the environment gets compromised; affecting our functional independence. Visuospatial skill for many years has been assessed using paper and pencil psychometric tests for example using the well-known paper-based mental rotation test (MRT, see Fig 1.) by Vandenberg and Kuse (1978; Peters et al., 1995). Although other psychometric tests have shown age-related declines, the MRT has recorded the largest age effect (Techetin et al., 2014), and the largest sex difference effect (males outperforming females; Voyer et al., 1995). A problem with the MRT however, is that its characteristics make it extremely complex to solve (even for young adults; Hoyek et al., 2012) and far from mimicking real-world environment interactions (i.e. object manipulation). de Bruin et al. (2016) developed and introduced ecologically valid hands-on tasks for visuospatial skills. These tasks also were demonstrated to have commonalities with the MRT in young adults (Aguilar et al. in press). In the current study we explored visuospatial skills in a group of older adults using the MRT and the hands-on tasks developed by de Bruin and colleagues. We wondered if commonalities between the tasks may also be present on this age group. Consequently, the hands-on tasks could be used as tools to assess and enhance visuospatial skills in the elderly, where functional independence is critical to improve quality of life.

Age-related declines in visuospatial cognitive functioning affect functional abilities. Particularly, this is true for complex functional abilities that demand the simultaneous use of all visuospatial skills (spatial visualization, spatial perception and mental rotation), one example is; driving. Spatial visualization, defined as the ability to manipulate spatial information that requires a multistep process, is used when imagining the path taken from point A to point B (Linn & Petersen, 1985), and is measured by psychometric tests like Paper Folding, Block Design, and Embedded Figures. Spatial perception, defined as the ability to, amidst distracting cues, interpret body to object or object to object locations in space (Linn & Petersen, 1985; Kolb & Whishaw, 2003), is commonly used when navigating the environment, and is measured by tests such as: Rod-and-Frame and Water Level tests. Mental rotation, defined as the ability to form a mental image of how an object would look when rotated from its original position (Shepard & Metzler, 1971), is used commonly used when looking through the rear view mirrors in our car; and this skill is consistently measured using the previously mentioned MRT. These psychometric tests have demonstrated large aging effects, with older adults performing poorly compared to young adults (Techetin et al., 2014); but particularly, the MRT has shown a linear and steep age-related decline (Jansen & Heil, 2009; Borella et al., 2014) and has also consistently demonstrated sex differences (males outperforming females) in older adults (Herman & Bruce, 1983; Jansen & Heil, 2009; Jansen & Kaltner, 2014; Borella, et al., 2014).

The effects of sex hormones on the brain have been suggested as partly causing the sex differences on mental rotation skill. Evidence across the literature, suggests cognitive processes are modified due to the effects of gonadal hormones on brain cell structure and function (Sisk & Zehr, 2005; Becker et al., 2008; Schulz et al., 2009; Thornton et al., 2009; Beltz & Berenbaum, 2013; Wierenga et al., 2018). Sex hormones' organizational effects cause permanent and irreversible changes to brain structures, while activational effects are reversible and can happen at any point in time. Organizational effects take place during sensitive developmental periods, when the developing brain is susceptible to changes in gonadal hormones (Arnold & Breedlove, 1985; Arnold, 2009). These sensitive periods happen prenatally (i.e. in utero) and postnatally (i.e. puberty). Natural experiments from hormonal disorders such as; Congenital Adrenal Hyperplasia (CAH) and Idiopathic Hypogonadrotopic Hypogonadism (IHH), substantiate the idea that sex hormones cause permanent effects on brain structures supporting visuospatial skills. CAH, a mostly female hormonal disorder is characterized by abnormal androgen levels in utero. During childhood, these females display a better performance on mental rotation ability tests in comparison to their sisters (without the disorder; Puts et al., 2007; Berenbaum et al., 2012). Males with IHH, a hormonal disorder characterized by low levels of androgens in utero, later in life show poor performance on mental rotation tests compared to controls (Hier & Crowley, 1982). Evidence also suggests the increasing levels of sex hormones during puberty may play a role in the organization of the brain for visuospatial functions. For example, sex differences appear to increase at this time (Blakemore et al., 2013), and the timing (e.g. earlier or later pubertal onset) has been shown to modulate performance on visuospatial tasks (Waber, 1976).

Strong evidence from activational effects on the brain comes from studying normally circulating hormones. The levels of these hormones vary in females and males. These variations however, are more apparent in females, due to the menstrual cycle. For example, during the menstrual cycle, the luteal phase is characterized by high estrogen (one of the dominant sex hormones in females) levels, while the ovulatory phase, is characterized by low estrogen levels. Multiple studies have found mental rotation performance is modulated by the levels of this hormone. Poor performance is seen when estrogen levels are high and a better performance when estrogen levels are low (Hampson, 1990; Hausmann et al., 2000; Hampson, et al., 2014). Furthermore, males with low levels of testosterone (the dominant sex hormone in males) show a poor performance on mental rotation tests (Yang et al., 2007). Natural aging, brings a decline in the levels of normally circulating dominant sex hormones in females and males due to their production decreasing. The decline in cognitive function has been linked to the lowering levels of these hormones (Zárate, Stevnsner, & Gredilla, 2017) and those older adults that choose to account for this decline by using hormonal replacement therapy (specially testosterone); have shown improvements in spatial cognition (Janowsky, 2006).

