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Aging and spatial abilities: Age-related impact on users of a sign language

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Aging and spatial abilities: Age-related impact on users of a sign language

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Résumé

Introduction. Les fonctions cognitives évoluent avec l'âge : certaines tendent à diminuer dans leur efficacité alors que d'autres se maintiennent. Des recherches ont montré que le vieillissement affecte la rotation mentale, la perception spatiale, la visualisation spatiale et la prise de perspective. Des facteurs sociodémographiques et comportementaux peuvent aussi influencer le cheminement du vieillissement cognitif des personnes âgées. À titre d'exemple, l'expérience langagière, comme le bilinguisme, agit comme un facteur neuroprotecteur contribuant à la réserve cognitive. L'impact de l'utilisation d'une langue des signes sur la cognition spatiale a suscité beaucoup d'intérêt chez les chercheurs s'intéressant aux langues des signes. Pourtant, aucune recherche n'a encore abordé l'effet de l'utilisation à long terme d'une langue des signes sur la cognition spatiale des signeurs aînés.

Objectif. Le but de cette thèse est d'examiner s'il existe des différences sur le plan des habiletés spatiales entre signeurs (sourds et entendants) et non-signeurs de différents groupes d'âge. Plus précisément, cette thèse a examiné i) si la performance à des tâches d'habiletés spatiales diffère selon l'âge (jeunes adultes/aînés) et l'expérience linguistique (signeurs sourds/entendants signeurs/entendants non-signeurs) et ii) si la performance diffère selon la sous-composante d'habiletés spatiales ciblée (perception spatiale; visualisation spatiale; rotation mentale; prise de perspective).

Méthode. Pour investiguer l'effet de l'âge et de l'expérience linguistique sur les habiletés spatiales, une collecte de données auprès de 120 participants a été effectuée : 60 adultes âgés de 64 à 80 ans (20 sourds signeurs, 20 entendants signeurs, 20 entendants non-signeurs) et 60 jeunes adultes de 18 à 35 ans (20 sourds signeurs, 20 entendants signeurs, 20 entendants non-signeurs). Afin de s'assurer de l'admissibilité des participants, une évaluation de l'acuité visuelle, de l'acuité auditive, des compétences langagières (français et langue des signes québécoise), de la santé cognitive et de l'intelligence a été effectuée. Les participants ont été appariés entre groupes d'expérience linguistique selon leur niveau d'éducation et d'intelligence. Les quatre sous-composantes d'habiletés spatiales ciblées (perception spatiale; visualisation spatiale; rotation

mentale; prise de perspective) ont été testées par l'entremise d'une batterie de sept tests psychométriques.

Résultats. Conformément à ce qui a été précédemment observé sur l'effet de l'âge sur les habiletés spatiales, les résultats en termes de justesse de la réponse ont révélé que les jeunes signeurs sourds obtiennent globalement de meilleurs résultats que les signeurs sourds aînés dans toutes les tâches d'habiletés spatiales. De plus, les résultats ont montré un avantage des entendants signeurs sur les entendants non-signeurs aux tâches de rotation mentale et de prise de perspective, quel que soit leur âge. Un avantage général des signeurs aînés (sourds et entendants) par rapport aux non-signeurs aînés a été observé uniquement pour les tâches de visualisation spatiale en termes de justesse de la réponse. Ces résultats suggèrent que les changements cognitifs associés au vieillissement ont un effet sur le traitement de l'information spatiale quelle que soit la modalité linguistique utilisée et que l'effet de l'utilisation de la langue des signes sur les processus spatiaux semblent différer entre les signeurs sourds et les signeurs entendants.

Discussion. Cette recherche transversale a permis d'étudier pour la première fois l'impact du vieillissement sur les habiletés spatiales des utilisateurs d'une langue des signes. Également, elle explore le facteur potentiellement atténuant de l'utilisation de la langue des signes quant aux effets de l'âge sur la performance à des tâches d'habiletés spatiales. Sur la base des résultats, il est proposé que l'effet de l'utilisation d'une langue des signes sur la cognition spatiale est spécifique aux sous-domaines d'habiletés spatiales (perception spatiale; visualisation spatiale; rotation mentale; prise de perspective), et que l'expérience linguistique, telle que le bilinguisme bimodal, est un facteur d'intérêt dans la relation entre l'utilisation d'une langue des signes et les processus spatiaux.

Conclusion. Les résultats rapportés dans la présente thèse seront utiles aux futurs chercheurs intéressés par l'étude de la cognition chez les aînés signeurs. Des recherches futures devraient se poursuivre dans cette direction afin de préciser l'impact du bilinguisme bimodal sur la cognition spatiale à la lumière de ce qui est connu des effets protecteurs du bilinguisme unimodal face au vieillissement. De plus, les recherches futures devraient envisager d'élargir la

perspective de l'effet de l'âge sur les habiletés spatiales des signeurs, en tenant compte des données cognitives et linguistiques. Ces recherches pourraient investiguer la cause de la distinction dans le traitement d'informations spatiales sur la production et la compréhension d'une langue des signes.

Mots-clés : bilinguisme bimodal, cognition spatiale, habiletés spatiales, langue des signes, perception spatiale, prise de perspective, rotation mentale, surdité, vieillissement, visualisation spatiale

Abstract

Introduction. Across the adult lifespan, cognitive abilities change: some tend to decrease with age whereas others are maintained. The results of previous studies have shown that performance on tasks spatial perception, spatial visualization, mental rotation and perspective taking are poorer in older adults than in younger adults. Sociodemographic and behavioral factors may influence the cognitive aging trajectories of older adults. For example, language experience, such as bilingualism, may be a neuroprotective factor contributing to the cognitive reserve. The impact of language experience in another modality, as it is the case for visual-spatial language, on spatial cognition has generated much interest. To date, no research has addressed this issue with regards of the potential effect of longtime use of sign language on the spatial cognition of older signers.

Aim. The aim of this thesis is to investigate whether there are differences in spatial abilities among signers (deaf and hearing) and non-signers of different age groups. More specifically, this thesis examined i) if performance on tasks of spatial abilities differs according to age (younger/older) and linguistic experience (deaf signers/hearing signers/hearing non-signers) and ii) if performance differs according to the type of spatial abilities subcomponent targeted (spatial perception; spatial visualization; mental rotation; perspective taking).

Methods. To examine the effect of age and linguistic experience on spatial abilities, data were collected from 120 participants: 60 older adults from 65 to 80 years of age (20 deaf signers, 20 hearing signers, 20 hearing non-signers) and 60 young adults ranging in age from 18 to 35 years (20 deaf signers, 20 hearing signers, 20 hearing non-signers). Prior to the experiment, participants were tested for visual and hearing acuity, language proficiency (Quebec Sign Language and French), cognitive health and intelligence. Based on their linguistic experience, the participants were matched on the basis of their educational level as well as their level of intelligence. The four subcomponents of spatial abilities were tested using a battery of seven tests.

Results. Consistent with previously published data on the effect of age on spatial abilities, accuracy results revealed that the younger deaf signers constantly performed better than the older deaf signers on all tasks. Results also highlighted a specific advantage of hearing signers over hearing non-signers in terms of accuracy on mental rotation and perspective taking tasks regardless of age. A general advantage of older signers (deaf and hearing) over older non-signers was observed on spatial visualization tasks only. These results suggest that age-related cognitive changes impact the processing of spatial information regardless of the linguistic modality used. Also, the effect of sign language use on spatial processes may differ between deaf signers and hearing signers.

Discussion. This cross-sectional research made it possible to investigate for the first time the impact of aging on spatial abilities among sign language users, as well as to explore the potential effect of sign language use with regards to performance on tasks of spatial abilities in an older population. Based on the results, it is proposed that the effect of sign language use is subdomain specific and that language experience such as bimodal bilingualism is a factor of interest in the relation between sign language use and spatial processing.

Conclusion. The results reported in the present thesis will be helpful to future researchers interested in investigating aspects of cognition throughout the lifespan of older signers. Future research should be pursued in order to investigate the impact of bimodal bilingualism on spatial cognition in the light of the aging factor. In addition, future research should consider broadening the scope of this research area by examining in detail the interaction between cognitive skills and linguistic modality. Researches could address the effect of the distinction observed between deaf signers and hearing signers in terms of spatial processing and investigate links between spatial processing and sign language production and comprehension.

Keywords: aging, bimodal bilingualism, deafness, mental rotation, perspective-taking, sign language, spatial abilities, spatial cognition, spatial perception, spatial visualization

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List of acronyms and abbreviations

A: ambidextrous

ACC: accuracy

ACE: Addenbrooke's cognitive examination

AD: age of deafness

ANOVAs: analyses of variance

ASL: American Sign Language

BECLA: *Batterie d'Évaluation Cognitive du Langage chez l'Adulte*

BSL: British Sign Language

BSL-CST: British Sign Language Cognitive Screening Test

c.-à-d.: *c'est-à-dire*

CI: cochlear implant

CRFT: Computerized Rod-and-Frame Test

CRIUGM: *Centre de recherche de l'Institut universitaire de gériatrie de Montréal*

CRT: Card Rotation Test

CST: Cognitive Screening Test

dB HL: decibels in hearing level

DS: deaf signers

F: female

Gr.: Group

GRÉMOTs: *Batterie d'évaluation des troubles du langage dans les maladies neurodégénératives*

DHL: degree of hearing loss

HNS: hearing non-signers

HS: hearing signers

HVOT: Hooper Visual Organization Test

Hz: Hertz

L: left dominance

LSF: *Langue des signes française*

LSQ: *Langue des signes québécoise*

LSQ-CST: *Langue des signes québécoise*-Cognitive Screening Test

M: mean

Ma: male

MMSE: Mini-Mental State Examination

MR: mental rotation

MRT: Mental Rotation Test

ms: milliseconds

n: total sample

N/A: not applicable

n.s.d.: no significant difference

ODS: older deaf signers

OHS: older hearing signers

p. ex.: *par exemple*

PP: *prise de perspective*

Prisma-Scr: Preferred Reporting Items for Systematic Reviews and Meta-analysis Protocols – Extension for Scoping Reviews

PS: *perception spatiale*

PT: perspective taking

pts: points

PTSOT: Perspective Taking/Spatial Orientation Test

R: right dominance

RCPM: Raven's Coloured Progressive Matrices

Rg: range

RM: *rotation mentale*

r-MPFBT or RMPFBT: Revised Minnesota Paper Form Board Test

RT: response time

SD: standard deviation

SLP: sign language proficiency

SLPI: Sign Language Profiency Interview

SP: spatial perception

STEM: science, technology, engineering, and mathematics

SV: spatial visualization

VS: *visualisation spatiale*

WLT: Water-Level Test

YDS: younger deaf signers

YHS: younger hearing signers

YO: years old

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Introduction

Global aging is a well-known demographic phenomenon. Between 2000 and 2050, it is expected that the population of adults who are over 60 years of age will double, increasing from 12% to 22% of the overall population (World Health Organization, 2020a). Along the same line, research on aging has increased and has already provided significant insights on the multifaceted phenomenon of aging in terms of neurobiology, physiology, sensory loss, pathologies, etc. (e.g. Manor & Lipsitz, 2013; Martin & Sheaff, 2007; Park & Reuter-Lorenz, 2009; Stern, 2012; Wahl & Tesch-Römer, 2001; Wyss-Coray, 2016). It is widely recognized that age-related biological changes can lead to alterations of behaviors and functional capacity. Also, it has become apparent that a causal relationship exists between life events and cognitive functioning among older adults. Occupational cognitive requirements (Pool et al., 2016), socioeconomic status across the lifespan (Lyu & Burr, 2016), propensity to engage in physical activities (Lin et al., 2019), mentally stimulating leisure activities (Scarmeas et al., 2001) are only a few sociodemographic and behavioral factors that may influence the cognitive aging path of older adults. The diversity of life experiences defines human beings. This experiential richness represents the cornerstone of the range of cognitive profiles across individuals, and may, at least in part, explain the large interindividual differences observed among older adults (Hayden et al., 2011; Valdois et al., 1990; Wilson et al., 2002; Wisdom et al., 2012).

Communication is fundamental to the socialization of human beings. Language is a capacity commonly shared by most of the population to express opinions and emotions, manifest interests, develop social relationships, answer questions, etc. Therefore, the use and understanding of a language represents, per se, a significant life experience. Previous research has highlighted the effect of language experience on cognitive aging. Bilingualism is a complex cognitive activity that has been shown to enhance working memory control (Bialystok et al., 2004), executive control (Bialystok et al., 2006) and metalinguistic awareness (Sun, 2016). In older adults, this *bilingual advantage* has been shown to delay the onset of dementia by as much as four years among bilinguals compared to monolinguals (Bialystok et al., 2007). It has been suggested that this effect is a manifestation of the *cognitive reserve*, which is the result of the

adaptability of cognitive processes to cope with brain changes. This reserve is shaped by sustained mentally relevant life experiences (Stern, 2002; Stern et al., 2018).

Given that language experience might influence cognitive function, one may ask: What is known about the effect of using a language in another modality, such as sign language, on cognition? And, more specifically: What's the effect of the signing brain on the normal aging process? Sign languages are visual-spatial in nature, and the production and comprehension of a sign language message rely on mechanisms of spatial cognition (Emmorey et al., 1993). However, investigations on the potential implications of sign language use on spatial abilities reveal important discrepancies in their findings (e.g., Emmorey et al., 1993; Hauser et al., 2006; Marschark et al., 2015; Talbot & Haude, 1993). Considering the concept of cognitive reserve, what can the aging process reveal about the relationship between sign language use and spatial abilities? More specifically, can sign language use mitigate the effect of aging on spatial abilities?

The present thesis aims to extend the existing knowledge on the effect of using a sign language on spatial abilities. Further, it examines the effect of aging on spatial processes among sign language users (i.e. signers). This cross-sectional research program examines the potential effect of age (younger vs. older adults) among participants with three different linguistic experiences (deaf signers/hearing signers/hearing non-signers) on performing tasks of spatial abilities.

The thesis which includes three articles is composed of five main chapters. Chapter 1 provides an overview of the literature on i) the general principles of cognitive aging, the effects of aging of spatial abilities, and the concept of cognitive reserve; and ii) the characteristics of signers (hearing and deaf), the specificities of visual-spatial languages, and the cognitive functioning of signers; and iii) the current state of knowledge on the aging process in older signers, and the available information on the relationship between sign language use and spatial processing The objectives, hypotheses and predictions of the research program are presented at the end of this chapter. The results of this research reported from three articles are presented in Chapter 2, 3 and 4. The current knowledge concerning the relationship between sign language use and spatial abilities and the factors influencing this relationship are discussed in Chapter 2

which consists of a scoping review on this topic. Chapter 3 presents the first experimental article which explores the impact of age on spatial abilities in deaf signers. Chapter 4 reports the differences in performance on spatial abilities among adults according to age (younger vs. older adults) and linguistic experience (deaf signers/hearing signers/hearing non-signers). The data collected across the empirical studies are summarized and interpreted in Chapter 5. In addition, the chapter includes a discussion on the scope of the results and the possible ramifications of these findings within the context of the existing literature.

Chapter 1 – Literature Review

This literature review will present the context of the research program in three sections. Normal cognitive aging processes are addressed in section 1.1, in which the effect of age on spatial abilities is emphasized. Also, part of this section includes a discussion of the modulating factors that influence performance on tasks of spatial abilities. Finally, the concept of cognitive reserve and the factors that contribute to this reserve are introduced. The characteristics of deaf and hearing signers as well as the modality specificities of sign languages are discussed in Section 1.2. The current state of knowledge on the impact of sign language use on the cognition of signers (hearing and deaf) are discussed. Finally, in section 1.3, what is known concerning the relation between signers' spatial abilities and the aging process is summarized.

1.1 Normal cognitive aging

Cognitive aging represents a lifelong process that begins in adulthood (Blazer, 2017). Changes in the volume of cerebral grey and white matter, loss of synaptic spines, and synaptic plasticity which results in the decrease of the neurons' ability to communicate are all potential mediators of age-related changes in cognitive performance (Blazer, 2017; Raz et al., 2005; Resnick et al., 2003; Terry & Katzman, 2001). These neurobiological changes are highly accountable for normal cognitive aging and lead, on a daily basis, to an alteration of behavioral and functional capacity (Harada et al., 2013). Older adults can feel that they hardly recall specific details of past events (e.g. year of their last trip to Italy), that they less efficiently achieve two tasks concurrently (e.g. following a recipe while listening to the radio), or that they tend to learn more slowly. Cognitive aging is not a unitary process translating in a general loss in all cognitive domains. Even if the brain, as a dynamic organism, aims to maintain homeostatic cognitive functioning, research has provided sufficient evidence that aging selectively affects distinct cognitive processes (Park & Reuter-Lorenz, 2009). For example, language skills (Park & Reuter-Lorenz, 2009), semantic memory (Rönnlund et al., 2005), and sustained attention (Carriere et al., 2010) are aspects of cognition that have been shown to be relatively maintained, and in some cases that may improve, with normal aging. These protected, or relatively resistant, aspects of

cognition are considered as crystallized abilities (Cattell, 1963). Since crystallized intelligence is built on the accumulation of information acquired through life experiences, additional years of experiences result in better crystallized abilities (Harada et al., 2013). On the contrary, aspects of cognition considered as fluid abilities (Cattell, 1963) tend to show a gradual age-related decline (Craik & Salthouse, 2008). These abilities vary in rate and severity of the decline, within and among individuals (McArdle et al., 2009). Abilities requiring problem-solving and reasoning, such as executive function (Harada et al., 2013; Wecker et al., 2005) and episodic memory (Brickman & Stern, 2009; Rönnlund et al., 2005), have been shown to peak at around 30 years of age and to gradually decline thereafter (Salthouse, 2012). The deterioration in these cognitive aspects are due to a decline in speed of processing and working memory, both mechanisms mediating age-related variance in cognitive measures (Park et al., 1996; Salthouse, 1991; Salthouse, 1996a, 1996b). The outcome of these age-related effects on cognition has been shown to affect performance of multiple cognitive tests (Akiyama et al., 1985; Park & Reuter-Lorenz, 2009; Salthouse, 1996b; Verhaeghen & Salthouse, 1997).

1.1.1 Cognitive aging of spatial abilities

Aging is also associated with a decline in the visuospatial domain (for reviews: Klencklen et al., 2012; Techentin et al., 2014). Representations supporting the visuospatial domain are known to be dependent on spatial cognition (Burgess, 2008). Spatial cognition supports a person's ability to encode, analyze, comprehend, and organize the surrounding spatial information in order to navigate in the environment (Spence & Feng, 2010). Humans can attend to specific objects, mentally manipulate objects, and communicate information about the environment (Klencklen et al., 2012; Spence & Feng, 2010). In that sense, spatial cognition provides mental representations and knowledge on a person's relative position or on the interrelationships among entities (people, objects, space: Devlin, 2001; Spence & Feng, 2010). Therefore, environmental analysis highly relies on spatial cognition.

Two kinds of approaches have been used to assess spatial cognition: the small-scale spatial abilities (visuospatial perception; mental imagery) and the large-scale spatial abilities (spatial memory; navigation: Klencklen et al., 2012). The small-scale spatial abilities (henceforth,

only *spatial abilities*), typically assessed through paper-pencil and computerized tests, are addressed as one of the main topics of this thesis.

Spatial abilities are skills used to manage day-to-day activities (Meneghetti et al., 2014). They are employed to help one navigate in a furnished space without bumping into any surrounding objects, assemble multiple pieces into a whole (e.g. furniture, puzzle), or read a map and identify the directions to a specific location without having to physically orient oneself geographically. Consequently, the age-related decline in spatial abilities can have important functional implications on one's activities of daily living (Hegarty et al., 2006; Techentin et al., 2014). For example, it has been shown that older adults who experience falls perform more poorly at a spatial perception task (e.g. Rod-and-Frame Task) compared to older adults of the same age who haven't experienced falls (Lord & Webster, 1990). Also, performance on a mental rotation task (e.g. Card Rotation Test) and a spatial visualization task (e.g. Paper Folding Test) has been shown to be associated with the capacity to drive safely (Anstey et al., 2012). These findings suggest that spatial abilities have real-life implications concerning the quality of life of older adults.

Spatial ability refers to a multidimensional construct that includes interrelated subskills (or factors: see Hegarty & Waller, 2005). It is defined as the capacity "to encode, maintain and mentally transform visual spatial information" (Hegarty et al., 2006, p. 157). Given the long history of research on spatial cognition, one might have expected an unequivocal definition of spatial abilities and clear parameters describing spatial subskills. However, a precise explanation of the perceptual and cognitive mechanisms that these subskills tap is still elusive and a subject of discord among the research community (Hegarty & Waller, 2005; Uttal et al., 2013). A consensus seems to have emerged for the categorization based on the cognitive perspective of Linn and Peterson (1985). In a comprehensive meta-analysis, these investigators identified three broad categories of measures that assess spatial abilities: spatial perception (SP), spatial visualization (SV), and mental rotation (MR). In addition, perspective-taking (PT: also labelled spatial orientation [Hegarty & Waller, 2004]) has been identified by Lohman (1988) as a fourth category.

As mentioned earlier, it is widely known that aging coincides with the maintenance of, or decline in, domains of cognition. However, the impact of age on higher-order intelligence, such as spatial abilities, is less consensual (Lohman, 1988). While some investigators claim that visuospatial abilities are maintained to a certain extent throughout the lifespan (de Bruin et al., 2016; Harada et al., 2013), a larger body of evidence supports the position that spatial abilities decrease as a function of age. Since spatial abilities rely on other cognitive processes that are also impacted by age, including speed of processing and central executive function (Hegarty & Waller, 2005; Techentin et al., 2014), the proportion of variance in performance attributable to the aging of spatial processes on cognitive tasks is still unknown. Nonetheless it is clear that speed of processing mediates the spatial domain (for a review: Techentin et al., 2014). A comprehensive overview of the age-related changes for each of the four spatial subskills is provided in the next section.

1.1.1.1 The effect of aging on spatial perception (SP)

SP refers to the ability to perceive a relation among objects from one's perspective and despite perceptual distractions (Linn & Petersen, 1985). SP is the subskill that has received the least attention in research investigating the age-related changes on spatial cognition (Klencklen et al., 2012). The vast majority of studies that have addressed this topic were published before 1980. SP tasks are commonly used to assess the predominance of perception in terms of field dependency (field-dependent vs. field-independent: e.g. Panek et al., 1978; Schwartz & Karp, 1967), spatial organization (egocentric vs. differentiation: e.g. Comalli et al., 1959), and relation among spatial information (categorical vs. coordinate: e.g. Bruyer et al., 1997; Meadmore et al., 2009). More precisely, field dependency, which translates in a difficulty to separate items from its background, has been shown to increase as a function of aging (Gruenfeld & MacEachron, 1975; Panek et al., 1978; Schwartz & Karp, 1967). This means that older adults tend to depend on their environment in order to analyze spatial relations among objects. Field dependency is traditionally measured in terms of angle disparity from a vertical or horizontal line (e.g. various versions of Water-Level Task, Plumb-Line Task, Rod-and-Frame Task). Concerning spatial organization, results from Comalli et al. (1959) suggested a preference for egocentric organization of space in older adults. This means that older adults use their own body as a frame

of reference to visualize and interpret the position of an item. Furthermore, it has been reported that older adults take longer to make spatial judgments and process information for both categorial (i.e. broad directional relationships—"to the left," "above," "in") and coordinate (i.e. exact location including distance and direction) spatial encoding (Bruyer et al., 1997; Meadmore et al., 2009). Despite these findings, the effect of aging on SP remains a topic of contention. Some investigators observed a decrease of performance in SP tasks as a function of aging (Comalli, 1965; Marendaz, 1984; Panek et al., 1978; Schwartz & Karp, 1967), with a noticeable decrease in performance on SP tasks beginning in the late fifties (Panek et al., 1978). Other investigators have failed to observe differences in performance between older and younger adults (Akiyama et al., 1985 [Water-Level task]; Lee & Pollack, 1980; Robert & Tanguay, 1990 [Water-Level task and Plumb-Line task]).