Importantly, age-related cognitive decline can be ameliorated by external factors, In particular, physical activity and cognitive training have been shown to act as protective factors against this decline (Harada, Natelson Love, & Triebel, 2013; Smart et al., 2017; Northey, Cherbuin, Pumpa, Smee, & Rattray, 2018). Older adults who follow a physically active lifestyle benefit from better working memory, attention, processing speed, executive function (Ahlskog, Geda, Graff-Radford, & Petersen, 2011) and visuospatial skills (Shay & Rith, 1992; Rogge et al., 2017) compared to those that engage in a sedentary lifestyle (Younan, 2018). Moreover, cognitive training has shown to be effective at improving cognitive function even in older adulthood. Visuospatial skills are a highly trainable and transferable cognitive function (Uttal et al., 2013) and older adults that engage on spatially engaging leisure activities have been shown to minimize aging effects (Fissler et al., 2018). Due to the importance of visuospatial skills for environment navigation (Techetin et al., 2014) it is essential to investigate them and their surrounding factors in older adults as impairments on these skills can considerably alter an individual's functional independence and quality of life.

In the present study, we evaluated visuospatial skills using our battery of hands-on tasks and the MRT in a group of older adults. The study had two purposes; the first one, was to investigate potential commonalities between all the hands-on visuospatial tasks and the well-stablished MRT in older adults. Based on previous findings (Aguilar et al, in press), we predicted the hands-on tasks and the MRT would show a relationship with each other. This relationship would be particularly strong with the high mental rotation demand (3D BBT). The second purpose, was to explore the sex difference on visuospatial skills in older adults. Because previous evidence has found a male advantage on the MRT, then the sex difference would likely appear on the BBT. However, low levels of sex hormones due to activational effects, may prevent the appearance of sex differences on visuospatial skills, and this should be found in both of the tasks (BBT and MRT).

4.3. Methods

Participants

Thirty-two older adults, females (n=18) and males (n=14) between the ages of 60 to 80 years old (M= 66) took part in the experiment. They were all healthy participants recruited through community and poster advertisements around the University of Lethbridge and the Lethbridge Seniors Citizens Organization. The experiment was approved by the University of Lethbridge Human Subject Research Committee.

Tasks

The participants were asked to read and sign an informed consent form. They then completed a battery of four spatial tasks: the BBT, 2D and 3D conditions (low- and high-spatial demand, respectively; Fig. 2, a) and b), a visual search task, and the MRT (Fig. 1). The 2D and 3D conditions of the BBT consisted of three trials each. Each trial involved duplicating a 12-brick model. Sixty unique bricks were pseudo-randomly placed in front of the participant, 30 pieces on the left side of the participant and 30 pieces on the right side. The pseudo-randomization ensured that half of the pieces for each model were on the left side and the other half on the right side. The visual search task used the same set up and models as the BBT. The difference was that participants looked on the table for the 12 bricks that composed a 2D model and placed those pieces into a bowl [without duplicating (i.e. building) the model]. The MRT consisted of 24 problems. The order of the tasks was counterbalanced for each participant, and the order of the conditions and trials within each task was randomized.

Procedure

For the BBT, participants were seated in front of a table facing the middle of the brick display (Fig. 3). The participants were instructed to build an exact replica of the model located in front of them using the bricks placed on the table as quickly and accurately as possible. They were told they could move or rotate the model as needed to investigate it. Additionally, they were told to start at the "go" signal and to say "done" when they were finished. For the visual search task, the participants were instructed to look for the blocks that made up the 2D model and place them in the container located in front of them as quickly and accurately as possible. For the MRT, participants were instructed to choose the two out of the four options that matched the target stimuli. They were told they had a time limit of three-minutes for each of two sets with a three-minute break between sets. At the end of the tasks, the participants were asked to complete two questionnaires; the Godin Leisure-Time Exercise Questionnaire (Godin & Shepard, 1997) and a questionnaire that documented the frequency of using bricks. The Godin Leisure-Time Exercise Questionnaire consisted of two questions; the first question required participants to answer how many times in a 7-Day period they engaged in three types of activities (i.e. strenuous exercise, moderate exercise, and mild exercise); the second question asked participants how often in a 7-Day period they engaged in an activity “long enough to work up a sweat”. The questionnaire documenting the frequency of brick play consisted of two questions (e.g. “how many times do you manipulate Lego [or similar] in a week on a scale from 1 [no manipulation] to 10 [continuous manipulation]”).

Data analysis

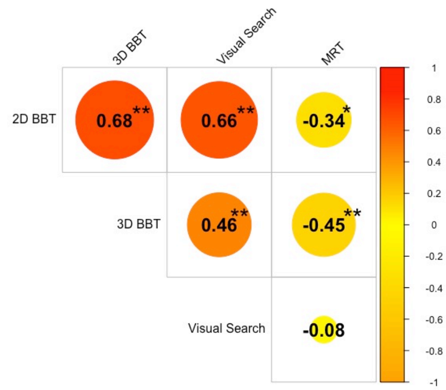
For the BBT (2D- and 3D-conditions), the time taken to replicate the models in each trial was recorded from the “go” signal of the experimenter to the “done” signal of the participant. Two types of errors during the BBT were recorded: when the participant placed a brick in the wrong position and when the participant grasped the wrong brick. The MRT was scored by giving one correct point if and only both answers were correct (perfect score = 24 points). The mean time for the three trials was calculated for each task (2D, 3D, visual search). The total time and number of correct responses (score) for MRT was also recorded. The relationships between all the tasks were examined with correlations (Pearson’s r); specifically, the participants’ performance (time and/or score) on each task were correlated with all the other tasks. The total leisure activity score for the Godin Leisure-Time Exercise

Questionnaire was calculated as instructed (see Godin & Shepard, 1997). Differences between the groups (females and males) were investigated with a one-way ANOVA for each task.