1.1.1.2 The effect of aging on spatial visualization (SV)

SV consists of the ability to perform a multistep manipulation of complex information presented spatially (Linn & Petersen, 1985). Although some SV tasks may comprise SP and MR components (de Bruin et al., 2016), SV differs from other spatial processes because of its high reliance on analytic strategies and need for flexible adaptative thinking in order to determine the relationship between figures (Linn & Petersen, 1985). Visual-spatial working memory is shown to be strongly involved during SV tasks, since they inherently involve the manipulation of several complex steps (Ariel & Moffat, 2017; Techentin et al., 2014). Because problem solving and working memory decline due to age-related brain changes (Chen et al., 2017; Rhodes & Katz, 2017), one could argue that the effect of age on these processes might influence SV ability through the lifespan. It has been shown that performance on SV tasks tends to decrease in adulthood (Ariel & Moffat, 2017; Hertzog, 1989; Meneghetti et al., 2011; Salthouse et al., 1990), with a more severe drop in performance beyond age 70 (Borella et al., 2014). Traditionally, assessing SV ability includes obtaining response-time data (Techentin et al., 2014). There is evidence that an important mediating factor of SV decline is visual information-processing speed (Bugg et al., 2006; Hertzog, 1989). It has been shown that when processing speed is controlled, the age difference in SV tasks between younger and older adults is drastically reduced, but remains significant (Bugg et al., 2006; Hertzog, 1989).

1.1.1.3 The effect of aging on mental rotation (MR)

MR is the ability to mentally rotate two- or three-dimensional visual stimuli in space (Linn & Peterson, 1985). Investigators have shown that a greater angle of the rotated view from a target figure is associated with a higher level of difficulty due to the angular disparity effect (Bors & Vigeau, 2001; Lee et al., 1998). It has been suggested that measures of reaction time on MR tasks reflect the magnitude of the degree of rotation to imagine (Shepard & Cooper, 1982). Along with SP and SV, there is evidence that older adults perform more poorly than younger adults on MR tasks, and that this distinction emerge at about 60 years of age (Borella et al., 2014; Hertzog & Rypma, 1991; Inagaki et al., 2002; Jansen & Heil, 2009; Meneghetti et al., 2011). MR is known to be a dynamic ability that is linked to working memory (Kaufman, 2007). It has been proposed that a poorer performance in MR tasks may be influenced by an age-related loss in working memory (Hertzog & Rypma, 1991). Nonetheless, an age effect on MR performance has been observed regardless of the type of outcome measure used (accuracy: e.g. Inagaki et al., 2002; response time: e.g. de Bruin et al., 2016) or the type of measures used (paper-pencil psychometric tests: e.g. Berg et al., 1982; computer-based chronometric tasks: e.g. Hertzog & Rypma, 1991) to assess this spatial ability. However, discrepancies have been observed in performance on MR tasks in older adults according to the type of task used (e.g. no age-related decline in Vandenberg and Kuse's mental rotations [Borella et al., 2014] vs. age-related decline in Piaget's three-mountain task [Inagaki et al., 2002]). In terms of accuracy measures, it has been proposed that the performance of older participants is highly influenced by the time pressure associated to accomplishing the task (Hertzog et al., 1993; Starns & Ratcliff, 2010). Consistent with this view, Sharps and Gollin (1987) provided evidence that the difference in accuracy scores between older and younger adults increases when an emphasis is placed on the speed at which the task must be accomplished. These findings suggest that the speed-accuracy trade-off provides a partial explanation to the discrepancies in accuracy scores observed between younger and older adults on MR tasks.

1.1.1.4 The effect of aging on perspective-taking ability (PT)

PT refers to the ability to imagine the appearance of an entity (someone or something) from a different perspective (Hegarty & Waller, 2005; Lohman, 1988). Traditionally, PT tasks

require respondents to imagine themselves facing a scene or an array of objects from a different position (of an object or a mark: Borella et al., 2014; Hegarty & Waller, 2005). PT tasks involve subjective spatial transformation processes, meaning that the respondent has to update his or her spatial frame of reference for i) the reference frame of an object presented and ii) the reference frame of the environment (Filimon, 2015; Zacks et al., 2000). These perspectives are different from the egocentric reference frame (the respondent's body). PT ability is associated with an age-related decline, starting around 50 years of age, with a more severe decline beginning at approximately 60 years of age (Borella et al., 2014; Herman & Coyne, 1980; Inagaki et al., 2002). More precisely, Zancada-Menendez et al. (2016) have shown that, compared to younger participants (mean age = 21.36 years), even middle-aged participants (mean age = 41.95 years) display poorer performance on the simplest items of the Perspective Taking/Spatial Orientation Test (Kozhevnikov & Hegarty, 2001). Thus, it appears that PT ability decreases gradually across the complete adult lifespan and not only in later life. However, the age effect tends to diminish when the test items are more complex and require higher levels of cognitive processing (Zancada-Menendez et al., 2016). Therefore, there is a limit to the cognitive load induced by PT processing (Kozhevnikov & Hegarty, 2001; Zancada-Menendez et al., 2016).

1.1.1.5 Specificities of PT and MR

The difference between PT and MR has been well documented in previous studies (e.g. Wang & Simons, 1999; Wraga et al., 2000; Zacks et al., 2000). They each represent a type of dynamic mental rotation: either an object-based spatial transformation for MR or a subject-based spatial transformation for PT (Hegarty & Waller, 2004; Meneghetti et al., 2018). MR is conceptualized as the ability to make spatial transformations with regard to the position of objects that are rotated within a unique egocentric environmental frame of reference (Hegarty & Waller, 2004). PT refers to the ability to make spatial transformations in which one's egocentric reference frame changes as a function of the environment (Hegarty & Waller, 2004). These abilities appear to differ in their sensitivity to age-related changes throughout the lifespan. The rate of decline is steeper for PT than for MR (Borella et al., 2014; Inagaki et al., 2002). For instance, Borella et al. (2014) reported that from a lifespan perspective the decline in performance observed in older adults occurs at an earlier age for tasks that require the participants to imaging

themselves standing along an object in a display, facing a second object, and pointing to a third one (Object Perspective Test: Kozhevnikov & Hegarty, 2001) than when they are asked to identify two three-dimensional rotated views of a target figure (Mental Rotation Test: Vandenberg & Kuse, 1978). Using an object-mental rotation condition (relying on MR) and a subject-mental rotation condition (relying on PT) in a modified version of the Piaget's Three-Mountain Task (Piaget & Inhelder, 1948), Inagaki et al. (2002) observed a larger difference between the two tasks in middle-aged participants (30–59 years of age) and in a group of older adults (60 years of age and older) compared to a group of younger age (18–29 years of age). They showed that egocentric response increased with age, leading to an increase of errors in the subject-mental rotation condition. Hence, the investigators proposed that the deleterious effect of aging is more important in tasks that require changing one's perspective as is the case in PT than in tasks that require executing mental rotations of objects.

1.1.1.6 Environmental factors that modulate the age-effect on performance on tasks of spatial abilities

Identifying the factors that account for the rate of cognitive decline of spatial abilities in older adults would require an in-depth investigation of the interactions between lifelong experiences and biological predispositions. Investigators that have addressed the inter-subject variability in cognitive decline as a function of age have focused their investigations on the impact of specific factors, including sociobehavioral factors. In a meta-analysis, Techentin et al. (2014) reported a general age-related effect across spatial abilities that is fairly consistent both in terms of ability level (i.e. accuracy measures) and speed of processing (i.e. response-time measures). However, environmental factors have been shown to influence the magnitude of age effect on performance in spatial abilities tasks. The case of education and sex will be discussed here.

Educational level is a factor that has an effect on performance in spatial abilities (Gruenfeld & MacEachron, 1975). Techentin et al. (2014) reported that educational level was a significant factor in the variance of effect size that emerged from a meta-analysis of 80 studies. When younger groups were more educated than their older peers, a significantly larger effect size was found compared to when there was no difference in their educational level. These

findings suggest that the difference in educational level typically in favor of younger adults exaggerates the age-related difference in performance observed on spatial tasks.

Sex has been shown to influence performance on tasks of spatial abilities, with men outperforming women (Goldstein et al., 1990; Parsons et al., 2005). A larger sex difference was reported for MR tasks compared to SV and SP tasks (Linn & Petersen, 1985; Voyer et al., 1995). Related to age, Jansen & Heil (2009) showed that the magnitude of the difference in performance on MR tasks between men and women tends to decrease with age, such that the sex differences in younger adults (20–30 years of age) is twice as large as the sex difference in older adults (60–70 years of age). Also, based on data from the Seattle Longitudinal Study, Maitland et al. (2000) reported that the advantage of men on tasks of spatial abilities is maintained across the adult lifespan (years of age at first measure: young [22–49], middle [50–63], old [64–87]) and over a 7-year longitudinal experimental design. Considering the impact of education and sex on performance in tasks of spatial abilities, researchers should consider controlling these factors in order to isolate age-related effects from other factors when investigating spatial abilities.

1.1.2 Cognitive reserve

1.1.2.1 Definition of cognitive reserve

Stern (2002) proposed a theory and discussed research applications related to the concept of cognitive reserve. The idea of “reserve” emerged from clinical data involving cognitively normal older adults for whom a post-mortem examination of their brain revealed an advance stage of Alzheimer’s disease (e.g. Katzman et al., 1989). Similar observations were made from patients who experienced different levels of impairment following a stroke of the same magnitude (discussed in Stern, 2002). The optimization of functional capacity supported by the concept of reserve is not only relevant for brain-injured patients: it also extends to healthy older adults (Stern, 2002, 2009). Stern (2002) aimed to provide a coherent theoretical account of the emerging concept of reserve by suggesting distinctions between reserve and compensation. Reserve refers to the optimization of performance and compensation refers to the endeavor to maximize performance despite age-related brain damage. Reserve, conceived as a heuristic more than a theory, provides a conceptual framework that helps to understand the individual

differences observed in the older adult population in terms of cognition, functional capacity, and clinical status (Stern et al., 2018). Two non-mutually exclusive categories of models depict the process of reserve: the passive models (e.g. Brain Reserve and Threshold) and the active models (e.g. Cognitive Reserve and Compensation). Passive models define reserve in terms of the amount of damage that the brain can support before age- or disease-related changes/symptoms appear (Stern, 2002). The active models propose that the brain actively attempts to cope or compensate for age- or disease-related manifestations (Stern, 2002). The Compensation model proposes that brain networks and structures that are not damaged might compensate for damaged areas of the brain, even if these structures are not normally used for this function. The Cognitive Reserve model proposes that brain networks that are less susceptible to disruptions are solicited to cope with task demand in healthy and brain-injured adults. The mechanisms involved in the complex construct of reserve are to date still under investigation, but it is presumed that they are dependent on both structural and functional brain mechanisms (Stern et al., 2018).

The concept of *cognitive reserve* refers to "the adaptability (i.e. efficiency, capacity, flexibility […]) of cognitive processes that helps explain differential susceptibility of cognitive abilities or day-to-day function to brain aging, pathology, or insult" (Stern et al., 2018, p. 1). In that sense, it has been suggested that cognitive reserve reflects the individual differences in terms of functional brain processes (i.e. networks of brain regions activated in task performance, and the interaction between these networks') affected by age- or disease-related changes (Stern et al., 2018). In terms of functional brain processes, these individual differences can be modulated by multiple factors, either genetic or life experience-based (Stern et al., 2018). Therefore, functional brain processes underlying cognitive reserve may be "cumulated" throughout life differently between individuals. When confronted with age-related changes or disease-related insults, the ability to adapt or compensate in order to maintain efficient functioning consequently varies from one individual to another (Stern, 2002; Stern et al., 2018).

1.1.2.2. Factors contributing to cognitive reserve

Cognitive reserve cannot be measured directly. Typically, sociobehavioural, residual, and functional imaging approaches are used in an attempt to quantify cognitive reserve in older adults. For the purpose of this thesis, the focus will be on sociobehavioural measures. Readers interested in residual and functional imaging measures of cognitive reserve are referred to Stern et al. (2018). Since individual differences in cognitive function can be influenced by lifetime experiences (Stern et al., 2018), it has been suggested that multiple sociobehavioural proxies may covary with or contribute to cognitive reserve. Relevant life experiences that have been investigated for their potential contribution to cognitive reserve include, but are not limited to, educational level, occupational cognitive requirements, and language experience (e.g. bilingualism). It has been suggested that engaging in stimulating experiences such as these can lead to an increase in cognitive reserve (Valenzuela & Sachdev, 2006). Because certain components of lifestyles are known to contribute to cognitive reserve, individual differences in cognitive reserve are likely to be due to the heterogeneity of activities that one may experience during his or her lifespan, both in terms of multiplicity and amount of exposure.

Formal education is commonly used as an example of a factor that contributes to cognitive reserve since it is considered as a critical experience that takes place over several years (Kramer et al., 2004). Findings from cross-sectional and longitudinal studies on the extent to which education has an effect on cognitive reserve are mixed. Results range from strong correlations between educational level and performance on memory tasks (Albert et al., 1995; Angel et al., 2010; Arbuckle et al., 1986; Lee et al., 2012), to weak or no correlations between education level and performance on tasks of executive function (Jefferson et al., 2011; Lee et al., 2012; Mueller et al., 2013) and general speed of processing (Christensen et al., 1997). Capitani et al. (1996) reported no effect of educational level on performance on verbal fluency and spatial memory tasks in later life. However, less-educated older adults had larger decrements on visual attention and verbal memory tasks. Consequently, contribution of educational level to cognition strongly depends on which aspects of cognition are targeted.

Experiential richness can also be related to one's occupational status. Research involving older adults has revealed a small correlation between the degree of cognitive requirements

associated with an occupation and working memory (Leung et al., 2010) and no correlation with episodic memory (Fritsch et al., 2007). Additionally, Finkel et al. (2009) reported a weak association between performance on tasks of visuospatial abilities and occupational status. On the other hand, Salthouse et al. (1990) showed that spatial skills used on a daily basis, such as in the context of one's employment, tend to be protected against the normal process of cognitive aging. Specifically, the investigators observed that architects between 60 and 78 years of age outperformed non-architect peers on five SV tasks (Salthouse et al., 1990).

Based on a series of studies that addressed the contributing factor of language experience on cognitive reserve, it was suggested that the constant switching between two languages involved in bilingualism is associated with better cognitive control and selective attention through aging (e.g. Bialystok et al., 2004, 2008; Salvatierra & Rosselli, 2011). To reach the right target in the desired language, the bilingual person must control the choice of the correct lexical form in the target language and eliminate competing lexical forms (Bialystok, 2001). Therefore, it has been proposed that bilinguals may be better "trained" than monolinguals in terms of executive function (Perani & Abutalebi, 2015). In addition to executive control tasks, the contribution of bilingualism on cognitive reserve extends to memory tasks. Wodniecka et al. (2010) found that older bilingual adults outperformed monolingual peers on a memory recollection task which recruit executive control in order to select the relevant details from memory. Similarly, in a longitudinal study of over 20 years, Ljungberg et al. (2014) reported a significant bilingualism advantage on episodic memory tasks in older adults.

These findings on the factors that contribute to cognitive reserve suggest that the effect of education, occupation, and language experience may be limited to certain aspects of cognition. In addition, these significant life experiences are, to some extent, intrinsically interrelated. A person with a higher education level has more propensity to be employed in an occupation with higher intellectual challenges, in turn leading to higher socioeconomic status. This means that the direct contribution of an isolated factor to cognitive reserve may be difficult to measure (Kramer et al., 2004). It is worth noting that the variety of methods used to assess these proxies may be accountable for part of the discrepancies found in studies addressing education (number of years of education; level of education; opposition of two categories of

education [high-education vs. low-education]) and occupation (level of complexity; cognitive abilities recruited; years of employment, etc.) on cognitive reserve (Opdebeeck et al., 2015). How cognition interacts with other experiential factors remains to be established (Kramer et al., 2004).

1.2 Sign languages and sign language users

Normal cognitive aging has been investigated in order to describe common characteristics shared by a large segment of the population. The main advantage of this type of approach is that results extracted from a smaller sample can be generalized to an important part of the population. However, the aging population is inherently heterogeneous in terms of their current or past lifestyles, their life experiences, their culture and beliefs. These social factors, added to individual genetic predispositions, lead to a great diversity of cognitive aging profiles. As discussed in the previous section, the cases of older adults that are bilingual, highly educated, or who have been architects showed that these subgroups display different patterns of cognitive aging compared to those of the general population of older adults. Along this line, the purpose of this thesis is to investigate an aspect of cognitive aging in the specific population of older users of a sign language (henceforth: signers) in order to assess the impact of long-term use of visual-spatial language on cognition.

1.2.1 Deaf signers

According to the World Health Organization (2020b), 466 million people in the world have a hearing loss. Etiology of hearing loss can be hereditary or acquired due to prenatal/perinatal/postnatal infections, premature birth, anoxia, trauma, etc. (Bavelier et al., 2006). Individuals with severe (71–90 dB HL) to profound (91 dB HL +) hearing loss are using either a sign language, technological devices such as hearing aids or cochlear implants, or a mix these choices (World Health Organization, 2020b). From a developmental perspective, the cognition of deaf individuals is influenced by a myriad of biological and environmental factors: degree of impairment (e.g. severity of hearing loss), history of the deafness (e.g. age of onset; cause [genetic; illness]), language experience (e.g. language background [sign language, lip-reading, cued speech]; parents' proficiency in sign language; language of education), age of sign language acquisition, family environment (e.g. deaf parents, deaf siblings, no deaf family

members), social identity, and sense of belonging to a certain community, etc. (Gerich & Fellinger, 2011; Holt & Kirk, 2005; Lazard et al., 2014; Lu et al., 2016; Mayberry, 2007; Mayberry & Squires, 2006; Shi et al., 2016). These factors, some of them confounded or covarying, contribute to the important heterogeneity of developmental trajectories observed within the deaf population (Dye & Bavelier, 2013).

An important majority of deaf individuals are not exposed to a sign language from birth (MacSweeney, Capek, et al., 2008). Between 90% and 95% of the deaf individuals are born from parents who have normal hearing acuity and who are non-signers (Mitchell & Karchmer, 2004). Developmental studies have shown that, regardless of the language modality, children who have been exposed to a language (sign or speech) from birth follow the same linguistic acquisition milestones (Mayberry & Squires, 2006; Spencer, 2004) at the same rate (Newport & Meier, 1985). For example, whereas hearing infants produce vocal babbles between 6 and 12 months of age, deaf infants babble with their hands during the same developmental period. First sign appears with a large individual variation between 8 and 16 months of age, with the first 10 signs produced around 12 months of age (Mayberry & Squires, 2006). Specific to the young deaf children, they acquire in early age non-linguistic spatial capacities in order to process sign language (Bellugi et al., 1990). However, this developmental path depends on the language exposure received by the children in infancy. Deaf children born from parents who are non-signers are at risk of having potential delayed first language exposure. This delay can vary depending on the age at which deafness is diagnosed and on the choice of the early intervention program that is provided (Mayberry, 2007). Developmental studies have investigated the extent to which the development of neural processing networks to process language is modulated by exposure to linguistic stimuli within a certain period of time (Malaia et al., 2020). This window, referred to as the sensitive period (around 5 years old: Hall et al., 2017; Mayberry & Lock, 2003; Newport, 1990), for first language acquisition has been shown to influence proficiency in the first language acquired and the neural areas activated while sign language processing (Mayberry, 2007, 2011). In this regard, deaf individuals evolve in unique developmental circumstances, which offers a unique window to investigate the effect of early and late exposure to first language. Malaia et al. (2020) have shown that late acquisition of sign language significantly increases the cognitive load

during the analysis of syntax. This difference between groups did not occur in word-level meaning. Since syntax is essentially expressed through space compared to word-level that consisted in the combination of multiple parameters, these results suggest that signers who acquired language in early age may be advantaged in terms of spatial processing. The effect of late exposure to language is, so far, difficult to measure.

Notwithstanding these developmental differences based on the age of language acquisition, neuroimaging studies conducted with adults have revealed similar brain sites activation (namely, frontal and temporoparietal areas) for processing and producing language regardless of the linguistic modality used (sign language or spoken language: Neville et al., 1998; Payne et al., 2019; Petitto et al., 2000). It has been shown that signs and words activate generally similar neuroanatomical areas for phonological processing (MacSweeney, Waters, et al., 2008), lexical retrieval (Emmorey et al., 2003) and representations of semantic categories (Evans et al., 2019). However, differences in cognitive functioning have been reported between users of a sign language and users of spoken languages in several aspects of domains (discussed in section 1.2.4).

1.2.2 Hearing signers

There are two types of hearing signers. The first consists of hearing individuals who grew up in a household with one or two deaf parents (Children Of Deaf Adults: CODA) and learned sign language as their first language. Navigating in the external world, they also learn the surrounding spoken language (MacSweeney, Capek, et al., 2008). The second consists of hearing individuals who acquired sign language later in life through immersion in the Deaf[1] community and/or instruction (Emmorey & McCullough, 2009: e.g. communicating with a deaf friend, being trained to become a sign language interpreter, interest in acquiring a new language). The term *bimodal bilingual* (i.e. a bilingual who learned two languages of different modalities—visual-spatial and aural-oral) is employed as an equivalent of *hearing signer*.

[1] Based on sociological convention, “deaf” refers to audiological status of an individual, while “Deaf” with the uppercase “D” refers to an individual that identifies as a member of the Deaf community (Emmorey, Borinstein, et al., 2008; Padden & Humphries, 2009; Woodward, 1972). For the purpose of this thesis, the designation “deaf” will be used in order to avoid inferring the cultural identity of the concerned individuals.

Bimodal bilinguals introduced a new type of bilingual phenomenon providing a different perspective on the human language capacity (Lillo-Martin et al., 2016). Bimodal bilingualism refers to the ability to communicate in languages of different perceptual and motoric systems (Emmorey, Luk, et al., 2008). As unimodal bilinguals (i.e. individuals who use two spoken languages), bimodal bilinguals acquire their languages at varying degrees of fluency and at various ages (Lillo-Martin et al., 2016). However, since the acquisition of a sign language in childhood not from deaf parents is rare, the vast majority of research investigating bimodal bilinguals has been performed with CODAs (Emmorey & McCullough, 2009; Lillo-Martin et al., 2016).

1.2.3 Modality specificities and space component of visual-spatial languages

Sign languages are natural languages (Sutton-Spence & Woll, 1999) and 144 of them have been documented so far (Eberhard et al., 2020). As is the case for spoken languages (e.g. French and Spanish), some sign languages are part of the same linguistic family (e.g. American Sign Language [ASL], French Sign Language [LSF], and Quebec Sign Language [LSQ]; Delaporte, 2006). However, sign languages are often not mutually intelligible despite the iconic features of some signs (Atkinson et al., 2015). Iconicity refers to a pairing between the form and the meaning of the sign that is non-arbitrary (see Figure 1 for the iconic sign SMOKING in LSQ). In addition, sign languages are structurally and grammatically unrelated to the spoken languages used in the same area (Sutton-Spence & Woll, 1999).