4.4. Results

Correlation Analysis

Significant correlations were found between all dependent variables (Figure 4). The largest correlations, were between the 2D and 3D conditions (r = .68) of the BBT and between the 2D condition and the visual search task (r = .66). These positive correlations suggested the longer the time taken in the 2D condition, the longer the time on the 3D condition and the visual search. The smallest non-significant correlation was between the visual search task and the MRT score (r = -.08); suggesting completely different visuospatial functions were used for these tasks. There was also a small negative correlation between the 2D condition and the MRT (r = -.34), a close to medium negative correlation between the 3D condition and the MRT (r= -.45), and a positive correlation between the 3D condition and the visual search task (r=.46). Notably, the correlation between the 3D condition and the MRT score (r= -.45) was stronger than the one found in the 2D condition, consistent with the finding of Aguilar et al. in press. The negative correlations suggested the longer the time taken to complete the 2D or the 3D condition, the lower the score was on the MRT.



* p < .05, ** p < .01

Figure 8. Correlation plot for the dependent variables: MRT scores and BBT times (2D and 3D conditions time).

Group Comparisons

The grand mean scores and mean scores by sex are shown in Table 1. The one-way ANOVA revealed significant main effects of sex for the visual search task, $F_{(1,30)} = 6.8$, $p < .05$, $n^2 = .19$, and the MRT score, $F_{(1,30)} = 9.3$, $p < .01$, $n^2 = .24$. Females were faster than males at the visual search task $p <.05$, and males scored higher in the MRT $p <. 01$. No sex effect was found on the BBT 2D condition, $F_{(1,30)} = 2.3$, $p > .1$, $n^2 = .07$ or the BBT 3D condition, $F_{(1,30)} = 0.2$, $p > .1$, $n^2 = .008$.

Table 3

Means and standard errors for the dependent variables

Dependent variable	Grand mean	Females	Males
2D BBT (s)	65.6 ± 3.2	62.4 ± 3.6	71.96 ± 5.4
3D BBT (s)	121.5 ± 7.3	124.6 ± 10.8	117.5 ± 9.5
Visual search task (s)	45.4 ± 3.3	38.4 ± 2.7	54.3 ± 5.9
MRT score	4.8 ± 0.6	3.3 ± 0.4	6.6 ± 1.1

There was no sex effect in the Godin Leisure-Time Exercise Questionnaire; for question one $F_{(1,30)} = .61$, $p > .1$, $\eta^2 = .005$ or for question two $F_{(1,30)} = .87$, $p > .1$, $\eta^2 = .03$. The questionnaire documenting the frequency manipulating bricks (Lego or similar) showed a low continuous manipulation (1.5 ± 0.13). Females and males were not different from each other in either comfort with bricks $F_{(1,30)} = .61$, $p > .1$, $\eta^2 = .02$ or manipulation of bricks $F_{(1,30)} = 2.3$, $p > .1$, $\eta^2 = .01$.

4.5. Discussion

To contribute to our understanding on the across the lifespan development of visuospatial skills and its well-known sex differences, in the current study we examined visuospatial abilities with our real world hands-on visuospatial tasks and the well-established MRT, in a group of older adults. Consistent with previous studies (see de Bruin et al, 2016 and Aguilar et al., in press), the hands-on tasks also served as a valid measure of visuospatial skills in this age group. Furthermore, compelling results regarding sex differences on visuospatial tasks were found.

Corroborating previous findings by Aguilar et al, in press, and supporting our first prediction, in the present study, the BBT showed a strong relationship with the well-established MRT. Participants that completed the 2D condition and 3D condition faster, also displayed a higher score on the MRT. Additionally, the correlation between the 3D condition and the MRT was stronger ($r= -.45$) than the 2D condition and the MRT ($r= -.34$). Conversely, no significant correlation was found between the visual search task and the MRT on this age group. This finding suggests very distinct visuospatial skills were used when performing these tasks. It is evident that the visual search hands-on task does not require the use of mental rotation to the same extent that the MRT does. The visual search task rather requires spatial perception and mostly spatial visualization skills, while the MRT requires mental rotation skill. However, the relationship found between the BBT and the visual search task (2D condition r= .66 and 3D condition r= .46) and MRT task (specified above), suggests that the visuospatial skills used to complete these tasks are also necessary to complete the BBT. It is clear that all main three visuospatial constructs are used to complete the BBT. Participants used visuospatial perception and spatial visualization to search and imagine amidst distractors which pieces perfectly matched the model, and used mental rotation to mentally rotate the model and accurately place the pieces.

In regards to the sex difference on visuospatial tasks our prediction was partially supported. Confirming previous evidence (Herman & Bruce, 1983; Jansen & Heil, 2009; Jansen & Kaltner, 2014; Borella et al., 2014) males outperformed females in the MRT but the opposite was seen in the visual search task where females outperformed males at the task. However, the male advantage found on the BBT previously in young adults (Aguilar et al., in press), was not replicated on this age group. As previously mentioned, to complete the BBT the skills used on the visual search and MRT tasks are necessary. Therefore, it may primarily be that the reversed sex effects found between the MRT and visual search task nullified the presence of a sex difference on the BBT. Also, it is important to acknowledge that for females the rotation of a three-dimensional image from a two-dimensional piece of paper has previously shown to be a challenge (Voyer & Doyle, 2010). Thus, because the BBT model can be physically manipulated/rotated by the participant, females at this age may greatly benefit from these aspects and thus, show a comparable performance to males.

The presence of the sex differences on the MRT and the absence of them on the BBT can also be explained by the biological theory of sex hormones. The male advantage in mental rotation up until this age, primarily supports organizational effects of sex hormones during sensitive developmental periods, that have permanently modified brain structures required for mental rotation skill. However, not ruling out the possibility that activational effects could also be playing a role that is perhaps minimal or is exhibited differently. In addition, because previously the BBT has shown sex differences in young adults; it may be that this is a more sensitive measure that is able to identify changes in visuospatial abilities at this age due to activational effects; lower levels of circulating testosterone which accompany normal aging may cause a decrease in performance on mental rotation tasks, thus, potentially eradicating the male advantage.

To understand the sex difference found on the visual search task, it is crucial to take age-experience and differences in strategy (when solving visuospatial tasks) into account; because, contrary to the male advantage on the MRT, a female advantage on this task has not previously been found in infants, children or even younger adults (Aguilar et al., in press). Even though it has been previously found that females are better at identifying matching objects (Kimura, 1992). To our knowledge, there is a lack of research on sex differences in specifically visual search tasks, with one previous study suggesting a male rather than a female advantage in young adults (Stoet, 2011). Therefore, this is a novel finding, from which we suggest it may be the result of the interplay between age experience and the preferred detail oriented approach of females when solving visuospatial tasks (Pletzer, 2014). Females are known to be more engaged than males in household tasks (Baxter, 1997) which necessitate the constant visual search of objects in space, for example; grocery shopping, cooking, or organizing. In addition, taking a detailed approach could have been the best approach to solve the task faster, as identifying specific object properties (i.e. shape and color) would have been especially helpful.

We considered it important to account for external factors that could have impacted the presence or absence of a sex difference, specifically; comfort and manipulation of bricks, use of hormonal replacement therapies, and physical activity. However, none of these factors influenced the results of the present study. There was not a sex difference found on comfort or manipulation of bricks, thus, females were not better than males at the visual search hands-on task due to familiarity of playing with bricks. Our participants were not in any type of hormonal replacement therapy. Lastly, no sex difference was found on the amount of time engaged on different types of exercise (as measured by the Godin Leisure-Time Exercise Questionnaire). Therefore, a better performance at the tasks from females or males was not due to the influence of these factors.

The hands-on tasks are a better tool than psychometric tests for the investigation and enhancement of visuospatial skills for this age group because of the following reasons. The MRT mostly requires mental rotation skill, process that has in particular demonstrated to slow down with age (Gay Lord & Marsh, 1975; Cerrella et al., 1981; Hertzog et al., 1993; Dror & Kosslyn, 1994; Zhao et al., 2019) conversely, the BBT measures the global and simultaneous use of all visuospatial constructs. In addition, measures using three-dimensional (3D) abstract stimuli (as the MRT), have shown to be significantly more challenging (Iachini et al., 2019) to complete for older adults than when less complex two-dimensional (2D) stimuli are used (Jansen & Kaltner, 2014; Iachini et al., 2019). The hands-on tasks, however, provide two different degrees of complexity (2D vs 3D models) and the stimuli have distinct features (different colors and shapes) which make them more suitable for this age group. Lastly, the BBT has an unlimited amount of time to complete it in contrasts to the MRT. In general, these tasks mimic real-world setting situations where we are constantly manipulating objects and constantly involved in complex functional activities that require the simultaneous use of all visuospatial constructs. Further, the purpose of these tasks is easy for the researcher to communicate and for the participant to understand also giving opportunities for the hands-on tasks to serve as part of cognitive training programs for older adults (Uttal & Cohen, 2012; Uttal et al., 2013), an age group that can vastly benefit from diminishing declines in cognitive functioning.

The current study carries certain limitations important to note. First, we did not account for our participants' socio-economic status, those participants with a higher socio-economic status may have had better visuospatial skills (Levine et al., 2005; Lippa, Collaer, & Peters, 2010). However, if socioeconomic status played a role this may have been minimal due to our small sample. Second, we did not account for our participants' educational and professional background. People that were involved in STEM (Science, Technology, Engineering, Mathematics) areas may have better visuospatial abilities than those that were not, more so those that were professionally engaged on these areas may have even trained these abilities towards improvement (Lubinski, 2010). But because our sample was recruited randomly throughout the community and not selected within a specific demographic; if educational level and professional background played a role, this role was also minimal. Lastly, involvement in leisure spatially stimulating activities (e.g. jigsaw puzzle play) or cognitive training could have impacted our participants age-related visuospatial cognitive declines (Fissler et al., 2018, Harada et al., 2013) as we did not account for involvement on these type of activities. However, there was not a single participant that showed to be particularly superior at the tasks, thus, it is improbable that the latter impacted the results.