Figure 1. – Iconic sign SMOKING in LSQ reproducing the real-world prehension of a cigarette, and the real-world movement that bring the cigarette to the signer's lips.

The different modalities used to express and perceive linguistic information remains one of the most salient distinctions between signers and individuals who use a spoken language to communicate (Tyrone, 2014). Spoken languages require the use of smaller articulators, all located at the midline of the body (e.g. larynx and supralaryngeal vocal tract), to generate speech sequentially as a function of time (Auer, 2009; Tyrone, 2014). In sign languages, signers use larger articulators to communicate. They primarily make use of their arms and hands, as well as their face, torso, and head, to produce discourse as a function of time (Elliott & Jacobs, 2013; Sandler, 2018). In addition to time, sign languages are produced in space through a three-dimension display (Bouchard & Dubuisson, 1995). In most instances, signers use both sides of their body to express and coordinate signs, despite an asymmetry that is dependent on handedness (Tyrone, 2014; Watkins & Thompson, 2017). At the perceptual level, speech is mainly processed through the auditory channel for spoken language users while signers perceive an incoming sign message visually. Despite these apparent differences between the two language modalities, sign and spoken languages obey to the same linguistic principles and share formal language structural components, notably at the sublexical levels (phonology and morphology) as well as at the syntactic level (Klima & Bellugi, 1979; Meier et al., 2002; Sandler & Lillo-Martin, 2006; Sutton-Spence & Woll, 1999). For example, sign and spoken languages are constructed of meaningless

units that, once combined, result in lexical forms. These meaningless units in sign languages take the form of phonological specifications of three main parameters: handshape, movement, and place of articulation (Stokoe, 1960). As it is the case in spoken languages[2], only a subset of phonological forms is allowed in a specific sign language, with some forms possible in one sign language that are not possible in another. It is the case of the configuration observed in Figure 2, which consists in a handshape allowed in LSF, but absent of the phonological forms allowed in LSQ.

[2] A relevant example of the non-universality of phonological forms in spoken languages would be the /ð/ perceived as the third phonological segment of *father* /ˈfɑːðə(r)/ that does not figure in the inventory of phonological forms of the French language.

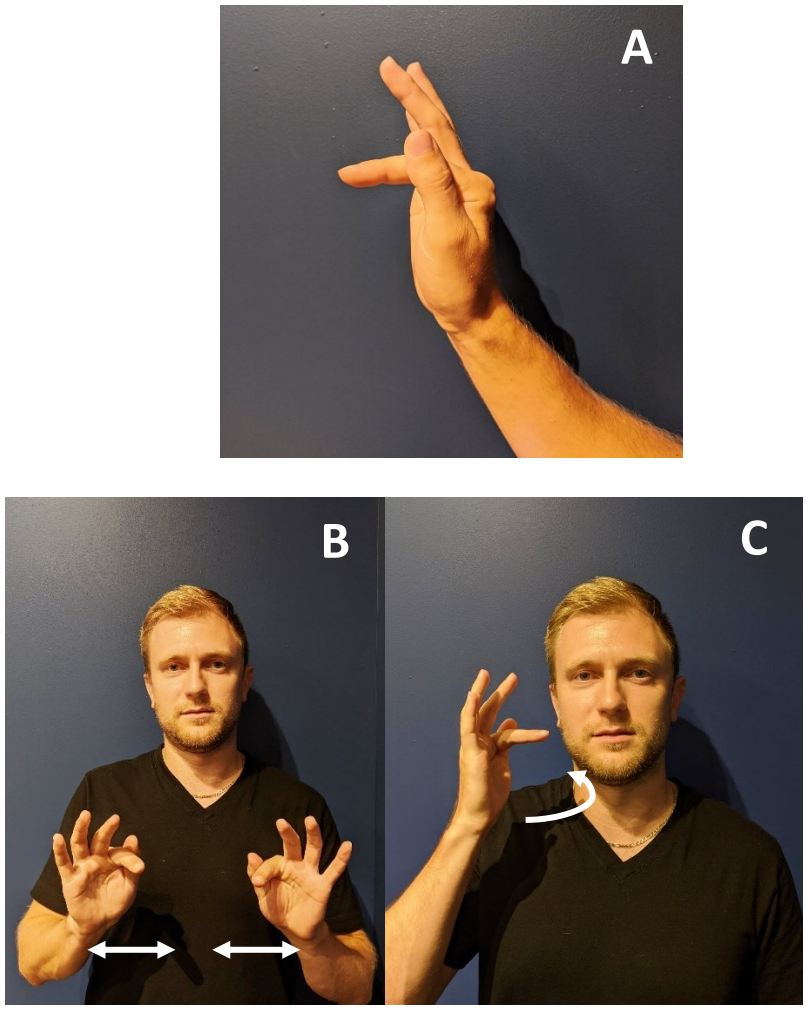

Figure 2. – A. /F/ configuration in LSF that is used in the BROTHER (B.) and CHEESE (C.) signs[3].

Being visual and spatial in nature, sign languages depend on spatial mechanisms for message production and perception. Signers make use of the space in order to express grammatical relations (e.g. verb agreement, inflectional and derivational morphological systems: Bellugi et al., 1990), to express spatial relationships among objects or entities in a topographic relation (i.e. representation of distance on a reduced scale: Quinto-Pozos et al., 2013), or for depictive functions (i.e. representation of a distance on a life-sized scale: Quinto-Pozos et al., 2013). By using the relative position of their hands in the space, it allows the signer to describe

[3] http://lsf.wikisign.org/wiki/Sp%C3%A9cial:Configs/F

spatial arrangements of objects through space instead of using functional items of the vocabulary as prepositions (e.g. under, to the left, above: Emmorey, Borinstein, et al., 2008). In addition, syntax makes use of the spatial nature of sign language to associate invisible spatial marks (also called loci) to referents denoted by lexical or grammatical elements (nominal, pronominal, anaphoric, etc.) in the signer's space (Rinfret, 2009). The directionality of the verb movement articulated between these loci transmits information concerning the referents' role (e.g. agent vs. beneficiary: Bellugi et al., 1990). Referents that have been previously associated to a locus remain in this invisible mark and can be reactivated in further discourse with a pronominal reference (e.g. pointing to a relevant locus to which a referent has been previously associated: Wilcox & Martínez, 2020). In other words, the physical space surrounding the signer allows to convey meaning. If these spatial mechanisms in sign language production have been documented in multiple sign languages, grammatical and syntactic variations can be observed among signers. These variations depend on whether they were born in a household with native signers and on the age of sign language acquisition (Newport, 1990).

Spatial mechanisms are also solicited in sign language comprehension. Because a sign language message is conventionally produced from the signer's perspective (Pyers et al., 2015; Secora & Emmorey, 2019), the addressee must execute a shift of perspective to access the mental representation of the scene that the signer intends to describe (Brozdowski et al., 2019; Emmorey et al., 1998). In a traditional face-to-face conversation, the perspective to adopt requires the addressee to execute a 180° rotation in order to obtain the signer's perspective. Figure 3 presents an example of this change of perspective with a signer producing a scene with a cat (right hand of the signer) and a tree (left hand of the signer) interpreted as "the cat is situated on the right of the tree." Due to the mirror effect of face-to-face communication, the cat is located to the left of the tree from the addressee's perspective. To correctly interpret the signed message, the addressee must execute a 180° mental rotation. Therefore, engaging in a sign language conversation leads to an increase in the cognitive demand of the addressee's spatial processes.

Figure 3. – Signer producing in LSQ the sign TREE on his left hand, and CAT with his right hand, with the addressee mentally mapping the disposition of signs by executing a 180° rotation of the signs.

Constructed action structures are also commonly used in sign languages (on the diversity of labels used, see Cormier et al. [2015]). Constructed actions are expressed by multiple articulators such as the face, head, eye gaze, and torso, alone or in combination. The primary function of these structures is to represent on the signer's body the role, thoughts, affects, or utterances of the referents (Cormier et al., 2015; Goswell, 2014). According to Janzen (2017, p. 11), these constructions "contain overt markers of perspectivization in that the signer conceptualizes the perspective of a referent and has an embodied view of the space around her in which articulation takes place." In other words, when constructed actions are produced by a signer, the addressee must adopt the perspective embodied by the signer to represent the referent and execute additionally a 180° mental rotation required in the face-to-face conversation. In that sense, signers need to manipulate mental representations from diverse angles and perspectives in order to process a sign language message.

1.2.4 Sign language effect on signers' cognition

Deaf users of a sign language represent a unique population to investigate the adaptability of the brain. Effects of deafness and effects of the use of a visual-spatial language on cognition need to be separated in order to avoid confounding results (Bavelier et al., 2006). However, the practical distinction of these two influential factors remains one of the major issues

in research related to cognition in deaf individuals. The theory of compensation (as discussed by Bell et al., 2019) proposed that enhancement of certain cognitive functions in deaf individuals is based on brain plasticity due to the deprivation of auditory stimulation. In this regard, the loss of a sense (audition) would lead to the reinforcement of remaining senses (e.g. vision, haptic feedback: Bavelier et al., 2006; Grafman, 2000; Neville, 1990). For example, auditory deprivation has been shown to be associated with the enhancement of reactivity to visual stimuli (for reviews: Bell et al., 2019; Pavani & Bottari, 2012). On the other hand, the "deficiency theory" states that for a normal development of each sense, all integrative processes are necessary (Proksch & Bavelier, 2002; Radell & Gottlieb, 1992; Turkewitz & Kenny, 1982). In other words, an undeveloped sense will negatively impact the development of the other senses. Although studies investigating the compensation and "deficiency" hypothesis provide interesting insights on the cross-modal interactions of brain organization, studies focusing on the effect of sign language use has supported that deafness *per se* was not the only factor modulating cognition. The experience hypothesis proposes that brain changes are an effect of early exposition and acquisition of a sign language. The experience of deaf people in producing and comprehending visual-spatial languages, a modality that requires mental transformations to process grammatical information (Emmorey, 1998), would thus lead to an enhancement of aspects of cognition (Bavelier et al., 2006; Emmorey et al., 1998). A few examples of the impact of the use of a sign language on the cognition of deaf and hearing signers are presented below.

One ability shown to be improved by sign language use consists of facial discrimination. Bellugi et al. (1990) found evidence that deaf users of ASL (aged from 3 to 10 years of age) consistently achieved higher scores on the Benton Test of Facial Recognition (Benton et al., 1978) than age-matched hearing non-signers. This task requires the participant to recognize faces through various conditions, including differences of lightning and changes in the position of the face. Investigators suggest that the important role of facial expressions as a feature of grammatical information in sign language (e.g. allowing to express interrogation and negation: Benitez-Quiroz et al., 2016; Zeshan, 2006) may impact cognition outside the linguistic domain. Because spoken languages use facial cues to express mainly paralinguistic information (Agnoletti,

2017), the higher frequency of facial analysis required in sign language comprehension might provide a tangible explanation of the advantage of signers over non-signers.

Using a task of haptic object exploration and spatial configuration learning, van Dijk et al. (2013) investigated the ability of signers (deaf and hearing) to match haptically ten shapes to the cut-outs of a board. Participants were blindfolded and were required to accomplish the tasks as fast as possible. Results showed that the deaf group in itself did not outperform hearing peers. However, when hearing and deaf signers were combined as one group, the signer group outperformed the non-signer group. These results suggest that it is unlikely that deafness in itself impacts active touch ability. Sign language experience is the factor that benefited the processing of haptic spatial configurations.

On motion detection, Klima et al. (1999) found that deaf signers outperformed hearing non-signers in the detection and the interpretation of moving lights. In their experimental design, participants were required to reproduce drawings of Chinese pseudo-characters that were represented in the air with light-emitting diodes. Results from this experiment showed that experience with sign language enhanced the recognition of dynamic movement in deaf signers. In addition, Bosworth and Dobkins (2002) performed a direction-of-motion discrimination task at different locations of the visual field and observed that both deaf and hearing signers exhibited a strong advantage in the right visual field. Based on these results, investigators proposed that the perceptual processes involved in sign language comprehension are recruited by the left hemisphere, which is the language-dominant hemisphere. Neville and Lawson (1987) presented results from a series of experiments investigating the direction of motion in the periphery of vision in signers (deaf and hearing) and non-signers. Subjects were required to detect the direction of the motion represented by the stimuli (e.g. small white square) in a sequence of position in their right or left visual field. Similarly to the results of Bosworth and Dobkins (2002), signers (deaf and hearing) were more accurate in detecting motion in the right visual field compared to hearing non-signers. The electrophysiological responses revealed that deaf and hearing signers exhibit an increased left hemisphere activation while performing the task of motion detection in comparison to hearing non-signers.

The above examples suggest that sign language use has an effect on the cognitive functioning of deaf signers. It is worth noting that the heterogeneity of the deaf population described in 1.2.1 brings a considerable amount of methodological challenges when it comes to investigating the effect of sign language use on cognition.

1.3 Interaction between sign language use, spatial abilities and the aging factor

1.3.1 Signers and cognitive aging

Few investigators have addressed how aging processes operate in older signers. Related to healthcare and sciences, existing research in the health field on the deaf signer population stresses the need to adapt senior centers for an inclusive cohabitation of the residents. For example, Becker and Nadler (1980) discussed the importance of having adapted senior centers that would be adequate for cohabitation between deaf and hearing older adults. They emphasized language and cultural differences between these community groups and noted that these differences need to be taken into account in the development of community-based support centers. Culture and language differences have also been considered as barriers to healthcare access, through their impact on communication (Witte & Kuzel, 2000). Deaf older adults reported difficulties in scheduling appointments with health professionals (especially when using the telephone), as well as during appointments with less experienced professionals.

Research has also highlighted the relevance of developing valid cognitive assessment tools specific to older deaf signers. Dean et al. (2009) showed that linguistic and cultural differences between signers and non-signers alter the validity of common cognitive screening tests such as the Mini-Mental State Examination (MMSE: Folstein et al., 1975). When the MMSE was administered through traditional sign language interpretation, scores of cognitively healthy deaf adults were lower than those of hearing older adults. Such results suggest that the interpretation of test results should take into account the lack of validity of certain test items for signers. It also indicates that alternative assessment modalities need to be explored. Based on these considerations, Atkinson et al. (2015) developed a cognitive assessment tool designed to be administered directly in British Sign Language (BSL). They showed that the linguistic and

cultural adaptation of this test for the British deaf signer community enabled the accurate and sensitive assessment of cognition for the detection of dementia in this population.

Finally, pathological manifestations of specific health conditions and exploratory findings on older deaf signers' cognition have been documented. In exploratory investigations focused on the manifestations of pathologies, Spanjer et al. (2014) documented linguistic particularities in four signers with dementia (e.g. word-finding, fillers). In a review, Tyrone (2014) reported multiple case studies on deaf individuals with movement disorders (e.g. dysarthria, apraxia, Parkinson's disease) that provided interesting insights on the distinction between linguistic and non-linguistic movements. Brentari et al. (1995) analyzed the impact of Parkinson's disease and aphasia on the production of sublexical structures among users of a sign language. In addition, Werngren-Elgström et al. (2003) reported that, relative to their hearing peers, there is a higher prevalence of depression and insomnia in older deaf adults.

It should be noted that aging with or without a pathology must be differentiated. In the general population, between 60% and 80% of older adults over 60 years of age carry out their daily activities without any or with few limitations (Brunel & Carrère, 2017; Camirand & Fournier, 2012; Kraus et al., 2018). According to the World Health Organization (2020a), most older adults do not have a significant disability, nor do they exhibit symptoms of an age-related health condition. Instead, they display a variety of gradual physical, cognitive, sensory, or behavioral manifestations that will be the result of what is called normal aging. The lack of background knowledge about normal aging among signers (deaf and hearing) opens up several possibilities for research, especially in the health domain. To understand the extent of the age-related changes in this population, stakeholders (clinicians, caregivers, researchers, etc.) need to have an understanding of the normal aging processes. Information on normal aging is crucial to establish norms on expected manifestations of cognitive aging in older deaf adults. Such knowledge contributes to the identification of pathological symptoms. To our knowledge, in the deaf signer population, only one study addressed issues of normal aging. Rudner et al. (2010) investigated the effects of modality on temporal and spatial organization of working memory in older signers. They reported that older signers perform more poorly than age-matched non-signers on tasks that require the retention of the order in which information appears in a

temporal display. We argue that such investigations on cognitive aging in older signers will provide important milestones that will make it possible to identify symptoms of pathologies in older sign language users.

1.3.2 Signers and spatial abilities

No research to date has provided insights on the impact of age on spatial abilities tasks performed by signers (deaf and hearing). However, much has been written on whether signers exhibit any form of advantage compared to hearing non-signers in terms of spatial skills. Major discrepancies have emerged from these studies.

Despite the frequency of the solicitation of SP ability in sign language use due to the regular evaluation of spatial relations between two entities (e.g., topographic and depictive function : Quinto-Pozos et al., 2013), studies that have addressed this ability in signers compared to non-signers have failed to show an advantage of signers in terms of accuracy. No difference in performance on spatial perception tasks were reported between signer and non-signer children and adolescents (McDaniel, 1980; Robertson & Youniss, 1969). However, Emmorey et al. (1993) and Emmorey and Kosslyn (1996), using the same stimuli to assess mental image generation, showed an advantage of signers over non-signers in terms of response time. Although the primary objective of that research was not to assess spatial perception *per se*, the design of their stimuli appears to engage spatial processes. Participants were required to identify if a X mark overlapped a memorized upper-case letter (drawn with black blocks) in a grid or between brackets. In addition to mental image generation, it can be argued that spatial perception in this display is solicited in order to process the relationship between the X mark dans the background of reference (grids or corner brackets). Results of these two studies showed that signers responded more quickly than non-signers. More precisely, signers had shorter response times in the complex condition (when the letters were formed of four or more segments in the grid [P, J, O, S, G] : Emmorey et al., 1993) and, when the stimuli were presented initially to the right hemisphere compared to the left (Emmorey & Kosslyn, 1996).

Studies that have addressed SV ability in the signer population reported mixed results. For example, Marschark et al. (2015) compared the performance of two deaf groups, deaf users

of a cochlear implant (CI) and deaf nonusers of CI, as well as and two hearing groups, hearing non-signers and hearing signers, on the Spatial Relations task (Woodcock et al., 2001) and the Embedded Figures task (Hauptman & Eliot, 1986). The results revealed no significant differences in performance between the two deaf groups regardless of their use of CI or hearing aids. Similarly, the two hearing groups showed no difference of performance regardless of whether or not they knew sign language. However, the results did show a significant difference between the hearing participants (two subgroups combined) and the deaf participants (two subgroups combined). Specifically, the hearing participants outperformed deaf participants in both tasks. An absence of differences in performance on SV tasks between signers and non-signers was also reported by Hauser et al. (2006) in a Paper Folding and Cutting test (Thorndike et al., 1986).

Previous studies investigating MR in signers have reported an advantage of signers over non-signers in MR tasks. More precisely, mental rotation has been shown to be influenced by general sign language use (Emmorey et al., 1993, 1998) and or the time of exposure to a sign language for hearing signers (Talbot & Haude, 1993). Using the Mental Rotations test (Vandenberg & Kuse, 1978), Talbot and Haude (1993) tested three groups of students that experienced a different exposure to American Sign Language (ASL) through instructions, with one group having no experience with ASL, one group who had a little bit less than a year of ASL instruction and one group who had more than 6 years of ASL instruction. The investigators reported that both groups who had less than one year of exposure to ASL performed similarly with a significantly lower score than the group that was exposed to ASL for about 6 years. Although experience with ASL and formal instruction in learning sign language appears to be predictive factors of performance on tasks that measure MR, pre-existing individual differences in spatial cognition cannot be ruled out since no pretest of baseline mental rotation abilities has been administered to the participants. Using a MR task like the one developed by Shepard and Metzler (1971), Emmorey et al. (1993) showed that the response times of deaf signers was shorter than the response times of hearing non-signers when processing 180° mirror rotation. Emmorey et al. (1998) reported that when MR tasks include linguistic stimuli, signers were more accurate in interpreting information displayed from the narrator's point of view (which require a 180° rotation) than when the interpretation was made from their own point of view (no rotation

required). More recently Secora and Emmorey (2019) showed no group differences between signers and non-signers in terms of accuracy using the revised version of the MR test initially developed by Vandenberg and Kuse (1978) and redrawn by Peters et al. (1995).

Very few studies investigated the potential difference of performance in PT ability between signers and non-signers. Presenting a case study, Quinto-Pozos et al. (2013) presented the results of a series of cognitive test performed by a deaf adolescent with impaired sign language development. Cognitive, language and perspective-taking assessments showed evidence that an impairment in PT ability resulted in atypical ASL acquisition. This was especially so for perspective-dependent structures using space in a topographical function and role shifting. However, it didn't impact the adolescent's use of grammatical structures that didn't require adopting another person's perspective. In addition, on the Perspective-Taking Spatial Orientation Test (from Hegarty & Waller, 2004), the participant performed significantly more poorly than proficient deaf signers of her age. The results of this case study suggest that PT is a key ability to process spatial aspects of sign language. Presenting results from a non-clinical sample of adults, Secora and Emmorey (2019) reported no differences in PT performance between signers and non-signers. Finally, Howley and Howe (2004) showed no differences between groups of deaf and hearing children on a PT test.

1.3 Contribution of the current thesis

Based on the results presented in 1.3.2, the effect of sign language on performance on tasks of spatial abilities appears to be specific to the given spatial subskills and specific to the type of measures (accuracy vs response time). Globally, experience with sign language did not provide a general advantage on tasks of spatial abilities. Studies investigating SP, SV and PT showed either an advantage of non-signers over signers or found no difference between groups in terms of accuracy. However, signers had shorter response times when processing information requiring the SP ability (Emmorey et al., 1993). These results do not support the general assumption that sign language use contributes to better performances, at least in terms of accuracy, in SP, SV, and PT abilities. Investigations reporting performance of signers and non-signers in MR tasks showed mixed results. In terms of accuracy, some investigations reported an

advantage of signers over non-signers while the others did not find a significant advantage. The discrepancies between these studies lead to confusions concerning the effect of sign language use on spatial abilities and a more thorough review would make it possible to explore the multiple factors that influence the relationship between sign language use and spatial abilities.

Section 1.1.1 of the current thesis has shown that normal cognitive aging generally has an effect on spatial abilities in hearing older adults. Older adults rely more on their environment when performing SP tasks. The age-related effect of problem solving and working memory have been identified as potential contributors to the decrease in performance observed on SV tasks. Older adults also exhibit poorer performances than younger adults on MR tasks, regardless of the type of task used to measure this subskill of spatial abilities. Finally, the performance of adults on PT tasks has been shown to decrease gradually once they reach middle age. In addition to the age-related effect on their level of ability, performance of hearing older adults in spatial abilities tasks has been shown to be influenced by the general decrease in terms of speed of processing (Salthouse, 1996a, 1996b). Investigators reported either shorter response times in younger adults compared to older adults, or a speed-accuracy trade-off where older adults tend to prioritize accuracy over response time.

The concept of cognitive reserve introduced by Stern (2002) proposes that extensive life experiences may lead to differences in functional brain processes underlying the cognitive reserve (Stern et al., 2018). Different experiential richness may result in individual differences in the ability of the brain to cope with age-related changes. In the spatial domain, older adults that pursued their career with an occupation that involved the use of spatial abilities (e.g. SV in architects: Salthouse et al., 1990) have shown a less pronounced age-related decline in these abilities compared to older adults who were not exposed to this kind of occupational experience. Language experience, such as bilingualism, has also been shown to influence cognitive aging. Older bilingual adults outperformed older monolingual adults on tasks measuring executive control and episodic memory (Ljungberg et al., 2013; Perani & Abutalebi, 2015; Wodniecka et al., 2010).

1.4 Objectives

Given that i) nothing is known about the spatial processes underlying performance on tasks of spatial abilities in older signers, ii) research on spatial abilities among children and younger adults who use sign language revealed important discrepancies in terms of performance, especially in SV and MR, and iii) significant life experiences, such as language experience, may influence functional brain processes underlying cognitive reserve, the main objectives of this thesis are to :

1) synthesize, based on the previous literature, the impact of sign language use on spatial abilities in children and adults (paper 1)
2) explore the effect of aging on spatial abilities in deaf sign language users (paper 2);
3) investigate whether there are differences in performance on tasks of spatial abilities (using both accuracy and response time data) that may be accounted by language experience (factor 1: deaf signers/hearing signers/hearing non-signers) and/or age (factor 2: older adults/younger adults) (paper 3).

Paper 1 consists of a scoping review of 22 sources of evidence published between 1969 and 2019. The studies selected reported findings on the relationship between performance on spatial abilities' tasks (spatial perception, spatial visualization, mental rotation and perspective-taking) as a primary or secondary outcome variable in a population of sign language users. This scoping review highlights the various labels used to refer to spatial abilities and expose the range of methodologies used in terms of the characteristics of the sample and experimental measures.

Paper 2 of this thesis reports the effect of normal cognitive aging on spatial abilities (SP, SV, MR, and PT) among older deaf signers. The accuracy of older signers was compared to the accuracy of younger deaf signers. In addition, since it is possible that age-related changes in spatial abilities may interfere with the processing of linguistic information among signers, potential implications of cognitive aging on sign language production and comprehension are discussed. This study provides evidence of age-related cognitive changes in the population of deaf signers.

Paper 3 explores the effect of language experience and age on performance on spatial tasks in terms of accuracy and response time. This study provides insights on the mitigating effects of sign language use on the age-related impact on spatial cognition. This study, which includes groups of deaf signers and hearing signers, allows to distinguish the effects of deafness from the effect of sign language use on performance on tasks of spatial abilities. It also explores the potential gain of long-term use of a visual-spatial language in terms of cognitive reserve.

A detailed description of the general method (description of participants, recruitment process, material, procedure, etc.) for paper 2 and 3 is presented in Appendix 1.

1.5 Hypotheses

Based on the information reviewed in Chapter 1, the following exploratory hypotheses and their related predictions were formulated:

<u>Hypothesis 1</u>

Spatial abilities tend to decrease with age for all adults, including deaf signers.

Prediction 1.1: In terms of accuracy, younger deaf signers will outperform their older peers on all tasks of spatial abilities (SP, SV, MR, PT) (Paper 2).

Prediction 1.2: In terms of response time, younger adults (DS, HS, and HNS) will outperform their older peers on all tasks of spatial abilities (SP, SV, MR, PT) (Paper 3).

<u>Hypothesis 2</u>

Due to their signing experience, there are differences on how signers (deaf and hearing) and non-signers process spatial information and spatial transformations.

Prediction 2.1: In terms of accuracy, hearing signers (older adults, young adults) will perform better on MR tasks compared to their hearing non-signer peers of the same age group. This difference will not be observed

between the deaf signers and the hearing non-signers, in their respective age group (Paper 3).

Prediction 2.2: In terms of accuracy, younger hearing non-signers will perform better on SV tasks compared to their deaf peers of the same age group, but not compared to hearing signers. Given the general effect of age on SV ability, this difference will not be observed in the older groups (Paper 3).

Hypothesis 3

Due to their signing experience, there are differences in terms of speed of processing of spatial information and spatial transformations between signers (deaf and hearing) and non-signers.

Prediction 3.1: In terms of response time, deaf signers and hearing signers (older adults, younger adults) will perform better on MR and SP tasks compared to the hearing non-signers of the same age group (Paper 3).

Given that a limited number of studies have addressed accuracy on SP and PT tasks in the adult population, this aspect of the research is exploratory, and no specific hypotheses are proposed. In addition, because no studies have investigated response time on SV and PT tasks, no specific hypotheses are proposed for these two subskills of spatial abilities. These subskills were explored in Study 2 and the results are discussed in the general discussion chapter of the thesis. Taken together, the results of these studies provide a starting point towards documenting the normal cognitive aging in older signers that are deaf or hearing.

Chapter 2 – Scoping Review

Paper 1: The Impact of Sign Language Use on Spatial Abilities: A Scoping Review

The format of this paper is conformed with the journal in which it was submitted, with the exception of figures and tables which are placed in their accurate place in the text to facilitate the reading.

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Abstract

Research on the impact of using a visual-spatial language on spatial cognition has led to inconsistent results. A scoping review on the relationship between sign language use (in deaf or hearing signers) and performance on spatial tasks was undertaken. This review highlights the various labels used to refer to spatial abilities as well as the range of methodologies used in terms of the characteristics of the sample and experimental measures. Six online databases were used to retrieve 22 sources of evidence published between 1969 and 2019 that included measures of spatial abilities (spatial perception, spatial visualization, mental rotation and perspective-taking; as classified by Linn and Peterson [1985] and Lohman [1988]) as a primary or secondary outcome variable in a population of sign language users. Results from the scoping review revealed that, for most studies in which spatial perception and perspective-taking tasks were reported, no difference was observed between signers and non-signers. For mental rotation and spatial visualization tasks, discrepancies did not make it possible to draw firm conclusions. Heterogeneity in terms of spatial tasks used and the characteristics of the participants recruited are discussed.

Keywords: Bimodal bilingualism; Mental rotation; Perspective-taking; Sign language; Spatial perception; Spatial visualization.

It has been argued that spatial cognition is dependent on language (Majid et al. 2004). Spatial terms (such as “left”, “inside” or “above”) facilitate the encoding of spatial features and spatial relations (Hermer-Vazquez et al. 2001; Pruden et al. 2011). When directly related to the tasks, nonspatial language can also contribute positively to spatial information processing (Dessalegn and Landau 2013; Shusterman et al. 2011). This facilitative effect of language has an influence on the respondents’ strategies to perform spatial tasks. Also, it has been suggested that spatial cognition is sensitive to the different frames of reference used across languages and cultures (Majid et al. 2004). Consequently, sign languages offer a unique window to explore the relationship between language and spatial cognition. Real-world spatial relations in sign language are linguistically marked by the relative positions of the hands in the signer’s space (Pyers et al. 2010). The canonical face-to-face interactions between signers require continuous perspective transformations to interpret accurately a sign language message and avoid miscommunication (Secora and Emmorey 2019). Thus, it can be speculated that the mapping of spatial representations accomplished while signing or when interpreting a sign language message involve high-level spatial processing.

Because spatial mechanisms are used to produce and comprehend sign language, it has been suggested that this life-long linguistic experience might provide signers with a cognitive advantage in processing information within the spatial domain. Previous research has demonstrated such advantage in several domains of cognition. For example, the ability to discriminate human faces under conditions of spatial transformations was shown to be better in signers than in non-signers (Bellugi et al. 1990). This result can be attributed to the fact that signers convey and comprehend basic grammatical information on the signers’ face (Brentari and Crossley 2002; Liddell 1980), such as interrogative and negative markers (Benitez-Quiroz et al. 2016; Zeshan 2006). Conversely, non-signers use facial cues to express complementary paralinguistic information in spoken language (Agnoletti 2017). The greater use of facial features analysis required to process sign language provides an explanation for the observed advantage of signers on tasks that require the processing of facial information. Based on the same rationale, advantages in favor of signers have been reported for tasks involving motion processing (Hauthal

et al. 2013; Neville and Lawson 1987; Shiell et al. 2014), spatial memory (Flaherty 2003; Wilson et al. 1997) and image generation (Emmorey and Kosslyn 1996; Emmorey et al. 1993).

As defined by Linn and Petersen (1985), spatial abilities involve a multidimensional use of intellectual abilities and interrelated subskills. Four subskills of spatial abilities have been labelled as follow: spatial perception (SP), spatial visualization (SV), mental rotation (MR) and perspective-taking (PT) (Linn and Peterson 1985; Lohman 1988). Specifically, SP refers to the ability to perceive a relationship among objects from one's perspective, despite any distractions. SV makes it possible to perform a multistep manipulation of complex information presented spatially. MR consists of the ability to mentally rotate a two- or three-dimensional visual stimuli in space. PT refers to the ability to imagine the appearance of an entity (someone or something) from another one's perspective (Borella et al. 2014; Linn and Petersen 1985; Lohman 1988; Mitolo et al. 2015).

Since the early 70's, several investigators have addressed the spatial skills of sign language users. In some studies, this issue was directly targeted (e.g., Comalli and Schmidt 1976; Hauser et al. 2006; Talbot and Haude 1993). In other investigations, spatial tasks are included as secondary measures in order to provide additional causal relationships to dress a cognitive profile of signers (e.g., relationship between mathematical problems, visual-spatial schematic and pictorial representation and visual-spatial skills [Blatto-Vallee et al. 2007]). A wide range of tasks have been used to investigate these issues and the characteristics of the participants vary considerably across studies. Consequently, major discrepancies have emerged in the findings reported. For example, sex is known to impact spatial processing, with men outperforming women (Goldstein et al. 1990; Parsons et al. 2005). A large sex difference in the distribution of groups may, if this factor is not taken into account, depict a false portrait of a group's performance. In addition, age of sign language acquisition and onset of deafness are two factors that have been shown to influence cognitive development among signers. It has been shown that age of sign language acquisition is an important predictor of brain maturation (Mayberry, 2010), and that a delay in acquisition leads to an increase in the cognitive load required to process structural components of sign language that relies on space, such as syntax (Malaia et al. 2020). Intrinsically related, a late onset of deafness (or a late diagnosis of deafness) can delay sign language acquisition resulting in cognitive difference with deaf signers who acquired sign

language in infancy. Therefore, heterogeneity of groups based on these factors, among others, led to the creation of confusions concerning the effect of sign language use on spatial abilities.

A scoping review was conducted in order to examine previous research and provide a comprehensive overview of the relationship between sign language use and performance on tasks of spatial abilities. The research question of this scoping review is: Relative to their hearing peers, what is known concerning the performance (accuracy or response time measures) of individuals who use a sign language (deaf and hearing) on tasks that measure spatial abilities? The three specific objectives of this review are to i) collate the results of published studies that have addressed the impact of sign language use on performance on tasks of spatial abilities, ii) summarize and analyze the studies retained in terms of the characteristics of their sample, spatial tasks used and outcome measures based on the spatial ability targeted (i.e.: SP, SV, MR and PT), and iii) discuss the inconsistencies that emerge from the analyzed sources.

Methods

Protocol

Scoping reviews make it possible to map a large body of sources of evidence and grey literature from different fields in order to provide an overview of studies surrounding a specific topic area (Pham et al. 2014). The present review was guided by the protocol recommended in the Preferred Reporting Items for Systematic Reviews and Meta-analysis Protocols – Extension for Scoping Reviews (PRISMA-ScR: Tricco et al. 2018) as well as the work of Arksey and O'Malley (2005) and Levac et al. (2010).

Eligibility criteria

Sources of evidence were included when the main or secondary objective of the study was to investigate spatial abilities (SP, SV, MR and/or PT) in deaf or hearing sign language users. Peer-reviewed journals, conference proceedings, theses and book chapters were included if they met the inclusion and exclusion criteria listed in Table 1.

Table 1

Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
• included comparative data between a signing and a non-signing group of participants (norms accepted) • provided statistical analyses of data collected • the data consisted of accuracy and/or response-time measures • they were written in French or English	• not consistent with the objectives of the present review • consisted of case studies or lesion studies • duplicates of the same study • the information provided did not make it possible to chart the data • consisted of conference abstracts or theoretical papers • retrieval not possible from any of the database consulted

These criteria were applied to a three-step screening procedure: i) title/abstract screening, ii) full-text screening and iii) data charting.

Data sources and search strategy

The sources used were retrieved between October 9–11, 2019. A research update was performed on June 19, 2020, but no additional sources were found. Specifically, the documents used were retrieved from five electronic research databases (PubMed; Embase; APA PsycNET; CINAHL; Web of Science). In addition, a manual search of the Google Scholar website (scholar.google.com) was conducted. For this latter search only the first 100 sources were considered since, according to Stevinson and Lawlor (2004), it is unlikely that additional relevant documents emerge when a more extensive search is undertaken. These databases were selected to ensure a wide coverage of studies in behavioral, biomedical, rehabilitation and social areas. Due to the specificity of the topic, a systematic search was performed on all published sources, without any limitations on the date of publication. The search query was structured around the

same specific keywords applied to each database (Medical Subject Headings [MeSH] of Pubmed; Embase thesaurus [EMtree]; Index terms of APA PsycNET; CINAHL Subject Headings) and non-specific terms in the title, abstract and keywords (see Table 2). The search strategy template was designed by an experienced librarian from the Health Library at the University of Montreal.

Table 2

Databases, specific and non-specific keywords used in the query

Databases	Specific keywords	Non-specific keywords
PubMed	**A**: spatial processing; spatial orientation space perception; distance perception; form perception; size perception **B**: persons with hearing impairment; deafness; sign language	**A**: "spatial cognition"; "spatial skill*"; "spatial abilit*"; "spatial perception"; "spatial visualization"; "spatial visualization"; "mental rotation"; "perspective-taking"; "perspective taking"; "spatial orientation"; "spatial relation"; "spatial processing"; "space perception"; "size perception"; "distance perception"; "form perception" B: deafness; "deaf person*"; "deaf"; signer*; "sign language*"; "spatial language*"
Embase	**A**: depth perception; spatial orientation; distance perception **B**: hearing impaired person; hearing impairment; sign language	
PsycNET	**A**: spatial ability; spatial orientation; spatial organization; spatial perception; visuospatial ability; mental rotation; role taking **B**: sign language; deaf	
CINAHL	**A**: spatial perception **B**: deafness; sign language	
Web of Science	-	
Google Scholar	-	

Themes: A- Related to spatial abilities; B- Related to sign language

The results obtained from collating A and B were cross matched to obtain the desired sample of sources of evidence. All studies retrieved from the crossmatch were imported in Zotero reference manager (5.0.77 version).

Screening titles and abstracts for relevance

First, all the duplicated sources were excluded. The remaining sources were screened for their relevance by title and abstract. Articles erroneously filtered by the search of the databases were excluded. All sources that passed this first step were then acquired and a full-text screening was conducted when the source was available.

The reference list of each source retained was scanned in order to identify any sources of evidence not retrieved during the initial search. This made it possible to add any relevant citation that emerged from applying a "snowball" technique (Hepplestone et al. 2011; Jaskiewicz and Tulenko 2012). All the new articles identified were submitted to a full-text screening to assess their eligibility. All the sources retained were included in the scoping review.

Data charting

A single spreadsheet form, developed in Microsoft Excel 2010 (Microsoft Corporation, Redmond, WA), was employed for data charting. The calibration of the form was made with an initial charting of ten sources of evidence. The charting process was iterative for the remaining sources of evidence. The final data-charting included the following information: source characteristics (e.g.: authors, year of publication, country of the study), sample description (e.g.: sample size, age, sex, hearing status, age of sign language acquisition[4], age of onset of deafness), spatial subskill targeted (e.g.: label, definition), task description (e.g.: name of the test, test description, authors of the test) and main outcome measures (e.g.: accuracy, response-time). One researcher accomplished the full data charting process and verification process. Results were

[4] The description of samples in terms of age of sign language acquisition was chosen rather than comparison of native vs non-native signers in order to provide the most detailed portrait possible of the participants included in each study.

grouped on the basis of the spatial subskill targeted by the experimental design (e.g.: SP, SV, MR and/or PT). Subgroups of sources of evidence were then summarized by extracting sample characteristics, tasks selected and general findings.

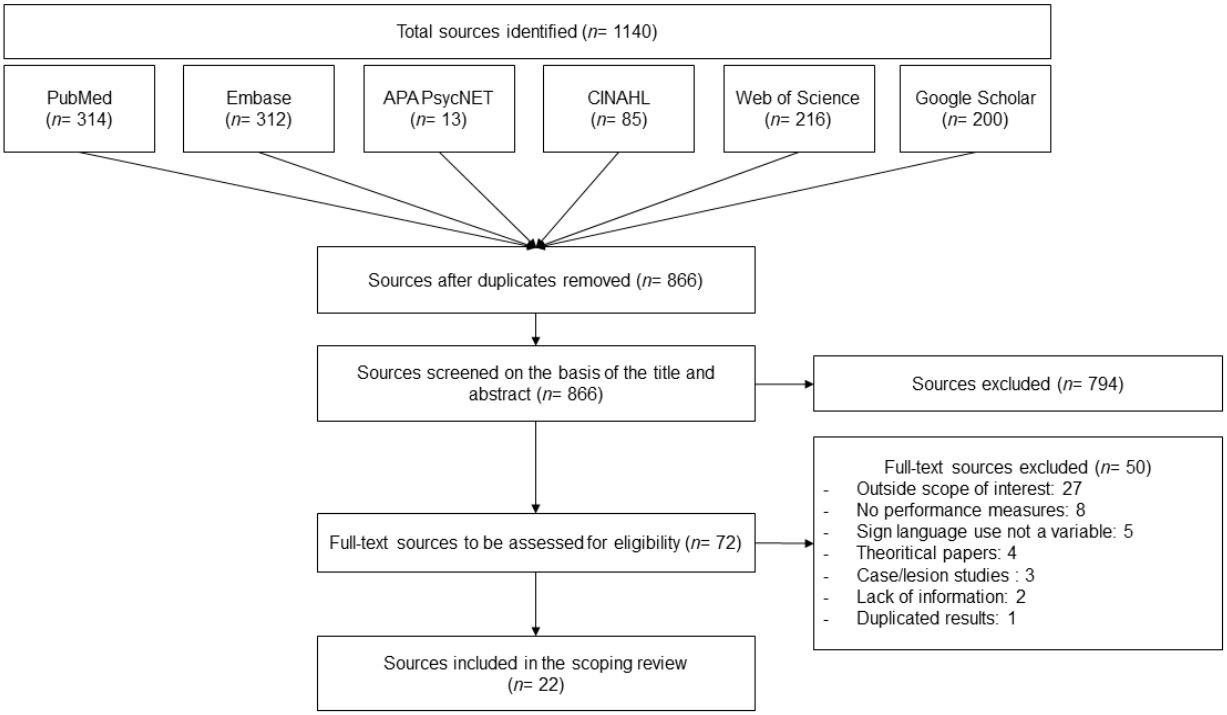
Results

Selection of sources of evidence

The initial search yielded 1140 potential sources from six electronic databases. After duplicates were removed, a total of 866 sources were screened on the basis of their title and abstract to ensure their eligibility. A total of 794 sources were thus excluded. The remaining 72 sources were retrieved and assessed for full-text screen. One unpublished source could not be accessed and was thus excluded from the review (Bettger 1992). From the 72 sources, 50 did not meet the eligibility criteria and were excluded for the following reasons: 27 did not fall within the scope of interest of the scoping review (e.g.: visual abilities, auditory spatial language, biology, deafferentation, rehabilitation treatment, etc.), eight did not provide results in terms of performance (i.e.: preference of perspective), five did not make it possible to compare the performance of signers to a group of non-signers (e.g.: deaf non-signers; no comparison group; comparison of signers from different sign languages), four were theoretical papers and did not report original empirical data, three were case or lesion studies, two lacked the information required to chart the data reported and one study reported the same results as another source (e.g.: published research article incorporated into a thesis). The remaining 22 sources were included in the analysis. A summary of the selection process is illustrated in Figure 1.

Fig. 1

PRISMA-ScR flowchart of sources selection process



General characteristics of the sources of evidence

The general characteristics of the sources included in the scoping review are reported in Table 3. Most of the studies were conducted in North America (81.8%: 18/22) while 13.6% were conducted in Europe (3/22) and 4.5% originated from Asia (1/22). All the sources were published between March 1969 and July 2019; 27.3% (6/22) of the documents were published before 1979, 9.1% (2/22) were published between 1980 and 1989, 27.3% (6/22) were published between 1990 and 1999, 18.2% (4/22) were published between 2000 and 2009, and 18.2% (4/22) were published after 2010.

The labels used to define the concept of spatial ability, spatial ability subskills or spatial processes measured by the spatial tasks used in the studies varied from: visual imagery (Arnold 1978; Emmorey et al. 1993; Robertson and Youniss 1969; Youniss and Robertson 1970), visual-spatial abilities/skills (Blatto-Vallee et al. 2007; Marschark et al. 2013; Marschark et al. 2015),

visual-spatial processing (Emmorey et al. 1998), spatial ability (Parasnis and Long 1979; Tomlinson-Keasey and Smith-Winberry 1990), visuospatial constructive skills (Hauser et al. 2006), mental image generation ability (Emmorey and Kosslyn 1996), perspective-taking skills (Hoemann 1972), spatial perspective-taking (Dwyer 1980), visual-spatial perspective-taking (Secora and Emmorey 2019), role-taking skills (Howley and Howe 2004), visual processing of shape recognition (Chen and Chen 1990), spatial organization (Comalli and Schmidt 1976), spatial visualization ability (Talbot and Haude 1993), spatial transformation abilities (Keehner and Gathercole 2007), mental rotation skills (Le et al. 2018) and perceptual abilities (McDaniel 1980).

Methodological characteristics of sources of evidence

Details of the methodological characteristics of the selected sources of evidence are reported in Table 3. Reporting the results of this scoping review was organized on the basis of the four spatial ability subskills. Of the 22 sources of evidence included, five used at least one measure of SP, seven used at least one measure of SV, nine used at least one measure of MR and six used at least one measure of PT. Emmorey et al. (1993) included measures of SP and MR. McDaniel (1980) included measures of SP, SV and PT. Secora and Emmorey (2019) included measures of MR and PT. Youniss and Robertson (1970) included measures of MR and PT. These four studies were duplicated in Table 3 to incorporate the information related to a specific spatial subskill into the appropriate section of the table. Tasks description and the spatial cognitive processes tested are shown in Online Resource 1 (for this thesis: at the end of the references).