CHAPTER 5
Discussion

5.1. General Discussion

This is the first set of studies that document MR ability using the same test across five developmental stages. Furthermore, this is the first time that MR ability was assessed for 3D stimuli using real objects. Numerous tests have been developed to assess MR ability (Quaiser-Pohl, 2003; Titze et al., 2010, Krüger et al., 2014; Ramful, Lowrie, & Tracy, 2017; Lütke & Lange-Küttner, 2015; Hawes et al., 2015), but only some have explored their relationship with the well-established MRT (Shepard and Metzler, 1971) and none used real objects to quantify the progress of MR ability across age groups. The fact that different MR measures have been used to assess different age ranges or age groups has limited our understanding of the development of MR function. Therefore, the purpose of this thesis was to close this gap by providing consistency in the tool used to measure MR across different age groups. The BBT not only proved suitable for testing MR in children, teenagers, young adults and older adults, but its characteristics may also make it a useful tool for training and further enhancement of MR abilities.

In the first study it was hypothesized that the hands-on task would share similarities with the MRT; this prediction was supported. In a group of young adults, it was found that the two conditions of the block-building task (2D- low-mental rotation demand and 3D-high-mental rotation demand) were negatively correlated with the MRT. This means that the longer the time taken to complete the BBT (worse performance) the lower the score was on the MRT. This suggests that similar mechanisms are used to complete both of these tasks. Additionally, in regards to sex differences, it was hypothesized that males would display an advantage on the BBT. This prediction was supported; a male advantage was found in the BBT and on the MRT in young adults. Males outperformed females on both conditions of the BBT; but this was more evident on the 3D condition (high mental rotation demand). However, on a visual search hands-on task (see Chapter 2), males and females were comparable with each other. The latter finding demonstrates the male advantage was not due to a faster time looking for the pieces but rather a faster time at rotating the stimuli to replicate it; corroborating a male advantage particularly for MR ability.

In the second study it was hypothesized that performance on the BBT would improve with increasing age, until late adolescence. The study involved three groups of participants of varying ages; younger children (ages 5 to 8), older children (ages 9 to 12) and teenagers (ages 13 to 17). All participants completed the BBT (2D and 3D conditions) and the MRT. The prediction in regards to age differences was partially supported; results demonstrated that teenagers and older children were comparable with each other but better than younger children in all tasks. This result suggests that considerable maturation of MR ability takes place between the ages of 5-12 years of age. Regarding sex differences, it was hypothesized that a male advantage will emerge during late childhood or adolescence. Also supporting this prediction; a male advantage was found on the MRT but only in the teenagers, and on the 3D condition of the BBT in the older children (surprisingly not in the teenagers). These results are in line with previous evidence in younger and older children (Marmor, 1975; Marmor, 1977; Kosslyn et al., 1990; Estes, 1998; Roberts & Bell, 2000; Frick et al., 2009; Frick et al., 2013; Lehman et al., 2014; Fernández et al., 2018; Barel & Tzischinsky, 2018; Rodán et al., 2019) and teenagers (Kail,1980; Waber et al., 1982; Kail et al., 1985; Kosslyn et al., 1990) that did not found a sex difference using 2D stimuli but have found it when using 3D stimuli (in children; Kerns & Berenbaum, 1991; Titze et al., 2010; Neuburger et al., 2011; Barel & Tzischinsky, 2018; Wilson, 1975; Johnson & Meade 1987; Kosslyn, 1990; Masters & Sanders, 1993; Codorniu-Raga & Vigil-Colet, 2003; Neubauer et al., 2010; Moé, 2016; Jansen, 2018). These results also support the findings of a recent meta-analysis that found that the sex differences in MR reached a moderate effect size by 13 years of age but only when 3D stimuli were used, when 2D stimuli were used the moderate effect size was not reached until 17 years of age (Lauer et al., 2019). The absence of a male advantage on the BBT in teenagers is intriguing; a potential explanation for this finding is that at this age female visuospatial abilities are at their peak, while males are still developing. However, as it can be noted in the next section, the male teenagers relative increase between the 2D condition and the 3D condition (Figure 9c) decreased in young adult males, thus, a more appropriate explanation could be that at this age ongoing development of executive function skills could particularly be causing their poor performance at the test.

In the third study it was hypothesized that MR ability declines with normal aging. This prediction was only supported when analyses comparing young and older adults was done (see the next section). In regards to sex differences it was hypothesized that no male advantage would be present in the older adult group as there is a decrease of circulating sex hormones. The prediction was only partially supported. There was a male advantage on the MRT, but no advantage was found on the BBT. Interestingly a female advantage on the visual search was found. The fact that females were better at the visual search task may explain in part why no male advantage was found on the BBT. Because the BBT necessitates visual search and MR, (a female and male advantage respectively), thus, performance may have evened out. With the purpose to discriminate between motor speed and ability from mental rotation ability, a closer look at the BBT data in this age group (see next section), revealed a male advantage when the time to complete the 3D models was expressed as percentage of the 2D models. This suggested that a male advantage remains for MR in senescence.

5.2. All groups together

To gain a better/bigger understanding of the developmental trajectory and possible sex differences in MR ability, the data from my three studies were put together and comparisons across age groups and sex were made for the 2D BBT (Fig.9a), 3D BBT (Fig.9b), and the MRT (Fig. 9c). It is important to note, that to allow for across age group comparisons for the MRT; the scores were expressed as a percentage (for children: amount correct/12 problems and for the rest of the groups amount correct/ 24 problems). Additionally, I explored the *relative* increase in difficulty from the 2D to the 3D condition across age and sex groups (3D/2D BBT Ratio**;** Fig. 9d). Exploring this is useful when discriminating between demand for mental rotation from that of motor speed (de Bruin et al., 2016). To do this the percent increase in the mean time to build the models in the 3D condition compared to the 2D condition was calculated. Specifically, mean time in the 3D condition was divided by the mean time of the 2D condition and then multiplied by 100 (to be expressed in percentage).

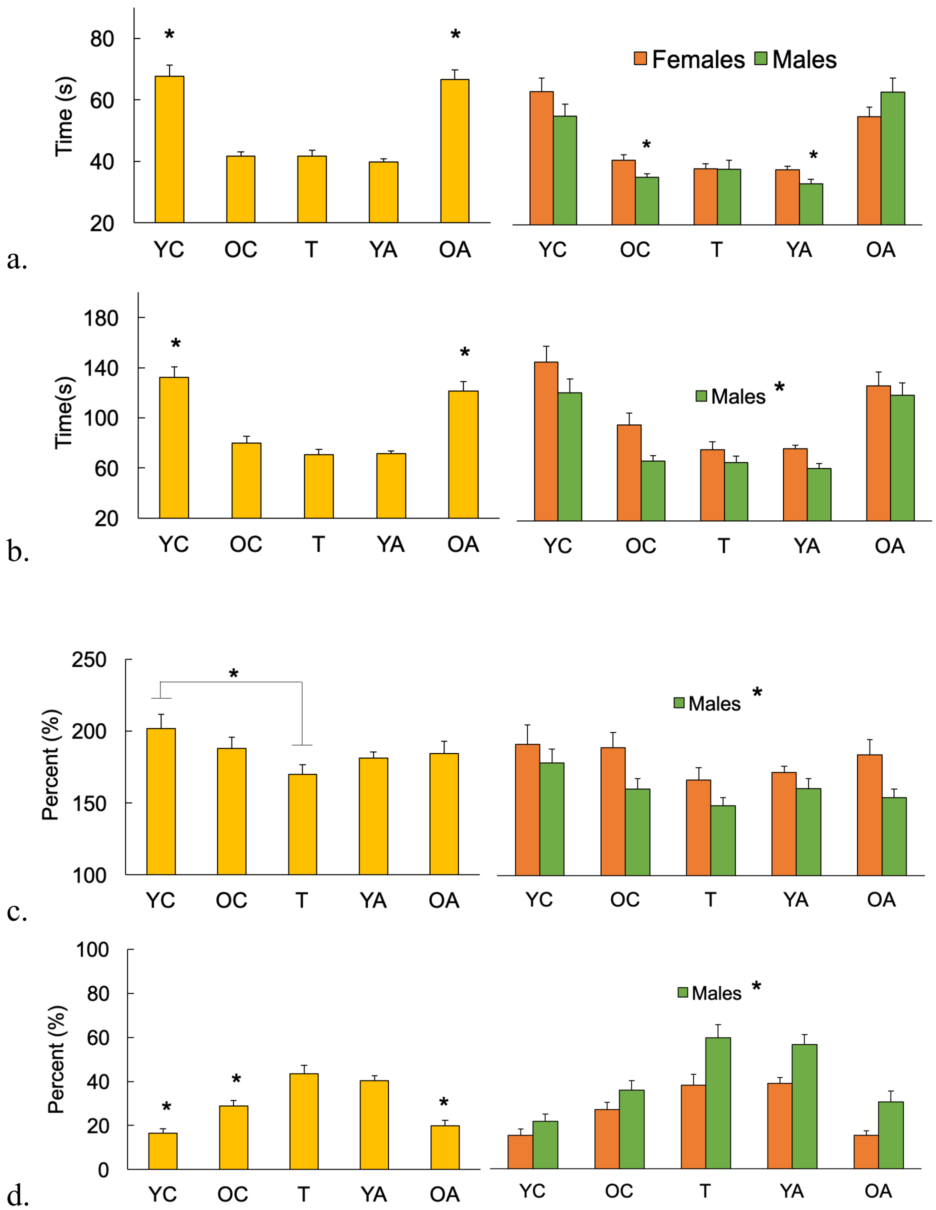


Figure 9. a) 2D Brick Building Task (BBT) mean times for Group (Younger Children-YC, Older Children-OC, Teenagers-T, Young Adults-YA, Older Adults-OA) on the left and Sex (Females and Males) on the right. b) 3D BBT mean times for Group on the left and Sex on the right c) 3D/2D BBT Ratio mean percent for Group on the left and Sex on the right. d) MRT mean percent correct for Group on the left and Sex on the right. (Note: On Group graphs [on the left] those marked with '*' are significantly different from those that are not marked. On Sex graphs [on the right], those marked with '*" denote a significant sex difference within that group age)