Table 3

Data charting

Authors	Yr of pub.	DS sample	HNS sample	HS sample	Tests used	Results‡	Information omitted
SPATIAL PERCEPTION							
Comalli & Schmidt	1976	n = 20 (10) Age: 10 to 13 DHL: profound	n = 20 (10) Age: 10 to 13	N/A	1. Apparent vertical – Plumbline 2. Apparent body position – lined up with the body	1. ACC: *n.s.d.* 2. ACC: DS outperformed HNS on ± 30° tilt condition	AD, SLA
Emmorey et al.	1993	n = 34 Age, *M* = 27 DHL: profound AD: 12 congenital; 22 < 4 YO	n = 28 Age, *M* = 23	n = 10 Age, *M* = 33 SLA: from birth	Letter drawings in grids/brackets (Podgorny and Shepard [1978], modified by Kosslyn et al. [1988])	ACC: *n.s.d.* RT: DS and HS had shorter RT than HNS in the complex letter condition, *n.s.d* in the simple letter condition	Sex[a], SLA[b]
Emmorey & Kosslyn	1996	n = 20 (9) Age, *M* = 26 DHL: profound AD: < 1;6 YO SLA: from birth (1 learned at 3 YO)	n = 20 (9) Age, *M* = 22	N/A	Letter drawings in grids/brackets (Podgorny and Shepard [1978], modified by Kosslyn et al. [1988])	ACC: *n.s.d.* RT: DS had shorter RT than HNS when stimuli were presented initially to the right hemisphere, *n.s.d.* when presented initially to the left hemisphere	
McDaniel	1980	n = 43 Age: 10 to 13	n = 56 Age: 10 to 13	N/A	Spatial Orientation of Objects (McDaniel 1973)	ACC: *n.s.d.*	Sex, DHL, AD, SLA
Robertson & Youniss	1969	n = 32 (16) Age: 8 to 13	n = 32 (16) Age: 8 to 13	N/A	Horizontal Water-level (Piaget & Inhelder 1963)	ACC: *n.s.d.*	SLA

		DHL: ≥ moderately severe AD: < 2 YO					
SPATIAL VISUALISATION							
Blatto-Vallee et al.	2007	n = 149 (60) Age: ~13 to 23 DHL: ≥ severe	n = 156 (78) Age: ~13 to 20	N/A	1. Primary Mental Abilities Spatial Relations (Optometric Extension Program, 1995) 2. Revised Minnesota Paper Form Board (Likert & Quasha 1994)	1. & 2. ACC: HNS outperformed DS	AD, SLA
Hauser et al.	2006	n = 20 (13) Age, *M* = 21 DHL: ≥ severe AD: congenital SLA: from birth	n = 20 (13) Age, *M* = 23	N/A	Paper Folding and Cutting Subtest (Stanford–Binet Intelligence Scale-4th Edition: Thorndike et al. 1986)	ACC: *n.s.d.*	
Marschark et al.	2013	n = 39 (21) *14 with CI DHL: profound	n = 32 (16)	N/A	1. Spatial Relations (Mather & Woodcock 2001) 2. Embedded Figures (Hauptman & Eliot 1986)	1. & 2. ACC: HNS outperformed DS	Age (not precise, but attending university), AD, SLA
Marschark et al.	2015	n = 106 Age, *M* = 19 DHL: ≥ mild SLA: CI users, *M* = 6.66 YO; non-CI users, *M* = 2.91 YO	n = 55 Age, *M* = 18	n = 14 Age, *M* = 21	1. Spatial Relations (Mather & Woodcock 2001) 2. Embedded Figures (Hauptman & Eliot 1986)	1. & 2. ACC: HNS and HS outperformed DS	Sex, AD (24/106 deaf signers), SLA for HS

McDaniel	1980	n = 43 Age: 10 to 13	n = 56 Age: 10 to 13	N/A	McDaniel 1973: 1. Embedded Figures 2. Successive Figures	1. ACC: HNS outperformed DS at age 10 and 11; age 12 and 13 = *n.s.d.* 2. ACC: *n.s.d.*	Sex, DHL, AD, SLA
Parasnis & Long	1979	n = 144 (67) Age, *M* = 20 DHL: profound	Norms	N/A	1. Group Embedded Figures (Witkin et al. 1971) 2. Spatial Relations (Bennett et al. 1966)	1. ACC: HNS outperformed DS 2. ACC: *n.s.d.*	AD, SLA
Tomlinson-Keasey & Smith-Winberry	1990	n = 66 (36) Age: ~13 to 16 DHL: profound AD: congenital SLA: from birth	n = 99 (55) Age: ~12 to 20	N/A	Bennett et al. 1966: 1. Block Design 2. Spatial Relations	1. & 2. ACC: *n.s.d.*	
MENTAL ROTATION							
Arnold	1978	n = 26 (16) Age, *M* = 15 DHL: profound AD: < 2 YO	n = 33 (20) Age, *M* = 15	N/A	Mental Rotations (Shepard & Metzler [1971], modified by Meudell [1974])	ACC: DS outperformed HNS	SLA
Chen & Chen	1990	n = 8 (4)	n=8(4)	N/A	Rotated Shapes and Patterns (Attneave & Arnoult 1956)	ACC: *n.s.d.* RT: *n.s.d.*	Age (not precise, but attending university), DHL, AD, SLA
Emmorey et al.	1993	n = 34 Age, *M* = 27 DHL: profound	n = 32 Age, *M* = 23	n = 10 (match to	Mental Rotations (similar to Shepard & Metzler 1971)	ACC: *n.s.d.* RT: DS and HS had shorter RT than HNS	Sex[a], SLA[b]

		AD: 16 congenital; 18 < 4 YO		10 DS and 10 HNS) Age, *M* = 33 SLA: from birth			
Emmorey et al.	1998	n = 15 (10) DHL: ≥ severe AD: 13 congenital; 2 prelingual[c] SLA: 13 from birth; 2 < 10 YO	n = 15 (8)	N/A	Mental Rotation of non-linguistic stimuli	ACC: DS outperformed HNS in the rotation condition for location and orientation accuracy	Age (not precise, but attending college or university)
Keehner & Gathercole	2007	N/A	n = 12 (9) Age, *M* = 27	n = 12 (9) Age, *M* = 27 SLA: acquired adulthood, between 1 and 5 yrs of experience	Adapted version of Corsi Block (Corsi 1973) 1. Array rotated by 180° 2. Array rotated by 0°, 90° and 180° 3. Array rotated by 0°, 90° and 180°, sequence shown by LED light	1. ACC: HS outperformed HNS in number of errors, *n.s.d.* in number of order errors 2. ACC: HNS showed a cost of mental rotation in between 0°, 90° and 180° conditions, *n.s.d.* in between conditions for HS 3. ACC: *n.s.d.*	
Le et al.	2018	n = 12 (6) Age, *M* = 28 DHL: profound AD: 10 congenital; 2 = < 2 YO SLA: from birth	n = 12 (6) Age, *M* = 29	N/A	Mental Rotations (Shepard & Metzler, 1971)	ACC: *n.s.d.* RT: DS had shorter RT than HNS	
Secora & Emmorey	2019	n = 44 (23) Age, *M* = 30	n = 45 (32) Age, *M* = 24	N/A	Revised Mental Rotation (Vandenberg & Kuse 1978: redrawn by Peters et al. 1995)	ACC: *n.s.d.*	DHL, AD

		SLA: 30 from birth, 14 < 6 YO					
Talbot & Haude	1993	N/A	n = 16 Age: 19 to 48	n = 16 Age: 19 to 48 SLA: Gr. 1 = 0.8 year; Gr. 2 = 6.1 years	Mental Rotation (Variation of Vandenberg & Kuse 1978)	ACC: HS with 6.1 years of experience with sign language outperformed HNS and HS with 0.8 year of experience with sign language	
Youniss & Robertson	1970	n = 48 Age: ~8 to 12 DHL: ≥ severe AD: < 2 YO	n = 48 Age: ~8 to 12	N/A	Rotation of square (Piaget & Inhelder 1966)	ACC: *n.s.d.*	Sex, SLA
PERSPECTIVE-TAKING							
Dwyer	1980	n = 18 (8) Age: 6 to 11 DHL: ≥ severe AD: < 2 YO	n = 18 (8) Age: 6 to 11	N/A	Spatial decentering tasks with radially symmetrical objects (e.g. a cylinder) and a scale model objects (e.g. elephant toy)	ACC: HNS outperformed DS, *n.s.d.* at age ~11	SLA
Hoemann	1972	n = 40 Age: 8 to 11 DHL: ≥ severe AD: < 3 YO	n = 40 Age: 8 to 11	N/A	1. Descriptive task (modified by (Glucksberg et al. 1966) 2. Perspective task (modified by Glucksberg et al. 1966)	1. & 2.: ACC: HNS outperformed DS	Sex (division almost equal), SLA
Howley & Howe[d]	2004	n = 25 (9) Age: 5 to 12 DHL: ≥ severe AD: prelingual[c]	n = 20 (7) Age: 5 to 12	N/A	Perceptual task (Hughes & Donaldson 1979)	ACC: *n.s.d.*	

		SLA: various, from infancy to school entrance					
McDaniel	1980	n = 43 Age: 10 to 13	n = 56 Age: 10 to 13	N/A	Driving test (McDaniel 1973)	ACC: *n.s.d.*	Sex, DHL, AD, SLA
Secora & Emmorey	2019	n = 44 (23) Age, *M* = 30 SLA: 30 from birth, 14 < 6 YO	n = 45 (32) Age, *M* = 24	N/A	1. Three Buildings (Clements-Stephens et al. 2013) 2. Perspective-Taking Spatial Orientation (Hegarty & Waller 2004)	1. & 2. ACC: *n.s.d.*	DHL, AD
Youniss & Robertson	1970	n = 48 Age: ~8 to 12 DHL: ≥ severe AD: < 2 YO	n = 48 Age: ~8 to 12	N/A	Perspective task (Piaget and Inhelder 1963)	ACC: *n.s.d.*	Sex, SLA

Note. All statistical results presented have a significance level of $p < .05$, or have no significant difference (*n.s.d.*)

[a] = sex is known for the global sample, but not for the subsample. [b] = SLA is known for the global sample, but not for the subsample. [c] = prelingual: reported by authors, without precise age of onset of deafness. [d] = only experience 2 is reported here since i) experiment 2 intend to reproduce experiment 1 with a larger sample and ii) no difference in results was reported between experiment 1 and experiment 2

ACC = accuracy. AD = age of deafness. CI = cochlear implant. DS = Deaf sample. Gr. = Group. DHL = hearing loss degree. HNS = hearing non-signers. HS = Hearing signers. *M* = mean. n=total sample (number of female). *n.s.d.* = no significant difference. RT = response time. SLP = sign language proficiency. YO = years old.

Spatial perception

The relationship between sign language use and SP in children/young adolescents was reported in 60.0% of the sources included for the review (3/5: Comalli and Schmidt 1976; McDaniel 1980; Robertson and Youniss 1969). The remaining 40% addressed SP in adults (2/5: Emmorey et al. 1993; Emmorey and Kosslyn 1996). All the studies included a deaf signer group and a hearing non-signer group. The study reported by Emmorey et al. (1993) is the only one that included an additional group of hearing signers who learned sign language from birth. All groups were comprised of more than 20 participants and were of equal size, with the exception of Emmorey et al. (1993) and McDaniel (1980) who had a difference of 6 to 24 participants between their experimental group and their control group. When the sex of the participants was reported (3/5: 60.0%), studies matched the participants on this variable. With one exception, the degree of hearing loss among the deaf participants ranged from severe to profound. Robertson and Youniss (1969) reported that the hearing loss of their deaf participants was moderately-severe or greater. McDaniel (1980) did not report any information on degree of hearing loss. Two studies indicated that the onset of deafness was before 2-years of age (Emmorey and Kosslyn 1996; Robertson and Youniss 1969). Emmorey et al. (1993) reported a mixed cohort of deaf participants consisting of 12 congenital deaf participants and 22 participants who became deaf before four years of age. Comalli and Schmidt (1976) and McDaniel (1980) did not indicate the age of onset at which the deafness occurred among the deaf participants. Sign language acquisition was implicit but unspecified in terms of age at which it was acquired in four studies (Comalli and Schmidt 1976; Emmorey et al. 1993; McDaniel 1980; Robertson and Youniss 1969). Emmorey and Kosslyn (1996) reported that all deaf participants learned a sign language from birth (with one exception; the participant learned sign language at three years of age).

Four of the five studies included only one measure of SP. Comalli and Schmidt (1976) used two different measures of SP in their research. SP ability was tested in relation to absolute vertically (Comalli and Schmidt 1976), horizontally (Robertson and Youniss 1969), body tilt (Comalli and Schmidt 1976) or to the relative position of apparent entities (Emmorey et al. 1993; Emmorey and Kosslyn 1996; McDaniel 1980).

Results of all five studies indicate no significant difference in terms of accuracy between the deaf participants and their respective non-signing hearing peers. When response time was considered (2/5: 40.0%), deaf signers had significantly shorter response times than hearing non-signers. Emmorey et al. (1993) reported that deaf signers and hearing signers had shorter response times than hearing non-signers under the complex letter experimental condition. No significant difference was detected under the simple letter condition. Emmorey and Kosslyn (1996) showed that deaf signers had shorter response times when coordinate or categorical stimuli were initially presented to the right hemisphere. No difference between groups was observed when the stimuli were initially presented to the left hemisphere.

Spatial visualization

Of the seven studies that addressed the relationship between sign language use and SV, six (85.7%) included participants that ranged in age from adolescents to young adults. In the study reported by McDaniel (1980) the participants were children. All studies included a deaf signer group and a hearing non-signer group. In addition, Marschark et al. (2015) included a group of hearing signers. Group size varied across studies. In two studies, the number of participants ranged from 20 to 39 (Hauser et al. 2006; Marschark et al. 2013). In two other studies the number of participants ranged from 43 to 99 (McDaniel 1980; Tomlinson-Keasey and Smith-Winberry 1990). Finally, more than 100 participants were included in two other studies (Blatto-Vallee et al. 2007; Parasnis and Long 1979). In one study the participants consisted of 106 deaf participants, 55 hearing non-signers and 14 hearing signers (Marschark et al. 2015). Five studies (5/7: 71.4%) had unequal group size, with group differences ranging from seven to 92 participants between experimental and control groups (Blatto-Vallee et al. 2007; Marschark et al. 2013, 2015; McDaniel 1980; Tomlinson-Keasey and Smith-Winberry 1990). When the sex factor was reported (5/7: 71.4%), the difference between male and female participants varied from 0% to 10%. Across studies the proportion of female participants varied from 40% to 60%. In five of the seven studies the group of deaf participants had a hearing loss that varied in degree from severe to profound (Blatto-Vallee et al. 2007; Hauser et al. 2006; Marschark et al. 2013; Parasnis and Long 1979; Tomlinson-Keasey and Smith-Winberry 1990). In the study reported by Marschark et al. (2015) the hearing status of the deaf participants was defined as a mild hearing loss or greater. McDaniel

(1980) did not report the degree of hearing loss of the deaf participants. In two studies the participants were deaf from birth (Hauser et al. 2006; Tomlinson-Keasey and Smith-Winberry 1990). The other studies did not specify the age at which deafness occurred. Sign language acquisition of the deaf participants was either from birth (Hauser et al. 2006; Tomlinson-Keasey and Smith-Winberry 1990) or later in childhood (Marschark et al. 2015: for cochlear-implant[CI] users, mean = 6.66; non-CI users, mean = 2.91). The other four studies did not report the age of sign language acquisition (Blatto-Vallee et al. 2007; Marschark et al. 2013; McDaniel 1980; Parasnis and Long 1979). Marschark et al. (2015) did not report the age of sign language acquisition for the hearing signer group.

Studies included one to three measures of SV. Five studies out of seven used tasks that evaluated the ability to mentally assemble multiple pieces into one target figure (Blatto-Vallee et al. 2007; Marschark et al. 2013, 2015; McDaniel 1980; Tomlinson-Keasey and Smith-Winberry 1990). Two studies used tasks that required a mental multistep manipulation of complex figures (Hauser et al. 2006; Parasnis and Long 1979). Four studies used tasks that required that the participant mentally retrieve individual figures from a complex background (Marschark et al. 2013, 2015; McDaniel 1980; Parasnis and Long 1979).

From a total of 13 SV measures, eight (61.5%) revealed a significant advantage of hearing non-signers over deaf signers in terms of accuracy (Blatto-Vallee et al. 2007; Marschark et al. 2013, 2015; McDaniel 1980 [Embedded Figures]; Parasnis and Long 1979 [Group Embedded Figures]). In addition, Marschark et al. (2015) showed that hearing signers outperformed deaf signers. The remaining measures failed to show a significant difference between groups. Using the Embedded Figures task that he developed in 1973, McDaniel (1980) reported a significant difference between hearing non-signers and deaf signers aged 10-11 years old, where hearing non-signers outperformed deaf signers. However, that difference did not hold for the groups of participants aged 12-13 years old. Response time measures were not reported in any studies.

Mental rotation

Nine sources of evidence reported results on the relationship between MR and sign language use. In seven of those studies (77.7%), the participants were adults. Anorld (1978)

investigated MR in groups of adolescents while Youniss and Robertson (1970) tested children. Six of the studies compared the results obtained from deaf signers to those obtained from hearing non-signers (6/9: 66.6%; Arnold 1978; Chen and Chen 1990; Emmorey et al. 1998; Le et al. 2018; Secora and Emmorey 2019; Youniss and Robertson 1970). In one study, differences among deaf signers, hearing signers and hearing non-signers were investigated (1/9: 11.1%; Emmorey et al. 1993). Two studies compared the performances of hearing signers and hearing non-signers (2/9: 22.2%; Keehner and Gathercole 2007; Talbot and Haude 1993). Group size of fewer than 16 participants were reported in 55.5% (5/9) of the studies (Chen and Chen 1990; Emmorey et al. 1998; Keehner and Gathercole 2007; Le et al. 2018; Talbot and Haude 1993). Typically, the size of control groups was relatively similar to the size of the experimental groups. In three studies, the difference between the experimental and the control group was one to seven participants (Arnold 1978; Emmorey et al. 1993; Secora and Emmorey 2019). When sex was reported (all but Emmorey et al. 1993 and Youniss and Robertson 1970), there is a relatively equal proportion of female and male participants between comparison groups (0% to 19% difference). However, across studies, the proportion of female-to-male ratio varies from 50% to 100% of the sample (Talbot and Haude 1993). In the seven studies that included a group of deaf participants, five reported that the degree of hearing loss of their participants ranged from severe to profound (Arnold, 1978; Emmorey et al. 1993, 1998; Le et al. 2018; Youniss and Robertson, 1970). Two did not mention the degree of hearing loss (Chen and Chen 1990; Secora and Emmorey 2019). Two studies reported that the age at which the participants acquired their deafness was less than 2 years of age (Arnold 1978; Youniss and Robertson 1970). The remaining studies simply reported that the participants had either a congenital or non-congenital deafness (Emmorey et al. 1993: 16 congenital, 18 before age four; Emmorey et al. 1998; 13 congenital, two prelingual; Le et al. 2018: 10 congenital and two before age two). Two studies did not report the age of deafness of their participants (Chen and Chen 1990; Secora and Emmorey 2019). One study included a group of deaf signers who acquired sign language from birth (Le et al. 2018). Two studies reported having mixed groups (Emmorey et al. 1998: 13 from birth, 2 before 10 years old; Secora and Emmorey, 2019: 30 from birth, 14 before 6 years of age). Four studies did not mention the age of sign language acquisition (Arnold 1978; Chen and Chen 1990; Emmorey et al. 1993; Youniss and

Robertson 1970). In the three studies that included a hearing signer group, one of them recruited participants who acquired sign language from birth (Emmorey et al. 1993), while the other two included participants who acquired sign language in adulthood (Keehner and Gathercole 2007) and had between 0.8 and 6.1 years of sign language experience (Talbot and Haude 1993).

Two studies included multiple MR tasks (Emmorey et al. 1998; Keehner and Gathercole 2007). In five studies, the task included three-dimensional stimuli (Emmorey et al. 1998; Keehner and Gathercole 2007; Le et al. 2018; Secora and Emmorey 2019; Talbot and Haude 1993). The remaining four studies used two-dimensional stimuli (Arnold 1978; Chen and Chen 1990; Emmorey et al. 1993; Youniss and Robertson 1970).

In terms of accuracy, an advantage of signers (deaf and hearing) over non-signers was observed in 44.4% (4/9) of the studies (Arnold 1978; Emmorey et al. 1998 [rotation condition]; Keehner and Gathercole 2007; Talbot and Haude 1993). On the other hand, 55.5% (5/9) of the studies failed to find any group differences (Chen and Chen 1990; Emmorey et al. 1993; Le et al. 2018; Secora and Emmorey 2019; Youniss and Robertson 1970). When measures of response time were considered (3/9: 33.3%), two studies showed a shorter response time among signers than among non-signers (Emmorey et al. 1993; Le et al. 2018). Chen and Chen (1990) failed to find a similar pattern of shorter RT for signers.

Perspective-taking

Of the six studies that investigated perspective-taking ability in signers, five (83.3%) of them reported data for children. Secora and Emmorey (2019) was the only study that investigated perspective taking in adults. All the studies included a group of deaf and hearing signers. Except for the study of Dwyer (1980) who reported data for 18 participants per group, all the studies included 20 or more participants per group. Three studies had equal size groups, while three had a difference ranging from one to 13 participants between experimental and control groups (Howley and Howe 2004; McDaniel 1980; Secora and Emmorey 2019).When the sex factor was reported (3/6: 50.0%), difference between male and female participants varied from 0% to 19%. Across studies, the female-to-male ratio varied between 35% and 71%. For the deaf group, four studies reported that their participants had a severe hearing loss or greater (Dwyer 1980;

Hoemann 1972; Howley and Howe, 2004; Youniss and Robertson, 1970). The other two studies did not mention the degree of hearing loss of their deaf participants. Concerning the age at which deafness was acquired, three studies mentioned that the participants became deaf before three years of age (Dwyer 1980; Hoemann 1972; Youniss and Robertson 1970), one in the prelingual phase (Howley and Howe 2004) and two did not provide this information (McDaniel 1980; Secora and Emmorey 2019). Two studies reported the age of sign language acquisition. Participants in the study reported by Howley and Howe (2004) learned sign language at various ages, between infancy and school entrance. Participants in the study reported by Secora and Emmorey (2019) learned sign language either from birth (n=30) or before 6 years of age (n=14).

Four of six studies reported results of one measure of perspective-taking (Dwyer 1980; Howley and Howe 2004; McDaniel 1980; Youniss and Robertson 1970). In two investigations, two measures of PT were included (Secora and Emmorey 2019; Hoemann 1972).

In terms of accuracy scores, two studies showed an advantage of hearing non-signers over deaf signers in PT (Hoemann 1972; Dwyer 1980). However, in Dwyer (1980) the superior performance of the hearing non-signers was observed only for the younger groups of participants. The four remaining studies failed to observe a significant difference between groups of participants (Howley and Howe 2004; McDaniel 1980; Secora and Emmorey 2019; Youniss and Robertson 1970).

Discussion

To our knowledge, this is the first scoping review to provide a comprehensive overview of the relationship between sign language use and performance on tasks of spatial abilities. Sample characteristics, spatial tasks used and outcomes were summarized for four spatial subskills: SP, SV, MR and PT. This made it possible to identify and discuss the inconsistencies that were observed among the studies retained for the review.

General results

The findings reported for each of the four spatial abilities are summarized in Table 4. The majority of the studies (8/11) in which SP or PT was investigated included children as participants.

With regards to the accuracy data, the vast majority of these studies (8/11) did not report any difference between the signer and non-signer groups. Of the three studies that reported significant differences between groups, one found an advantage for signers in the SP tasks (Comalli and Schmidt 1976: Apparent body position, ± 30° tilt condition only) and the other two observed an advantage for non-signers in the PT tasks (Dwyer 1980; Hoemann 1972). It is worth noting that Dwyer (1980) found a significant difference only between the groups of participants that were 6 and 8 years old. There was no significant difference between the two groups that were 11 years old. Response-time data were only reported in two studies that investigated SP (Emmorey et al. 1993; Emmorey and Kosslyn 1996). Both studies were the only ones that obtained data from adults. Moreover, the investigators used the same tasks, but in two different experimental designs. In those studies, the findings showed that signers had shorter response times in the complex condition (when the letters displayed contained four or more segments in the grid [P, J, O, S, G] : Emmorey et al. 1993) and, when the stimuli were presented initially to the right hemisphere (Emmorey and Kosslyn 1996).

Studies investigating MR and SV abilities mainly reported data obtained from adolescents and adults (14/16). Compared to the relatively consensual findings in SP and PT subskills, considerably more variability was observed in the studies that addressed either SV or MR. For both subskills, results were discordant. For SV, Blatto-Vallee et al. (2007) and Marschark et al. (2013) found an advantage for non-signers over signers in terms of accuracy. Marschark et al. (2015) showed a general advantage of hearing individuals (signers and non-signers) over deaf signers. Parasnis and Long (1979) and McDaniel (1980) reported an advantage for non-signers but only in one of their two SV tasks (respectively, Group Embedded Figures task: Witkin et al. 1971; Embedded Figures: McDaniel 1973). Additionally, McDaniel (1980) found that the advantage held for the participants who were 10-11 years of age was not sustained for participants who were 12-13 years of age. No response-time data were collected for any SV tasks.

Of the nine studies that have investigated MR, nearly half found an advantage of signers over non-signers. Interestingly, even when using adapted versions of the same task (Shepard and Metzler 1971), the results reported revealed discrepancies across studies (Arnold 1978 vs Emmorey et al. 1993 and Le et al. 2018). This may be due to the age differences of the participants

across the three investigations: Arnold (1978) tested adolescents while Emmorey et al. (1993) and Le et al., (2018) obtained their data from adults. In terms of response time, signers were found to have shorter response times than non-signers (Emmorey et al. 1993; Le et al. 2018). The lack of difference in response time between groups reported by Chen and Chen (1990) is difficult to explain. Differences among the participants may account, at least in part, for the results reported. Specifically, little information concerning the characteristics of the participants were reported by Chen and Chen (1990).

An examination of the results revealed that hearing signers constantly outperformed the group to which they were compared. Emmorey et al. (1993) reported a general advantage of sign language users (deaf and hearing) over hearing non signers on tasks that measured either SP or MR. However, based on the results of SV tasks Marschark et al. (2015) reported better performances from the hearing participants (signers and non-signers) than from the deaf participants. When comparing hearing signers and hearing non-signers, Keehner and Gathercole (2007) reported that hearing signers deployed less cognitive resources than hearing non-signers. Similarly, Talbot and Haude (1993) showed that hearing signers with long experience in using sign language (6.1 years) outperformed hearing individual with little (0.8 years) or no experience with sign language.

Table 4

Summary of the results as a function of spatial subskills

Subskill	Outcome	Result[‡]	Sources of evidence
SP	ACC	Signers outperformed non-signers	Comalli and Schmidt, 1976 [Apparent body position]
		n.s.d.	Comalli and Schmidt, 1976 [Apparent vertical]
			Emmorey et al. 1993
			Emmorey and Kosslyn, 1996
			McDaniel 1980
			Robertson and Youniss 1969

	RT	Signers had shorter RT than non-signers	Emmorey et al. 1993
			Emmorey and Kosslyn 1996
		n.s.d.	-
SV	ACC	Non-signers outperformed signers	Blatto-Vallee et al. 2007
			Marschark et al. 2013
			Marschark et al. 2015
			McDaniel 1980 [Embedded Figures]
			Parasnis and Long 1979 [Group Embedded Figures]
		n.s.d.	Hauser et al. 2006
			McDaniel 1980 [Successive Figures]
			Parasnis and Long 1979 [Spatial relations]
			Tomlinson-Keasey and Smith-Winberry 1990
	RT	-	-
MR	ACC	Signers outperformed non-signers	Arnold 1978
			Emmorey et al. 1998
			Keehner and Gathercole 2007
			Talbot and Haude 1993
		n.s.d.	Chen and Chen 1990
			Emmorey et al. 1993
			Le et al. 2018
			Secora and Emmorey 2019
			Youniss and Robertson 1970
	RT	Signers had shorter RT than non-signers	Emmorey et al. 1993
			Le et al. 2018
		n.s.d.	Chen and Chen 1990
PT	ACC	Non-signers outperformed signers	Dwyer 1980
			Hoemann 1972
		n.s.d.	Howley and Howe 2004

			McDaniel 1980
			Secora and Emmorey 2019
			Youniss and Robertson 1970
RT		-	-

‡ Significant difference in one condition or more. ¦ Hearing signers also outperformed deaf signers. ACC = Accuracy. DS = Deaf signers. HS = hearing signers. RT = Response time. S = Signers. NS = Non-signers. *n.s.d* = no significant difference.

Inconsistencies in spatial abilities research involving participants who sign

In the present scoping review, the tasks used to measure a given spatial subskill were noted as were the characteristics of the signing participants. Of the 29 tasks used to measure spatial subskills, on only six occasions was the same task used more than once across different studies (6/29: 20.6%[5]). Of the six tasks that were used more than once, three of them were re-used by investigators within the same laboratory or research team (e.g., Spatial Relations [Mather and Woodcock, 2001] was used by Marschark et al. [2013] and used again by Marschark et al. [2015]). Additionally, in some instances, within a spatial subdomain, the complexity of the tasks used varied substantially (e.g.: for MR, 2-dimensional stimuli vs 3-dimensional stimuli), or involved distinct perceptual processes (e.g.: for SV, mentally assemble multiple pieces vs mental multistep manipulation of complex figures vs mentally retrieve individual figures from a complex background). It is likely that the diversity of labels used to define spatial ability, spatial subskills or spatial processes contributes to the challenges encountered when an attempt is made to analyze/compare studies that aim to measure dimensions of spatial abilities. Therefore, these inconsistencies across investigations makes it difficult to reach general conclusions concerning the level of aptitude in spatial abilities across populations of individuals with unique linguistic experience.

Providing a detailed description of the characteristics of the participants is a crucial issue in sign language research (Schembri, 2019). The heterogeneity of experience assumed when the

[5] The modified versions of Shepard and Metzler (1971) were considered to be the same task, as were the two versions of the task of Vandenberg and Kuse (1978). However, it is worth noting that Vandenberg and Kuse (1978) is also considered as a mental rotation task that has been modified from Shepard and Metzler's (1971) task.

term “deaf” is used to describe a group of participants is a concern and may account for the inconsistencies in the results reported in the social, biomedical and linguistic field (Young and Temple 2014). Several biological and environmental factors may contribute to the large variability in performance observed among deaf individuals. These include, but may not be limited to: etiology of deafness, family environment, age of onset of deafness (congenital, pre- vs postlingual), age of sign language acquisition and degree of hearing loss (Holt and Kirk 2005; Lazard et al. 2014; Lu et al. 2016; Shi et al. 2016; Young and Temple 2014). In the present scoping review, when available, degree of hearing loss, age of onset of deafness and age of sign language acquisition were charted and included in the analysis. Etiology of deafness and family environment were not considered because most of studies did not provide this information. Since sex has been shown to be accountable for differences on tasks of spatial subskills (Goldstein et al. 1990; Parsons et al. 2005) and because cognition changes as a function of age, sex and age were considered as relevant characteristics in this review.

Eleven of the 22 studies (50.0%) did not report the age or period of sign language acquisition, seven (31.8%) failed to mention the age at which deafness occurred, three (13.6%) did not mentioned the degree of hearing loss and three (13.6%) did not indicate the sex distribution of their sample. Because the date of publication was not an exclusion criterion, to a certain extent the studies retained for the review provide a historical perspective concerning investigations of cognitive function among deaf individuals. Of the 11 studies that did not report the age of acquisition of sign language, nine were published before the 1990. Research conducted before the 1990s tended to focus on the cognitive implications of deafness *per se* and on the cognitive impact of the lack of access to full communication on children development (Marschark and Hauser 2008). Beginning in the 1980s, the growing interest in linguistic research on sign language resulted in a shift in research interest towards the cognitive development of deaf individuals under optimal environments (i.e., deaf children who acquired sign language from deaf parents) and with rehabilitation treatments (i.e., hearing aids, cochlear implants, speech-language therapy). In addition, important advent in terms of disability rights, such as the Americans with Disabilities Act and the Newborn Hearing Screening State Laws both implemented in 1990, put forward the fundamental rights of access to language from birth. Therefore, age of

sign language acquisition, as an important predictor of brain maturation in deaf children (Mayberry 2010) was recognized as an important factor mainly after the 1990. Of the nine studies published before 1990, seven involved children who were described as attending state schools for the deaf. Due to the variability in exposure to sign language that children who attended state schools for the deaf had at that time, it is difficult to assess the proficiency of the participants in sign language. Notwithstanding this information, and regardless of whether the formal language of instruction was sign or spoken language, deaf children learned sign language from their surrounding conversational partners (e.g., family members, classmates, teaching staff, etc.) who had different levels of sign language proficiency (Woll 2019; Young and Temple 2014). Therefore, one can surmise that sign language proficiency was highly variable among children who were recruited in studies prior to 1990. This phenomenon may account, at least partially, for the variability in performance on spatial ability tasks documented in the present review. Although the presentation of these studies published before 1990 adds a layer of variability that is difficult to interpret compared to other studies, the current inclusive review provides a global portrait of the research that has been done on the relationship between the sign language use and spatial abilities. By considering these particularities of cohorts, future research will benefit from prudently interpreting these researches published before 1990.

Limitations of the scoping review process

This review presents some limitations. First, due to the heterogeneity of the results in MR and SV subskills, it was impossible to observe patterns of performance in signers and non-signers. Moreover, based on the inclusion criteria, this scoping review excluded sources of evidence on deaf non-signers that would have provided a broader overview of the impact of sign language vs deafness on spatial processing. This conscious choice was motivated by two considerations: i) defining the population of deaf non-signers in terms of the severity of hearing loss and the aid of communication used (e.g., cochlear implant(s), hearing aids, none) presents its share of challenges for the systematicity of a scoping review, and ii) of the 1140 sources identified during the initial inquiry of this scoping review, only two studies addressed the relationship between sign language use and performance on spatial ability tasks in deaf non-signers (i.e.,.: Chamberlain, 1994; Parasnis et al. 1996). This small number of studies would not have made it possible to

provide a valid interpretation of the results compared to those of deaf signers, hearing signers and hearing non-signers. Finally, for the purpose of this review, experimental paradigms in which linguistic stimuli were used to investigate spatial processing in deaf individuals were discarded because the same test material cannot be administered to the signing and non-signing population. These studies should be considered in future reviews; they may shed additional information concerning the spatial abilities of deaf signers.

It is worth noting that this scoping review provides an in-depth account of the state of knowledge on the relationship between sign language use and performance at spatial abilities tasks. It would be unrealistic to conduct a systematic review on the relationship between sign language use and performance at spatial abilities in the population of signers. The large heterogeneity in the characteristics that define this population, the partial information available on the characteristics of the participants in studies conducted prior to 1990 and to the diversity of tasks used to assess spatial abilities are all factors that justifies the scarcity of the researched on the subject. However, to deepen our knowledge of the relationship between sign language use and spatial abilities, the following recommendations are offered: i) describe as precisely as possible the the participants in terms of their age, sex, hearing status, age of sign language acquisition and age of the diagnosis of deafness and ii) consider the two outcome measures of accuracy and response time. In addition, future research should consider documenting background information on the two confounding factors of the frequency of signing and the duration of signing in order to provide a more comprehensive description of the language experience of participants. As noted in the present review, the scarcity of available studies did not make it possible to draw general conclusions concerning the relationship between sign language use and performance on spatial abilities tasks.

Conclusion

This scoping review investigated the relationship between sign language use and performance on spatial abilities among individuals who use a sign language. Six online databases were interrogated to achieve an extensive review. 22 studies showed that the performances of signers differed depending on the spatial subskills targeted by the tasks administered and that

there was a high level of variability in the results due to the heterogeneity of the samples (especially for MR and SV measures). Inconsistencies might also be attributable to the great diversity of tasks used to measure spatial processing.

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Online Resource 1 – Tasks description and the spatial cognitive processes involved

Task name	Task author	Description*	Sources of evidence
SP; the ability to perceive a relationship among objects from one's perspective, despite any distractions			
Apparent vertical – Plumbline	*n.m*	"adjustment of a luminous rod in a dark room to a position that appears vertical"	Comalli and Schmidt 1976
Apparent body position – lined up with the body	*n.m*	"adjustment of a luminous rod to a position that appears parallel to the longitudinal axis of the subject's own body"	Comalli and Schmidt 1976
Horizontal Water-level	Adapted from Piaget and Inhelder 1963	"…[the subject] was given a sheet of paper on which a picture duplicating the position and shape of the bottle [of water] appeared; he was told to draw in the liquid with a blue pen as he saw it"	Robertson and Youniss 1969
Letter drawings in grids/brackets	Podgorny and Shepard 1978; modified by Kosslyn et al.1988	"Subjects first memorized upper-case block letters that were formed by blackening sets of cells in 4 x 5 grids, and then were shown a series of grids that contained only two X marks. A lower-case letter was beneath each of these grids, and the subjects were asked to decide as quickly as possible whether the corresponding upper-case block letter would cover both of the X marks if it were in the grid."	Emmorey et al. 1993 Emmorey and Kosslyn 1996
Spatial Orientation of Objects	McDaniel 1973	"After watching three colored pegs move into new positions on a board, the child marks one	McDaniel 1980

		of three illustrations to show final position of pegs."	
SV; the ability to perform a multistep manipulation of complex information presented spatially			
Block Design	Bennett et al. 1966	"requires subjects to reproduce a given geometric pattern using red and white blocks"	Tomlinson-Keasey and Smith-Winberry 1990
Embedded Figures	Hauptman and Eliot 1986	"required identification of objects hidden within a visually noisy background, that is, separating figure from ground. »	Marschark et al. 2013 Marschark et al. 2015
Embedded Figures	McDaniel 1973	"After viewing a geometric figure briefly, the child must choose the design containing the original figure from among four camouflaging designs."	McDaniel 1980
Group Embedded Figures	Witkin et al. 1971	"The subjects' task is to find a simple form which is embedded in a complex display."	Parasnis and Long 1979
Paper Folding and Cutting Subtest	Thorndike et al. 1986	"The Paper Folding and Cutting subtest consists of a sequence of drawings that show the process of a rectangular piece of paper being folded a number of times. The number of folds increases and directions of the folds vary in complexity throughout the test. The final sketch shows a gap on the paper indicating where the paper has been cut. The subject is asked to select one of five drawings that correctly represents how the paper would appear when unfolded"	Hauser et al. 2006
Primary Mental	Optometric Extension Program 1995	"participants are presented with the line drawing of an incomplete square and then	Blatto-Vallee et al. 2007

Abilities Spatial Relations		instructed to choose the corresponding missing part from five choices that would complete the square."	
Revised Minnesota Paper Form Board	Likert and Quasha 1994	"participants were instructed to consider the component parts of a figure and then discern the correct form of the whole figure if those parts were pieced together. The format of this visual–spatial test is multiple-choice."	Blatto-Vallee et al. 2007
Spatial Relations	Mather and Woodcock 2001	"requires individuals to identify the two or three shapes (out of six) that can be combined to form a complex target shape."	Marschark et al. 2013 Marschark et al. 2015
Spatial Relations	Benett et al. 1966	"requires subjects to mentally fold up a box displayed in two dimensions and then to determine how the box will appear when it is folded"	Parasnis and Long 1979 Tomlinson-Keasey and Smith-Winberry 1990
Successive Figures	McDaniel 1973	"After watching several lines appear successively, the child must indicate the design that would be formed if the lines were combined."	McDaniel 1980
MR; the ability to mentally rotate a two- or three-dimensional visual stimuli in space			
Corsi Block	Corsi 1973; modified by Keehner and Gathercole, 2007	Exp. 1: "identical but rotated nature of the two Corsi sets was explained to the participant, and the experimenter demonstrated the correspondence between the configuration of blocks on set A (as viewed from the experimenter's perspective) and set B (as seen from the participant's perspective). Using the index finger of the right hand, the experimenter tapped a spatial sequence on	Keehner and Gathercole 2007

	Corsi set A […]. [T]he participant was then required to tap the corresponding (180º rotated) sequence on Corsi set B, preserving the correct order.” Exp. 2: “As in Experiment 1, two identical Corsi sets were used. […] Three different orientation conditions [of sets] were presented: 0º, 90º, and 180º. […] The experimenter tapped a spatial sequence on Corsi set A […]. [T]he participant was then required to tap the corresponding sequence on Corsi set B, preserving the correct order and taking account of the angle of rotation, if any.” Exp. 3: “As in Experiments 1 and 2, two identical Corsi sets were used. […]On the Corsi set closest to the experimenter (set A), a light-emitting diode (LED) was attached to the top surface of each block. The LEDs were operated remotely by means of a small handheld keypad constructed with momentary switches, which allowed brief illumination of the LEDs at each location. […] As in Experiment 2, three different orientation conditions were presented: 0º, 90º, and 180º. […] Using the remote keypad, held out of view of the participant, the experimenter illuminated a sequence of LEDs	

		on Corsi set A […]. [T]he participant was then required to tap the corresponding sequence on Corsi set B, preserving the correct order and taking account of the angle of rotation, if any.”	
Mental Rotation	Shepard and Metzler 1971; modified by Meudell 1974	“Forty slides each of two 4X4 matrices contained four random dots one in each of the 16 possible cells. Half of the pairs of matrices were angular rotations of each other, while the others were angular rotations of mirror images of each other and so were dissimilar when, rotated; no physical rotation could bring rhe pairs into congruence. […] The subjects saw each projected pair of matrices and were required to rotate them mentally and to underline the words same or differed on a printed answer sheet.”	Arnold 1978
Mental Rotation	Shepard and Metzler 1971; modified by Emmorey et al. 1993	“They showed subjects pairs of forms created by juxtaposing cubes to form angular, multi-segment arms, and asked the subjects to decide whether the two forms were the same regardless of orientation. […] Our task used two-dimensional analogs of the forms used by Shepard and Metzler.”	Emmorey et al. 1993
Mental Rotation	Shepard and Metzler 1971	“In the classic Shepard and Metzler mental rotation task (Shepard & Metzler 1971), subjects were shown 3D drawings of stacked blocks or reversed mirror images thereof,	Le et al. 2018

		both rotated at various angles. The subject was required to judge whether these differently rotated 3D figures were identical or reversed mirror images."	
Revised Mental Rotation	Vandenberg and Kuse 1978; redrawn by Peters et al. 1995	"participants were shown a target black and white line drawing of a threedimensional block and four response pictures […]. Two pictures of the four response pictures showed the target block rotated through three-dimensional space presenting slightly different faces of the same block. The other two pictures depicted blocks that could not be mentally rotated into alignment with the target block. Participants were instructed to draw an 'x' over the two pictures that matched the target picture."	Secora and Emmorey 2019
Variation of Mental Rotation	Vandenberg and Kuse 1978	"Each item is composed of a criterion figure, two correct alternatives, and two distractors. The correct alternatives are identical to the criterion figure but are displayed in a rotated position. The distractors are either rotated mirror-images of the criterion figure or rotated criterion figures from other items."	Talbot and Haude 1993
Mental rotation of non-linguistic stimuli	Emmorey et al. 1998	"subjects viewed videotapes of objects appearing briefly and sequentially on a board marked with an entrance. The entrance of the board either matched the entrance on an identical board in front of the subject or was rotated 180°. Subjects were asked to place	Emmorey et al. 1998

		objects on their board in the orientation and location shown on the video, making the appropriate rotation when required.”	
Rotated Shapes and Patterns	Attneave and Arnoult 1956	“Three random shapes of 6, 12, and 24 points generated by Attneave and Amoult (1956) were used (Figure 1). The three shapes and their reflected images represented three levels of rated complexity and three sizes of linear scales: 1.6,0.8, and 0.4. The isometries used were rotations and reflections. Each shape of a scale had four orientations: 0°, 60°, 120°, and 180° (clockwise angular departures from the standard shape for rotation) and 0°, 30°, 60°, and 90° (angular departures of the mirrors for reflection). The angular departure of the position of a reflected image was twice as much as the angular departure of its mirror. […]. They were instructed that forms would be presented to them on the screen one at a time and that they were to press the left-hand key if the displayed form was a rotated image of one of the standard forms. If the image was identical to one of the standard forms, they were to consider it a 0° rotated image of the standard form and to press the left-hand key accordingly. If the	Chen and Chen 1990

		displayed form was a reflected image of one of the standard forms, they were to press the right-hand key."	
Rotation of square	Piaget and Inhelder 1966	"Trials of the rotation-of-square task presented eight uncorrected trials in which a rotating square was moved around a fixed square of a different color. […] A small arrow appeared at the middle of the bottom horizontal line of the rotating square to indicate its location as it was moved. In succession the variable square was rotated to locations 45°, 90°, 135°, 180°, 225°, 270°, 315°, and 0°. The board was covered during rotations, and a replica of the arrow was set on top of the cover, as in the pretest, to indicate how far the rotation had been carried out. The S made his response by selecting from four alternatives. Besides the correct choice the three incorrect choices included (a) the variable square in correct location but distorted in shape (e.g., appearing as a triangle); (b) the variable square removed 45° or 90° from its correction location; and (c) the pivot point misplaced off its correct location.	Youniss and Robertson 1970
PT; the ability to imagine the appearance an entity (someone or something) from another person's perspective			
Descriptive	Glucksberg et al. 1966; modified	"a sender was required to describe referents for the benefit of a peer receiver. […] The pictures were drawn on cardboard disks 10	Hoemann 1972

	by Hoemann 1972	inches in diameter. There were 10 disks with six pictures each and 'one disk with four pictures. The pictures were placed on a turntable between [subjects], who were seated opposite each other at a low table. The base of the pictures was on the outside of the disks, with the result that both Ss saw the pictures from the same perspective. […] The sender was required to describe this picture to a receiver in whatever manner he preferred. […] The receiver was then required to make a nonverbal pointing response, and the sender was in- formed after each trial whether the receiver's selection was correct.”	
Driving	McDaniel 1973	“After watching a toy truck move through the intersection of a model village, the child must draw the path of the truck on a picture of the village which is rotated 90° from the original point of observation.”	McDaniel 1980
Perspective	Piaget and Inhelder 1963	“perspective task began when E set up the scene shown in figure 1 on the table in front of S. He was asked to imagine what the scene would look like from eight distinct locations.”	Youniss and Robertson 1970
Perceptual	Hughes and Donaldson 1979	“the perceptual task involved hiding a boy doll: (a) from one toy policeman positioned at the end of a wall which intersected at right angles with another wall, thereby creating four sections in which the doll might be placed; (b) from two toy policemen positioned	Howley and Howe 2004

		at the ends of adjacent walls and therefore at right angles to each other with, between them, views into 3 of the 4 sections. […] The perceptual task began with the apparatus being set up, and a toy policeman placed at the end of one of the intersecting walls. The boy doll was introduced and placed in one of the four sections formed by the walls. The child was asked 'Can the policeman see the boy?'. The question was then repeated with the doll placed in the other three sections. […] Part A addressing awareness of what can be seen and Part B addressing awareness of how things are seen."	
Perspective	Glucksberg et al. 1966; modified by Hoemann 1972	"In the perspective task two sets of six pictures each were presented on a drum that rotated either left to right or right to left between the [subjects]. In this setting the [subject] seated opposite saw the pictures from a different perspective. There were six trials in which, for the receiver, the pictures were upside down (up-down trials) and six trials in which the pictures were reversed left and right (left-right trials). […] Messages were evaluated as to whose perspective the sender took, his own, the receiver's, or the picture's, and whether the message stated whose perspective was taken, left it ambiguous, or	Hoemann 1972

		omitted entirely the cues that were related to perspective.”	
Perspective-Taking Spatial Orientation	Hegarty and Waller 2004	“participants saw a fixed array of two-dimensional objects on paper and were instructed to imagine adopting a specific spatial perspective within that array relative to two objects (e.g., standing at the flower facing the tree; see Figure 2A). Their task was to indicate the relative position of a third object (e.g., the cat) by drawing an arrow on a response circle”	Secora and Emmorey 2019
Spatial decentering	*n.m.*	“The next stage in the pretest was a rehearsal for the test procedure, starting with S[subject] taking up 0° and E[experimenter] opposite at 180°. The subject was first to all required to choose the photograph which depicted his own view of the model. Correct choice had to be achieved before proceeding to the subsequent stage in the task in which S was required to select the photograph showing the view from E’s position at 180° displacement.”	Dwyer 1980
Three Buildings	Clements-Stephens et al. 2011	“participants viewed two different building displays, one at a time. Each display had three unique buildings (six total across both displays) constructed with Lego blocks […]. Seven perspective-taking targets were placed at 45° intervals around the display corresponding to 45°, 90°, 135°, 180°, 225°,	Secora and Emmorey 2019

	270°, and 315° with the participant seated at 0° […]. The perspective-taking targets were constructed from a wooden candlestick holder, cube, and triangular prism. The wooden cube and triangle were painted with one of seven colors: blue, white, green, red, yellow, pink, and purple. […] Participants viewed photographs representing possible viewpoints on a 15-inch Apple laptop placed on a separate small table […]. Response keys were labeled with colored stickers corresponding to the color of the perspective-taking target at that spatial location with the participant's view […]. The participants' task was to decide: "Which triangle is at this view?" and to press the key on the keyboard labeled with the same color."	