5.2.1. Age and sex effects on the 2D BBT (Fig. 9a)

A two-way ANOVA was used to analyze the effects of age (younger children, older children, teenagers, young-adults, older-adults) and sex (female, male) on the time to complete the 2D BBT. The results revealed a main effect of age ($F_{(4,236)} = 39.95$; $p < 0.0001$), no main effect of sex ($F_{(1,236)} = 1.62$; $p = 0.2$; and an age by sex interaction that approached significance ($F_{(4,236)} = 2.37$; $p = 0.053$). Post-hoc analyses (Bonferroni corrected) indicated that the main effect of age was due to the younger children (5-8 year olds) and the older adults (60-80 year olds) taking significantly longer time to complete the 2D models when compared to the older children, the teenagers, and the young adults (all p's < 0.05). No significant difference was found between younger children and older adults ($p = 1$). No significant differences were found amongst older-children, teenagers and the young-adults ($p = 1$). Although the two-way interaction was not significant, when looking at each age group (one-way ANOVA), sex differences emerged for the older children and the young adult groups ($p < 0.05$). In both groups males completed the task significantly faster than females. No sex differences were found in the other age groups.

5.2.2. Age and sex effects on the 3D BBT (Fig. 9b)

Results revealed a main effect of age ($F_{(4,236)} = 33.26$; $p < 0.0001$), a main effect of sex ($F_{(1,236)} = 12.51$; $p < 0.0001$), but no significant interaction ($F_{(4,236)} = .65$; $p = 0.6$). Post-hoc analyses (Bonferroni corrected) indicated that (as it was the case for the 2D models) the main effect of age was due to the younger children and the older adults taking significantly longer to complete the 3D models when compared to the older children, the teenagers, and the young adults (all p's < 0.05). No significant difference was found between younger children and older adults ($p = 1$). No significant differences were found amongst older-children, teenagers and the young-adults ($p = 1$). The main effect of sex was due to the males completing the task significantly faster than the females.

5.2.3. Age and sex effects on the 3D/2D BBT Ratio (Fig. 9c)

Results revealed a main effect of age ($F_{(4,236)} = 2.64$; $p < 0.05$), a main effect of sex ($F_{(1,236)} = 13.08$; $p < 0.0001$), but no significant interaction ($F_{(4,236)} = .55$; $p = 0.7$). Post-hoc analyses (Bonferroni corrected) indicated that the main effect of age was due to a significant difference between younger children and teenagers ($p < 0.05$). Younger children took longer to complete the 3D models when expressed as a percentage of the 2D models than teenagers. No other significant differences were found amongst the age groups. The main effect of sex was due to the males having lower ratios than females (i.e. better performance).

5.2.4. Age and sex effects on the MRT (Fig. 9d)

Results revealed a main effect of age ($F_{(4,236)} = 23.89$; $p < 0.0001$), a main effect of sex ($F_{(1,236)} = 26.93$; $p < 0.0001$), but no significant interaction ($F_{(4,236)} = 1.14$; $p = 0.3$). Post-hoc analyses (Bonferroni corrected) indicated that the main effect of age was due to both children groups having significantly lower scores in the MRT when compared to the teenagers, and the young adults (all p's < 0.05). Older-adults were not significantly different from younger- or older-children groups. Put differently, teenagers and young-adults, which did not differ between each other, were significantly different from every other group. The main effect of sex was due to the males having higher scores than females (i.e. better performance).

5.2.5. Correlations between "frequency and comfort playing with bricks questionnaire" and the BBT and MRT

To explore the possibility of an existent relationship between frequency and comfort playing with bricks an better performance in the 2D BBT and 3D BBT a Bivariate correlation analysis was run with all participants. No significant correlations were found between the frequency of manipulation and the 2D BBT ($r= -.03$) or the 3D BBT ($r= -.05$). A non-significant correlation was also found between comfort with bricks and the 2D BBT ($r= -.09$). Significant but weak correlations were found between comfort with bricks and the 3D BBT ($r= -.17$, $p = 0.04$), the 3D/2D ratio ($r= -.18$, $p = 0.02$), and the MRT ($r=.19$, $p = 0.02$). These significant correlations indicate that those participants that self-report as more comfortable playing with bricks might have better MR ability. Caution should be taken on this suggestion however, as these correlations are weak at best.

As it can be appreciated in Figure 9, there are similarities in the results of all tasks. Performance is poorer at either extreme of the age spectrum (younger children and older adults) and best in the middle (teenagers and young adults). An important point should be made here. Although it seems as though younger children and older adults have difficulties in MR tasks because of their poor performance in the MRT and the BBT, a closer look at the BBT task would suggest differently. Older adults were not significantly different from any group when the 3D time was expressed as percentage of the 2D time. The reason it took longer for them to complete both the 2D and 3D tasks is likely due to a decrease in manual speed and skill (normal with aging) plus the unfamiliarity of building with bricks. The fact that older adults are not different from teenagers or young adults in the 3D/2D BBT Ratio suggests that the ability to mentally rotate real objects does not decline with age (as de Bruin and colleagues suggested). This result is contrary to what the MRT results would indicate. It is tempting to speculate therefore, that the reason why younger children and older adults do poorly in the MRT is not because they lack mental rotation ability, but rather because the MRT instructions or the type of stimuli might make it challenging for them to understand the task.