Chapter 3 – Empirical study 1

Paper 2: Spatial Abilities of Older Deaf Signers

The format of this paper is conformed with the journal's standards of *Journal of Deaf Studies and Deaf Education*, with the exception of figures and tables which are placed in their accurate place in the text to facilitate the reading.

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Abstract

Research involving the general population of people who use a spoken language to communicate has demonstrated that older adults experience cognitive and physical changes associated with aging. Notwithstanding the differences in the cognitive processes involved in sign and spoken languages, it is possible that aging can also affect cognitive processing in deaf signers. This research aims to explore the impact of aging on spatial abilities among sign language users. Results showed that younger signers were more accurate than older signers on all spatial tasks. Therefore, the age-related impact on spatial abilities found in the older hearing population can be generalized to the population of signers. Potential implications for sign language production and comprehension are discussed.

Previous research has provided important insights on the multifaceted phenomena of aging (e.g., neurobiological, cognitive, physiological, psychological). However, the focus has mostly been on describing the aging processes of the majority of the population. The main advantage of this type of research is that the results can be generalized to a large segment of the population. Unfortunately, these findings do not necessarily extend to segments of the population who exhibit distinctive characteristics, such as language experience or hearing status. For example, the norms and standards established for the general population might not hold for the subgroup of older deaf adults who use a natural sign language to communicate (hereinafter referred to as signers).

Older adults experience cognitive and physical changes associated with aging. Cognitively, some skills tend to decline as a function of age. It is the case for selective and divided attention (Carlson et al., 1995), executive function (Harada et al., 2013; Wecker et al., 2005), episodic memory (Rönnlund et al., 2005) and visuo-spatial abilities (Klencklen et al., 2012; Techentin et al., 2014). Decline in these cognitive domains is mediated in part by a general decrease in speed of processing (Salthouse, 1996; Salthouse & Ferrer-Caja, 2003). Biomechanically, the ability to execute the physical movements needed to accomplish daily activities is affected by age (John et al., 2009). Movements (amplitude, frequency and rapidity) are not only limited by age-related biomechanical constraints but also by the effort required to produce them (Carmeli et al., 2003; Chaput & Proteau, 1996; John et al. 2009; Ketcham & Stelmach, 2004). More specifically related to fine motor skills, changes in the hand (diminished muscle strength, limited range of joint motion, changes in bones and joints morphology, etc.) tend to affect dexterity, precision and coordination of the arms and hands (Carmeli et al., 2003). Even though these age-related changes involve similar processes in all populations, it is not clear how aging affects communication in signers.

It has been shown that sign and spoken languages share several fundamental properties. For example, as natural languages, sign languages are structured with segments (i.e., minimal discrete units) that are governed by combinatorial rules (Brentari, 1998; Goldin-Meadow, 2017). Specifically, they contain analogous structural components at the sublexical (namely phonetics,

phonology, morphology), syntactic and prosodic levels (Meier et al., 2002; Sandler & Lillo-Martin, 2006; Sutton-Spence & Woll, 1999; Tyrone & Mauk, 2010; Wilbur & Martínez, 2002). Based on brain imaging investigations, it has been established that sign and spoken language users recruit similar brain regions (namely, frontal and temporoparietal areas) for the processing and production of language (Neville et al., 1998; Payne et al., 2019; Petitto et al., 2000). Signs and words activate similar neuroanatomical areas for lexical retrieval (Emmorey et al., 2003), phonological processing (MacSweeney et al., 2008) and the representation of semantic categories (Evans et al., 2019). Notwithstanding these similarities in linguistic processing, differences in cognitive and physical functioning have been shown for sign and spoken languages.

The most salient difference between signers and individuals who use a spoken language is related to the modalities that are used to express and perceive linguistic information (Tyrone, 2014). Spoken language involves smaller articulators located in the midline of the body (larynx and supralaryngeal vocal tract) to produce speech sequences (Auer, 2009; Tyrone, 2014). Sign language users communicate with larger articulators, primarily their arms and hands, as well as their face, torso and head, to produce a discourse, but they make use of space in three dimensions (Bouchard & Dubuisson, 1995; Elliot & Jacobs, 2013; Sandler, 2018; Tyrone, 2014). In most instances, signers use both sides of their body to produce and coordinate signs. Moreover, they do so with an asymmetry that is dependent on hand dominance (Tyrone, 2014; Watkins & Thompson, 2017). At the perceptual level, speech perception depends mostly on the auditory channel, while signers process the incoming message visually. Based on these differences, studies have investigated the potential effect of language modality on cognition. Differences between deaf signers and hearing individuals using a spoken language to communicate (henceforth, hearing spoken language users) have been reported for several cognitive processes, including peripheral and central attentional resources (Chen et al., 2010; Proksch & Bavelier, 2002; Stoll & Dye, 2019), haptic orientation processing (van Dijk et al., 2013), relationship between linguistic and spatial working memory and language comprehension (Emmorey et al., 2017). At the biomechanical level, investigations have shown that deaf individuals have an increased gait ground reaction force compared to individuals with typical hearing (Jafarnezhadgero et al., 2017). However, they show poorer performance in terms of in balance (Siegel et al., 1991), visuo-motor

skills and general dynamic coordination (Gkouvatzi et al., 2010; Wiegersma & Vander Velde, 1983). Even though deaf signers and spoken language users share common fundamental linguistic properties as well as brain activations for language processing, existing research suggests that linguistic background and auditory experience have an influence on cognitive processing and biomechanical function in humans. It is widely known that the aging process is influenced by experience, including occupation, linguistic experience, leisure, social participation, physical activities, etc. (Bak et al., 2014; Foubert-Samier et al., 2012; Marioni et al., 2012; Rodrigues et al., 2020; Salthouse et al., 1990; Wang et al., 2002). Therefore, it is reasonable to expect differences in age-related cognitive processes between individuals who use a visuo-spatial language and those who use a spoken language.

Few investigators have addressed how aging processes operate in older deaf signers. Existing research on this population in the health field stresses the need to adapt senior centers for an inclusive cohabitation of the residents (Becker & Nadler, 1980; Witte & Kusel, 2000) and highlights the relevance of developing valid cognitive assessment tools specific to older signers (Atkinson et al., 2015; Dean et al., 2009). In addition, other studies report exploratory findings on language processing of older deaf signers with a pathology such as unspecified dementia, aphasia, Parkinson disease and movement disorder (Brentari et al., 1995; Spanjer et al., 2014; Tyrone, 2014) or discuss prevalence of chronic conditions such as insomnia and depression in this population (Werngren-Elgström et al., 2003).

In the general population, about 60-80% of adults over 60 years of age carry out their daily activities without any, or with few limitations (Brunel & Carrère, 2017; Camirand & Fournier, 2012; Kraus et al., 2018). Thus, most older adults do not have significant disabilities, nor do they exhibit symptoms of age-related illnesses. A variety of gradual physical, cognitive, sensory or behavioral manifestations resulting from “normal” aging may however be displayed. In comparison to what we already know in the health domain on deaf older signers, there is a lack of background knowledge about how normal cognitive aging operates in this population. Information on normal aging of deaf adults is crucial to establish an accurate cognitive profile of older deaf signers that could, subsequently, provide comparative norms on manifestations of illnesses related to aging. To our knowledge, in the deaf signer population, only one study

addressed issues of normal aging. Rudner et al. (2010) investigated the effects of linguistic modality on temporal and spatial organization of working memory in older signers. They reported that older signers perform more poorly than age-matched non-signers on tasks that require the retention of the order in which information appears in a temporal display. Such studies on cognitive aging in older signers are important milestones that will help clarify specific aging patterns in sign language users.

It has been argued that visual-spatial properties of sign languages have an influence on signers' cognition (Bellugi et al., 1990; Emmorey et al., 1993; Talbot & Haude, 1993). This research proposes to extend the knowledge related to the impact of normal aging on spatial abilities among older deaf signers.

Spatial ability is defined as a multidimensional construct that includes interrelated subskills (see Hegarty & Waller, 2005). In a comprehensive meta-analysis, Linn and Peterson (1985) identified three broad categories of spatial abilities: spatial perception (SP), spatial visualization (SV) and mental rotation (MR). Additionally, perspective-taking (PT) has been identified by Lohman (1988) as a fourth category. More precisely, SP refers to the ability to perceive, despite perceptual distraction, a relation among objects from (Linn & Peterson, 1985). SV consists of the ability to perform the manipulation of complex information presented spatially through multisteps (Linn & Peterson, 1985). MR is the ability to mentally rotate visual stimuli that are two- or three-dimensional in space (Linn & Peterson, 1985). Finally, PT refers to the ability to mentally imagine the appearance of an entity (someone or something) from a different perspective (Lohman, 1988; Hegarty & Waller, 2005). The literature does not offer a unequivocal and consensual definition on spatial abilities. However, Linn & Peterson's categorization appears to be accepted by a number of researchers investigating small-scale spatial skills.

Spatial abilities contribute to one's ability to navigate through day-to-day activities (Meneghetti et al., 2014). For example, SP helps one navigate in a crowded area without bumping into anyone; SV contributes to assembling multiple pieces into a whole as would be the case in sewing a piece of cloth; MR allows you to interpret correctly gestures of your interlocutor when he shows you with his/her hands that the item is "on the right"; and finally PT is actively solicited

when you need to imagine if a person on the other side of the room is able to see an object from his/her perspective.

Since spatial abilities rely on other cognitive processes that have been shown to be impacted by age (e.g., speed of processing and central executive function: Hegarty & Waller, 2005; Techentin et al., 2014), multiple studies have reported a decrease of spatial abilities as a function of age. Age-related decline in spatial abilities is expected to have important functional implications on the daily activities of older adults (Hegarty et al., 2006; Techentin et al., 2014). Lord and Webster (1990) have shown that older adults who experienced falls perform more poorly on an SP Rod and Frame task compared to older adults who haven't experienced falls. According to Antsey et al. (2012), performance on a MR Card Rotation task and an SV Paper Folding Task is associated with the capacity to drive safely. Taken together, these findings suggest that spatial abilities have real-life implications and that age-related changes in these skills can have an important impact on the quality of life of older adults.

This research aims to: i) investigate the impact of aging on spatial abilities in sign language users and ii) explore associations between age-related effects on spatial abilities and sign language processing (production and comprehension) among deaf signers.

Method

Participants

Forty prelingually deaf signers, equally divided into two age groups (18-35 y/o; 65-80 y/o), took part in this study. All participants were assessed for far and near vision with a Snellen chart, to confirm that they had normal or corrected-to-normal vision. Both groups were screened for cognitive impairment to ensure the reactiveness and the responsiveness of the participants. For this experimental purpose, a translated and adapted version of the British Sign Language Cognitive Screening Test (Atkinson et al., 2015) in Quebec Sign Language[1] (LSQ) was used. Individuals whose past or present occupation involved spatial skills (e.g., architects, taxi drivers) were excluded from the study because it has been shown that these occupations improve spatial abilities (Salthouse et al., 1990). Table 1 provides an overview of demographic characteristics of

participants age, years of education, hearing status (deafness from birth vs. deafness acquired before 2;6 y/o), deafness in family history). Given the documented sex differences on spatial processing (Goldstein et al., 1990; Herrera-Guzmán et al., 2004; Voyer et al., 1995), groups were matched for sex.

Table 1

Participants demographic characteristics.

Variable		M	(SD)	rg
Older adults				
Age		71.5	(4.6)	66-80
Years of education		11.4	(2.7)	6-15
Gender (Ma:F)	10:10			
Hearing status (Native:<2;6 yrs)	14:6			
Deaf family (yes;no)	10:10			
Younger adults				
Age		30.8	(3.5)	25-35
Years of education		15.0	(3.0)	11-23
Gender (Ma:F)	10:10			
Hearing status (Native:<2;6 yrs)	16:4			
Deaf family (yes;no)	8:12			

Note. DS = deaf signers; F = Female; M = mean; Ma = Male; SD = standard deviation; rg = range.

All participants had a bilateral sensorineural severe to profound hearing loss and reported using sign language as their primary mode of communication. To observe their language preference (i.e., LSQ) and confirm their language proficiency in LSQ and to confirm that they did not rely on lipreading spoken French to communicate (i.e., deaf oralists), subtests of the *Batterie d'Évaluation Cognitive du Language* (BECLA – Macoir et al., 2016)[2] and the *Batterie d'évaluation des troubles du langage dans les maladies neurodégénératives* (GRÉMOT – Bézy et al., 2016) were administered in both languages. All deaf participants were successful on the BECLA subtests adapted into LSQ and failed the same tests in spoken French. These results indicate that

participants were sign language users and did not rely on spoken French to communicate. We acknowledge the fact that the current study did not make it possible to investigate the effect of ethnicity on spatial cognition of deaf signers.

Material

All participants completed four computerized spatial tasks that covered the four subcomponents of spatial cognition: perspective-taking, spatial perception, spatial visualization, mental rotation.

Perspective Taking/Spatial Orientation test (PTSOT: Hegarty & Waller, 2004). The PTSOT was used to assess perspective-taking ability. For this test, participants viewed drawings of seven common objects (car, stop sign, house, cat, flower, tree and traffic light) that were displayed in a specific layout that appeared in the upper-left quadrant of the screen. In the upper-right quadrant, participants viewed a circle that contained two of the seven objects from the left quadrant. One of the objects was positioned in the center of the circle while the 2nd object was positioned at the top of the circle. The two objects were connected by an arrow. At the bottom of the screen, there was a box with an LSQ signer giving instructions for the current set of stimuli. For each test item, participants were instructed to imagine themselves in the upper-left layout: (1) in the same position as the object that appeared at the center of the circle and (2) facing a second object that appeared at the top of the circle. While imagining this spatial configuration they had to draw a line with their index finger showing the relative direction of a third object named by the LSQ signer in the video instruction. For example, participants were instructed to imagine that they were standing in the cat's position, facing the tree. From that perspective, they were asked to draw a line in the direction of the car (i.e., the third object named by the LSQ signer) by moving their finger on the monitor from the center of the circle to the third object placed on the circle's circumference. Participants viewed the video-instructions twice: at first, the signed instructions appeared as a full-screen presentation. Then, the size of the video was reduced, and the test items also appeared on the screen. The task consisted in drawing a line for 12 stimuli presented consecutively. Each participant completed one practice trial. Six of the 12 items required a perspective change of more than 90°, and six required a change of 90° or less. The

score for each trial was determined according to the absolute angular disparity (AD) in degrees between the response provided and the expected correct response using Heron's formula and trigonometric functions based on the coordinates of participants' answer extracted from the E-Prime log (Psychology Software Tools, Pittsburgh, PA). The mean performance was computed for the 12 items. For a more detailed analysis of perspective-taking skills, the potential effect of magnitude of perspective change involved two scores: i) the AD in cases where a perspective change of 90° or less was required (on both sides), and ii) AD with perspective change equal or greater than 91°. In addition, the proportion of answers (lines traced) given from a frontal perspective (i.e., the two upper quadrants of the circle) were compared to the rear perspective (i.e., the two lower quadrants of the circle).

Computerized rod and frame test (CRFT: Docherty & Bagust, 2010). The CRFT (version 3.2) was used to assess spatial perception ability through the verticality of lines. In this test, the participant had to adjust a tilted linear marker (rod) under two conditions: in isolation on a dark background or embedded within a square frame. The participant was instructed to move the rod until it was vertical, independently of surrounding information (e.g., tilted frame). The orientation of the frame and the rod varied (frame: 0°, 18°, -18°, absence of frame; rod: 20°, -20°). Participants adjusted the rod using the right and left button of a computer mouse. The computer screen was placed 70 centimeters in front of the participant. To constrain their dependence on the visual field, participants wore a pair of goggles from Low Vision Simulators (model R104), reducing their visual field to a tunnel of 20°. Lighting in the experimental room was reduced to its minimum. The test includes 18 trials. Performance errors were calculated based on the deviation (in degrees) of the rod relative to the expected response (invariant = 0°). To be awarded a point, participants needed to place the rod at an angle of ±2° of inclination. Means of absolute angles (e.g., $+3.5^{o}$, $-4{,}5^{o}$, $+2.0^{o}$, etc.) were analyzed for two conditions: i) sensitivity to the initial rod's angle ($rod_{-20^{o}}$; $rod_{+20^{o}}$) and, ii) sensitivity to the initial angle of the frame ($frame_{-18^{o}}$; $frame_{+18^{o}}$; $frame_{0^{o}}$; $frame_{\emptyset}$).

Card Rotation test (CRT: Ekstrom et al., 1976). This test was used to assess mental rotation ability. In this task, a two-dimensional target figure is displayed on the left of the screen, followed by eight similar figures. Participants were instructed to identify, by touching the tactile screen, all the figures that represented a rotation of the target figure, avoiding those involving a mirror

effect, with or without a rotation. On each trial, correct answers can vary between two to seven figures. The test includes 20 trials. Performance was calculated by awarding one point for each correct identification and deducting one point for each incorrect answer. Group differences were analyzed in terms of the mean number of correct identifications as well as the mean number of incorrect identifications.

Revised Minnesota Paper Form Board test (r-MPFBT: Likert & Quasha, 1941). This test was used to assess spatial visualization ability. It is comprised of multiple-choice test items that require the participant to manipulate two-dimensional geometrical shapes cut into two to five segments. For each item, the participant had to look at the target figure cut into fragments (upper left corner of the screen) and touch on the tactile screen the correct option (choices: A-E) showing what the figure would look like if all the pieces were put together. The level of difficulty increased from one item to the next. This test comprised 64 trials. Each correct answer was awarded one point. Differences between group performances were compared under two conditions: i) lower complexity items with 2-3 segments and ii) higher complexity items with 4 or 5 segments.

The stimuli for the CRFT were programmed with Python 2.7 software (Docherty & Bagust, 2010). E-Prime 3.0 software (Psychology Software Tools, Pittsburgh, PA) was used to program the stimuli for the three other tests. Automatic data collection was made with a 14'' Lenovo ThinkPad Yoga X1, enabling data collection through the touchscreen and mouse device. A meta-analysis performed by Techentin et al., (2014) on the effect of age on spatial abilities showed that administration settings, such as the administration of a spatial task through a paper-and-pencil or a computer, are not a significant moderator of the aging effect. In order to limit any potential effect of technology, touch-screen device was selected instead of a regular computer using a mouse and a keyboard. A mouse was only used for the CRFT task. For all tasks, a trial phase of one to eight items allowed the older adults to familiarize themselves with the movement that had to be performed on the screen (line to trace or simple contact) or the manipulation of the mouse. There was no time restriction for all four tasks.

Procedure

This study followed the principles established in the Helsinki Declaration and requirements of the Ethics Committee for Aging-Neuroimaging Research of the *Centre de recherche de l'Institut universitaire de gériatrie de Montréal* (CRIUGM). All the participants voluntarily signed a consent form before taking part in the investigation. Test sessions took place at the participants' home, in a private room of a public building (e.g., a library) or at the CRIUGM, based on their convenience. The whole test protocol took between 1:30 and 2:30 hours to complete (divided into two sessions). The time required to perform the four experimental tasks was approximately one hour.

Results

For PTSOT, a two-way mixed ANOVA showed a significant interaction between Magnitude of perspective change (⩽90° or ⩾91°) and Group (younger vs older adults) $F(1, 38) = 10.00$, $p = .003$, $\eta_p^2 = .208$, indicating a significant difference of AD between the younger and older adults. Younger signers ($M = 24.52$, $SE = 1.99$) outperformed the older signers ($M = 53.77$, $SE = 3.08$), $t(38) = -7.98$, $p < .000$. A large effect size was observed ($r = .79$; Cohen, 1988; 1992). When a shift of perspective was required, the mean performance of younger signers were: for angles ⩽90°, $M = 21.57$, $SE = 2.65$; and for angles ⩾91°, $M = 27.47$, $SE = 2.44$. The older signers' performance on the same tasks were: for angles ⩽90°, $M = 40.42$, $SE = 3.32$; for angles ⩾91°, $M = 67.12$, $SE = 5.07$. For both angles, the group of younger participants performed better than older participants (for items with perspective changes ⩽90°, $t(38) = -4.59$, $p < .000$, $r = .60$; for items with perspective changes ⩾91°, $t(38) = -7.05$, $p < .000$, $r = .75$). For both perspective changes, a large effect size was observed. When only data for older signers was considered, significantly larger AD were observed for items requiring a ⩾91° perspective change compared to those requiring a ⩽90° perspective change, $t(19) = 4.63$, $p < .000$, $r = .73$. This within-group comparison was not significant when the data obtained from the younger participants were considered, $t(19) = 1.87$, $p = .078$, $r = .39$ (Figure 1). Finally, analyses were conducted to compare the predominance of the perspective adopted by each group of participants (i.e., frontal vs. rear perspective). A two-tailed t-test revealed that the responses of older adults were more frequently in the two upper quadrants ($M = 8.25$, $SE = .62$) than those of the younger adults ($M = 6.10$, $SE = .38$), $t(38) = -2.95$, $p = .005$, $r = .49$. A large effect size was observed.

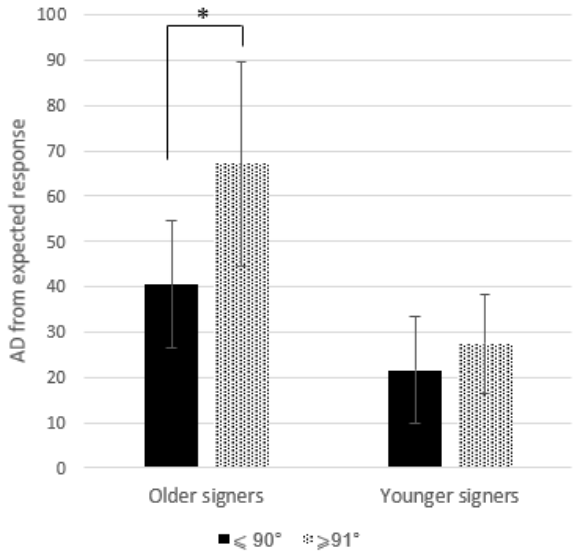

Figure 1. Group comparison of AD for items requiring a perspective change of more or less than 90°.