5.3. Limitations and future directions

5.3.1 Limitations

The studies presented on this thesis have certain limitations that are important to note. In the current section, I present limitations in general that could have impacted the results across age groups and sex differences (limitations of each of the studies included in this thesis are noted on their corresponding discussion section).

Experience with spatially engaging activities (i.e. building with blocks, putting puzzles together, or playing video games) could have impacted performance in the BBT and to a certain extent in the MRT in all age groups. This is because as mentioned in Chapter 1 (section 1.5) using spatially engaging activities can serve as training and as a result enhancement of MR ability. By giving participants the “frequency and comfort playing with bricks” questionnaire I attempted to get to this issue. Children scored the highest in this questionnaire but their performance in the BBT task was not better than that of teenagers of young adults. Neither did I find a significant correlation between the questionnaire and performance on the BBT in young adults. This suggests that if experience playing with blocks influences MR ability, this influence is small. Future studies should try to have a more comprehensive history of MR activities.

With respect to sex differences, none were found in the questionnaire (i.e. female and male reported similar manipulation frequency) in any of the age groups yet, sex differences were found in all MR tasks. Similarly, when experience with spatially engaging activities (e.g. puzzles, board games, block games) is controlled for in children, research has shown that a boy advantage on spatial tasks remains (Jirout & Newcombe, 2015). This suggests that the male advantage is not only due to spatial play experience (Jirout & Newcombe, 2015) but that there are also other factors (either biological and/or environmental) contributing to the sex differences. Some studies have found a relationship between video game play and performance on spatial tasks (Okagaki & Frensch, 1994; Subrahmanyam & Greenfield, 1994; De Lisi & Cammarano, 1996). Thus, this may have been another factor contributing to better performance on the BBT and MRT; particularly on the teenage and young adult groups (due to the prevalence of videogame play at these ages). Video game experience was not accounted for in any of the age groups investigated on the studies presented in this thesis. However, it is important to note that not all video games have been shown to contribute to better spatial performance (Collins & Freeman, 2014) and in fact some research has not found sex differences in experience with video games in teenagers (Moreau, 2013; Rodán et al., 2016) or young adults (Terlecki et al., 2011; Moreau, 2013). A more recent meta-analysis even found no relationship between video game play experience and better cognitive abilities (including spatial abilities; Sala, Tatlidil, & Gobet, 2018).

Another limitation was that type of strategy when completing the tasks was not accounted for in any age group. The use of different strategies to complete the BBT and/or the MRT could have been different between ages or sexes. For example, it was recently found that young and old adults differ on the type of strategy (holistic versus piece by piece) used during a 2D and 3D computer based MR test (Zhao, Della Sala, & Gherri, 2019). In addition, using the MRT in middle school children and adolescents (Geiser, Lehmann, & Eid, 2006; Geiser, Lehmann, Corth, & Eid, 2008) it was found that again, the type of strategy used (global vs featured based), mediated the scores on the test. Those that used a global strategy were more successful than those that did not. Notably, males were more likely than females to use this type of strategy which may have accounted for the lager sex effect found in this paper (Hegarty, 2018). However, although the type of strategy might impact performance on the MRT or similar paper/computer- based test, it still remains to be shown if the same is the case when real world objects are used as stimuli. I would speculate that either strategy (global versus focal) could be equally helpful when completing the BBT but this remains to be tested.

Last but not least, another limitation is the fact that socioeconomic status (SES) was not controlled for. Research in this area has found that SES can mediate age and sex differences in visuospatial performance (Levine et al. 2005). Children of low-SES have shown to lag behind in block assembly tests (Verdine et al., 2014). Furthermore, although boys of medium and high SES performed better in a block assembly test, no sex differences were found in children of low SES (Verdine et al., 2014). I am currently collaborating with Dr. Blinch (at Texas Tech) in a research study investigating the impact of SES in visuospatial abilities in children of very marginalized families.

5.3.2. Future Directions

Studies have shown a strong link between sensorimotor interactions and the capacity to mentally rotate stimuli (see sections 2.4 and 4.4). Play with blocks has particularly shown to improve spatial abilities (Jirout & Newcombe, 2015) including MR ability (Newman & Hansen, 2016). The BBT involves structure block play and unlike paper and pencil tests, it requires sensorimotor interaction. This makes the BBT ideal to be used as a training tool or as part of an intervention program for the enhancement of visuospatial abilities. This may reduce the sex gap and might encourage young girls to get involved in STEM related activities. Enhancing visuospatial abilities might also help children lagging behind in math or arithmetical abilities, and could help a variety of populations of different ages and SES. The BBT could also be used to discriminate between type of strategy (ego vs allocentric) predominantly used by different ages and sexes when solving real world tasks. Lastly, because spatial play has proven to elicit use of spatial language between parent and child and in turn these interactions have been shown to positively influence MR ability (Ferrara, Hirsh-Pasek, Newcombe, Golinkoff, & Lam, 2011); the BBT could also serve to investigate differences in parental use of spatial language and again, as a tool to enhance this experience. After all isn't every parent/grandparent dream to play Lego with their children?

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