In terms of global performance, younger signers performed significantly better (*M* = 14.35, *SE* = .73) than older signers (*M* = 10.25, *SE* = 1.06) in the CRFT, $t(38) = 3.18$, $p = .003$, $r = .49$. When the rod tilts ($Rod_{-20°}$; $Rod_{+20°}$) were considered, results of two-tailed t-tests revealed that the older signers' performance was poorer ($Rod_{-20°}$, *M* = 6.97, *SE* = .77; $Rod_{+20°}$, *M* = 6.64, *SE* = 1.40) than that of younger signers ($Rod_{-20°}$, *M* = 3.01, *SE* = 1.49; $Rod_{+20°}$, *M* = 2.54, *SE* = 0.56). This difference was observed for both rod conditions: $Rod_{-20°}$, $t(38) = -2.36$, $p = .024$, $r = .36$, and $Rod_{+20°}$, $t(38) = -2.71$, $p = .01$, $r = .40$. The effect size was medium to large. Within-group performances showed no difference between the $Rod_{+20°}$ and $Rod_{-20°}$ conditions (older signers: $Rod_{-20°}$, *M* = 6.97, *SE* = 1.49, $Rod_{+20°}$, *M* = 6.64, *SE* = 1.40, $t(19) = .24$, $p = .81$, $r = .05$; younger signers: $Rod_{-20°}$, *M* = 3.02, *SE* = .77, $Rod_{+20°}$, *M* = 2.54, *SE* = .56, $t(19) = 1.16$, $p = .26$, $r = .26$). When the frame condition was considered ($Frame_{-18°}$; $Frame_{+18°}$; $Frame_{0°}$; $Frame_{\emptyset}$), the results of older participants ($Frame_{\emptyset}$:*M* = 5.29, *SE* = .93; $Frame_{+18°}$:*M* = 9.59, *SE* = 2.22) revealed a higher degree of disparity from the expected 0° target than those of the younger participants ($Frame_{\emptyset}$, *M* = 1.97, *SE* = .43; $Frame_{+18°}$, *M* = 2.59, *SE* = .52). The differences were significant under both conditions: for $Frame_{\emptyset}$, $t(38) = -3.24$, $p = .002$, $r = .47$; and $Frame_{+18°}$, $t(38) = -3.07$, $p = .004$, $r = .45$. Group differences were not

significant for the two other frame conditions: $Frame_{0°}$, $t(38) = -1.43$, $p = .161$, $r = .23$; and, $Frame_{-18°}$, $t(38) = -1.65$, $p = .108$, $r = .26$.

For CRT, the global performance of younger signers ($M = 66.75$, $SE = 1.74$) was significantly better than that of the older signers ($M = 49.35$, $SE = 4.35$), $t(38) = 3.71$, $p = .001$, $r = .52$. A large effect size was observed. A more detailed analysis of the data revealed a significantly higher number of correct items identified by younger signers ($M = 74.95$, $SE = 1.30$) compared to older signers ($M = 61.60$, $SE = 2.74$), $t(38) = 4.39$, $p < .000$, $r = .58$. When the number of incorrect responses was considered, the comparison between the two groups failed to reveal a significant difference (younger, $M = 8.10$, $SE = 1.33$; older, $M = 11.65$, $SE = 1.62$), $t(38) = -1.69$, $p = .099$, $r = .26$).

Performance on the r-MPFBT was lower for the group of older signers ($M = 37.35$, $SE = 1.94$) compared to their younger peers ($M = 46.00$, $SE = 1.81$), $t(38) = 3.27$, $p = .002$, $r = .47$. When only test items with a high level of complexity were considered (four to five segments), younger signers ($M = 20.70$, $SE = .91$) outperformed older signers ($M = 14.90$, $SE = 1.14$), $t(38) = 3.99$, $p < .000$, $r = .54$. For this analysis, a large effect size was observed. Analysis of items with a lower level of complexity (two to three segments) also revealed an advantage for the younger signers ($M = 25.30$, $SE = 1.01$) over older ones ($M = 22.45$, $SE = .92$), $t(38) = 2.09$, $p = .04$, $r = .32$. For this analysis, a small effect was observed. A summary of these results is presented in Table 2.

Table 2

Comparison of older and younger signers: mean (M) and standard error mean (SE) for PTSOT, CRFT, CRT and r-MPFBT

	Older signers		*Younger signers*		
	M	(SE)	M	(SE)	*t*
PTSOT (degree difference)					
Global	53.77	(3.08)	24.52	(1.99)	-7.98***
AD if ⩽90°	40.42	(3.32)	21.57	(2.65)	-4.59***
AD if ⩾91°	67.12	(5.07)	27.47	(2.44)	-7.05***
Frontal perspective	8.25	(.62)	6.10	(1.68)	-2.95**
CRFT (M of correct response)					
Global	10.25	(1.06)	14.35	(.73)	3.18**
$Rod_{-20°}$	6.97	(.77)	3.01	(1.49)	-2.36*
$Rod_{+20°}$	6.64	(1.40)	2.54	(0.56)	-2.71*
$Frame_{-18°}$	5.11	(.86)	3.16	(.82)	-1.65
$Frame_{+18°}$	9.59	(2.22)	2.59	.52	-3.07**
$Frame_{0°}$	6.61	(2.09)	3.32	(.95)	-1.43
$Frame_{\emptyset}$	5.29	(.93)	1.97	(.43)	-3.24**
CRT (M of correct response)					
Global	49.35	(4.35)	66.75	(1.74)	3.71**
Correct	61.60	(2.74)	74.95	(1.30)	4.39***
Uncorrect	11.65	(1.62)	8.10	(1.33)	-1.69
r-MPFBT (M of correct response)					
Global	37.35	(1.94)	46.00	(1.81)	3.27**
High complexity items	14.90	(1.14)	20.70	(.91)	3.99***
Low complexity items	22.45	(.92)	25.30	(1.01)	2.09*

AD = Angle disparity; M = mean; SE = Standard error mean; *p <.05; **p <.005; ***p < .000

Although sex differences had been reported for tasks involving spatial perception (Linn & Peterson, 1985; Voyer et al., 1995), no sex differences were observed on any of the spatial ability tests used in this study (see Table 3).

Table 3

Comparison of male and female: mean (M) and standard error mean (SE) for PTSOT, CRFT, CRT and r-MPFBT

	Male		*Female*			
	M	(SE)	M	(SE)	*t*(38)	*p*
PTSOT	36.38	(4.31)	41.91	(4.07)	.93	.357
CRFT	13.45	(0.92)	11.15	(1.06)	-1.64	.109
CRT	61.05	(2.74)	55.05	(4.63)	-1.114	.272
r-MPFBT	42.55	(1.82)	40.80	(2.37)	-.586	.561

Discussion

The aim of the present study was to investigate the effects of age on spatial cognition tasks in deaf signers. Specifically, four spatial abilities were considered: perspective-taking, spatial perception, mental rotation and spatial visualization. Possible implications of the present results on the impact of cognitive changes in sign language production and comprehension will be discussed.

Our results are consistent with the overall effect of age on perspective-taking, spatial perception, spatial visualization and mental rotation. The group of younger signers was more accurate on all four tasks. This result is consistent with previous research that investigated spatial abilities as a function of age in the hearing population (for a review, Techentin et al., 2014). In hearing participants, this effect extends to other subdomains of spatial cognition, such as spatial navigation and image generation (Klencklen et al., 2012). It would be interesting to investigate spatial navigation and image generation abilities among older deaf signers. As is the case for

hearing non-signers (Akiyama et al., 1985; Ariel & Moffat, 2017; Borella et al., 2014; Hertzog & Rypma, 1991; Inagaki et al., 2002; Robert & Tanguay, 1990; Zancada-Menendez et al., 2016), the present results revealed an overall age effect on spatial abilities among deaf signers.

Higher perspective shifts were particularly more difficult for older deaf adults than younger deaf adults. Further, based on the proportion of lines traced in the two upper quadrants of the circle, it appears that older adults adopt a frontal perspective, while younger adults can use both frontal and rear perspectives. This suggests that older signers are more likely to adopt egocentric frames of reference (Zhang et al., 2014). Thus, they would tend to imagine the position of an object from their actual relative position, although variations might be observed with possible shifts in the shoulder or the head angle, which could facilitate the shift of perspective (self-to-object perspective). In comparison, younger adults did not exhibit this preference; they could switch from egocentric to allocentric frames of reference (*M* = 6.10/12 items). This indicates that younger signers can imagine the position of an object from another perspective (object-to-object perspective), independent of their actual perspective (Zhang et al., 2014).

Concerning the CRFT, the results showed that older signers obtained lower scores than younger signers under the $\text{Frame}_{\emptyset}$ condition. However, both groups performed similarly under the $\text{Frame}_{0^{\circ}}$ condition. These results suggest that older signers tend to rely more on salient cues available in their visual environment when they need to establish the verticality of lines, compared to younger signers. A similar age-related pattern of field dependence in spatial perception has been reported in older hearing participants (e.g., Agathos et al., 2015; Eikema et al., 2012; Kausler et al., 2007; Kobayashi et al., 2002). It is somewhat surprising that older signers' performance was significantly reduced compared to younger signers under the $\text{Frame}_{+18^{\circ}}$ condition, but not under the $\text{Frame}_{-18^{\circ}}$ condition. It is known that the contrast between the orientation of the rod and the frame side (clockwise/counterclockwise; degree of inclination, etc.) can have an effect on performance in rod and frame tasks (Wapner & Demick, 1991); indeed, tilting of the frame will induce an illusion of a rod tilt in the opposite direction (Dyde & Milner, 2002). Since the stimuli were chosen to represent all conditions equally (i.e., +Rod, +Frame; +Rod, -Frame; -Rod, +Frame; -Rod, -Frame), the expected illusion effect cannot justify the difference

between the $Frame_{+18^o}$ and $Frame_{-18^o}$ conditions that was observed between the two groups. Furthermore, it should be noted that the distribution of hand dominance among the members of both groups was similar (older signers: 14 right-handed, 5 left-handed, 1 ambidextrous; younger signers: 16 right-handed, 4 left-handed). Thus, it is unlikely that this result can be explained by handedness. Nonetheless, previous investigators have shown that both hemispheres specialize in the processing of different types of spatial relations and representations (Hellige & Michimata, 1989; Kosslyn et al., 1988; Kosslyn et al., 1995; Rybash & Hoyer, 1992). While the left hemisphere encodes categorical spatial relations (e.g., under, beside), the right hemisphere tends to be more efficient in the encoding of coordinate spatial relations (e.g., metric, degree of inclination). The lower performance of older signers in the evaluation of verticality in the $+18^o$ frame condition may indicate an age-related weakness of the left hemisphere in the processing of coordinate spatial relation. Future investigations are required to gain further insights into these results.

The number of correct matches observed in the CRT indicates that younger adults achieved a significantly higher level of performance than older adults. Participants were informed that incorrect matches would be penalized. Groups did not differ in the number of incorrect identifications. This result could indicate that the older group was more conservative when faced with more challenging test items. Instead of risking an incorrect match that would lower their scores, older signers might have refrained from answering. However, the non-response pattern, where 54% of the figures were unselected by older adults compared to 48% of figures for younger adults, shows a small difference and partially supports this explanation.

In the r-MPFBT, younger adults performed better than older adults, regardless of the complexity of the sorting task (2-3 vs. 4-5 figures). In addition, all participants were more accurate in trials involving the manipulation of fewer segments (2-3), meaning that older and younger adults had more difficulty in the more complex trials (4-5 segments). This suggests that some spatial visualization tasks involving additional cognitive resources required to process complex items might not be sensitive to age-related differences.

Scores of female participants tended to be lower than those of male participants in all experimental tasks. However, in all these tasks, the difference did not reach significance. This

result contrasts with previous studies that investigated the impact of sex on spatial abilities. In the hearing population, there is a significant advantage for males over females (Jansen & Heil, 2009; Zancada-Menendez et al., 2016). It is worth noting that in all the experimental tasks of the present study, no time constraint was imposed on participants. Emmorey et al. (1998) failed to observe a significant sex difference in a mental rotation task that did not limit response time. However, when a fixed response time was set, Secora and Emmorey (2019) reported a better performance of males compared to females for the PTSOT, as well as for a revised version of the MRT. This suggests that, in the absence of a time constraint, females perform as well as males on tasks that measure spatial abilities. It should be noted that our analysis was made by pooling the two age groups together for each sex in order to increase the sample size. Sex was not planned as an independent variable in the present investigation. In future research studies, it may be of interest to investigate the effects of age on sex on spatial perception. Given the limited knowledge on the sex/gender interaction and the scope of stereotype threats on this interaction, only a partial interpretation can be proposed for the difference observed in previous studies and the current findings.

Potential Implications for Sign Language Production and Comprehension

As described earlier, sign and spoken languages differ intrinsically in their linguistic modality. As a visuo-spatial language, sign languages employ mechanisms of spatial cognition to produce and interpret language. Therefore, it can be expected that cognitive changes that occur as a function of aging may interfere with the processing of linguistic information among signers.

The signer's space is used to express multiple relations between linguistic entities, such as grammatical relations (e.g., verb agreement, inflectional and derivational morphological systems: Bellugi et al., 1990), description of topographic relations (i.e., representation of distance on a reduced scale: Quinto-Pozos et al., 2013), or for depictive functions (i.e., representation of a distance on a life-size scale: Quinto-Pozos et al., 2013). In doing so, signers use their spatial perception abilities to perceive relationships between objects from their own perspective (Linn & Peterson, 1985).

Most documented sign languages are described as having a signed letter system complementary to lexical signs to express proper names and words that are not associated to a sign (e.g., for LSQ: Dubuisson et al., 2000; for American sign language: Mulrooney, 2002; for British sign language: Sutton-Spence & Woll, 1999). This fingerspelling system consists of complex and subtle manual configurations associated to alphabet letters of the surrounding spoken language (Bhat et al., 2016; Talbot & Haude, 1993). The visual identification of those quickly coarticulated letter-signs requires a high level of spatial visualization (Talbot & Haude, 1993). Analysis of fingerspelled words requires a rapid multistep mental manipulation of a sequence of complex configurations that leads to the identification of the graphic form of words and the retrieval of their meaning.

For sign comprehension in traditional face-to-face interactions, the addressee interprets a signed message from the signer's point of view (Pyers et al., 2015). To accomplish this, the addressee must mentally rotate the signs produced in space to access the right mental representation of the signer's discourse (Brozdowski et al., 2019). Therefore, the addressee uses his/her mental rotation ability to reverse his perspective (i.e., to put himself in the signer's perspective).

Sign languages are also known to use constructed action structures to represent the role, thoughts, affects or utterances of referents (Cormier et al. 2015; Goswell, 2014). In these structures, signers use multiple articulators such as the face, head, eye gaze and torso to shift roles when they adopt another person's perspective. For the person producing the discourse, these constructions require the adoption of another referents' perspective in order to represent it (e.g., looking upwards to adopt the perspective of a dog seeking his master's attention). The addressee will accomplish the same perspective shift but add to the existing cognitive load the 180° mental rotation required in a conventional face-to-face conversation.

Spatial mechanisms involved in sign languages contribute to the creation and manipulation of mental images. As shown by the results of the present investigation, there is an age-related alteration of spatial perception, spatial visualization, mental rotation and perspective-taking in signers. Therefore, we can speculate that these changes might affect

language production of older signers as well as their comprehension and expression of spatial relations among entities (grammatical, topographical and depictive function), of complex forms such as fingerspelled words and of discourse mapping due to changes in mental rotation and perspective-taking abilities. The impact of the aging process on linguistic structures of sign languages is still unknown. So far, there is no evidence of the magnitude of the age effect on, for example, the topographic use of space (classifiers, depicting verbs, etc.) compared to the grammatical use of space.

Concerning sign language production, the findings in the available literature do not provide sufficient evidence to dress a comprehensive picture of the potential variations in sign language processes as a function of age. It is well known that, in the hearing population, age-related biomechanical changes influence movement choices in amplitude, frequency and rapidity (Carmeli et al., 2003; Chaput & Proteau, 1996; John et al., 2009; Ketcham & Stelmach, 2004). John et al., (2009) also reported that the amount of effort expended varies as a function of the movement that is made. Because sign languages are primarily expressed by hand and arm movements in space, signs used by older adults may change as a consequence of effort required to produce them or biomechanical constraints that accompany aging. In addition, changes in hand motion, especially fine motor skills, could lead to an alteration of hand coordination and fingerspelling skills in older signers. Investigations on how older adults adapt and adjust their movements in response to potential perceptual and physiological constraints would provide interesting insights on how the production of sign languages is modified through aging.

In a study involving a sample of 13 older deaf adults (aged 64 to 84) using French sign language who were recorded with a three-dimensional motion-capture system, it has been shown that the signing rate of older signers tends to slow down and that the standard duration of signs increases as a function of age (Blondel et al., 2019). Movement amplitude and segment distribution (e.g. rotation angle of certain segments) can also be considered as measurements of prosodic characterization for the older signers' production (Blondel et al., 2019). Although these insights concerning the production of sign language in older signers contribute to the general understanding of how they manage spatial attributes as a function of time, the trade-off between clarity of the message and articulatory cost is still unclear.

Overall, our research provides new insight on spatial processing in older and younger signers. We showed evidence that aging influences spatial cognitive functioning in signers. More detailed analysis showed that older signers tend to rely on an egocentric frame of reference for the processing of perspective changes. They also appear to be more field-dependent on salient environmental cues for spatial perception compared to younger signers. We speculate that these changes in cognition might have an effect on sign language production and comprehension. Future cross-sectorial studies should investigate the impact of changes in spatial abilities on linguistic data and consider the potential impact of age-related biomechanical changes that affect upper limbs through aging.

Notes

[1] The Québec Sign Language Cognitive Screening Test (LSQ-CST) is a cognitive screening test administered in about 30 to 40 minutes. The seven domains of cognition included in the test are orientation, attention, delayed recall, verbal fluency, language, visual-spatial abilities and executive function. The total score of the test is 110 points. The BSL-CST adapted in LSQ have its own limits. The test was culturally and linguistically adapted in LSQ with Deaf consultants. However, the test was not normalized prior to its use. The main objective underlying the use of this cognitive test was to ensure that the deaf participants performing the spatial tasks did not have cognitive difficulties limiting their reactiveness and the responsiveness.

[2] Specifically, subtests included: i) pairing of images based on their semantic, ii) noun and verb naming, iii) repetition of words/signs, iv) repetition of non-words/non-signs, v) pairing of words/signs with images and vi) syntactic comprehension.

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Chapter 4 – Empirical study 2

Paper 3: Spatial Abilities: Effects of Age and Use of a Sign Language on Spatial Cognition

The format of this paper is conformed with the journal's standards in which it was submitted, with the exception of figures and tables which are placed in their accurate place in the text to facilitate the reading.

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Abstract

Research on brain and cognitive function has demonstrated differences between deaf individuals who use a sign language to communicate and hearing individuals. Being visual-spatial in nature, sign languages rely on spatial mechanisms for the production and the perception of language. It has been argued that spatial cognition, shown to depend on language, could be influenced by the use of a sign language. Investigators have failed to show consistently that there exists a relationship between performance on spatial ability tasks and sign language experience. Given that spatial abilities are known to deteriorate as a function of age among older hearing adults who use a spoken language to communicate, could the lifelong use of a sign language as a primary mode of communication serve to prevent age-related changes in spatial abilities? The aim of this study is to investigate whether there are differences among signers (deaf and hearing) and non-signers of two age groups (younger and older adults) in terms of performance on spatial abilities tasks. More precisely, this study investigates the subskills of spatial perception, spatial visualization, mental rotation, and perspective-taking in 120 participants (60 older adults [20 deaf signers, 20 hearing signers and 20 hearing non-signers] and 60 younger adults [20 deaf signers, 20 hearing signers and 20 hearing non-signers]). Participants performed seven psychometric tasks assessing the four spatial subskills. Scores were recorded in terms of accuracy and response time. Consistent with the results of previous studies on the age-related effect on cognition, the accuracy data revealed that the younger participants constantly performed better than the older participants across all tasks. In addition, older signers (deaf and hearing) outperformed older non-signers in spatial visualization tasks, suggesting a lifelong beneficial effect of sign language use. Further research is needed to better understand the differences in spatial processing between deaf signers and hearing signers.

Keywords: Aging; Bimodal bilingualism; Deafness; Sign language; Spatial abilities;

Introduction

When investigating cognitive abilities among the deaf population, several factors must be considered to fully understand the separate effects of auditory deprivation and the use of a sign language. Concerning this specific sub-group of deaf signers (i.e., individuals who use a sign language to communicate), the recent literature provides evidence of differences in their brain and cognitive function compared to individuals who hear, and use spoken languages. One of the most prominent explanations for these differences is that transmission of linguistic information via a visual-spatial modality is different from the auditory-oral mode with regards to the biological mechanisms used to communicate. Despite the apparent differences between signed and spoken languages, these modes of communication share common formal properties in their structural components at the sublexical levels, namely phonology and morphology, and at the syntactic level (Meier et al., 2002; Sandler & Lillo-Martin, 2006; Sutton-Spence & Woll, 1999). Neuroimaging studies have revealed similar brain site activations (namely, frontal and temporoparietal areas) for processing and producing language regardless of the linguistic modality used (Neville et al., 1998; Payne et al., 2019; Petitto et al., 2000). Also, studies have revealed that signs and words activate similar neuroanatomical areas associated with phonological processing (MacSweeney et al., 2008), lexical retrieving (Emmorey et al., 2003) and representations of semantic categories (Evans et al., 2019). Notwithstanding these findings, differences in cognitive functioning have been reported between deaf signers and users of spoken languages in several domains such as peripheral and central attentional resources (Chen et al., 2010; Dye, 2014; Proksch & Bavelier, 2002), mental image generation (Emmorey & Kosslyn, 1996), face recognition (Bellugi et al., 1990), haptic orientation processing (van Dijk et al., 2013) and motion detection (Neville & Lawson, 1987). These findings suggest that linguistic background, or in some cases auditory experience, impacts cognitive function.

Based on the sensory compensation hypothesis, it is assumed that auditory deprivation enhances perception in other senses such as vision and haptic feedback (Bavelier et al., 2006). Several studies have investigated the potential cognitive advantage of signers in the visual domain, including for example visual attention (Bavelier et al., 2006; Dye, 2014; Parasnis & Samar, 1985), visual contrast sensitivity (Finney & Dobkins, 2001) and motion detection in peripheral

vision (Neville & Lawson, 1987). It has been suggested that deaf signers possess an enhanced reactivity to visual stimuli (for a review: Pavani and Bottari, 2012). However, there is no consensus on whether the lifelong use of a sign language can influence visuospatial or spatial processing among signers. The lack of consensus regarding this issue might be explained by the heterogeneity of the participants recruited for these studies. Alternatively, it may be due to the elusive definitions given to the term 'spatial abilities' conflating visual and spatial processes (McGee, 1979). In this article, the terms "spatial processing" or "spatial abilities/skills" will be used to refer to cognitive processes of spatial abilities and visuospatial abilities.

Spatial abilities, as components of spatial cognition, refers to a multidimensional construct that includes interrelated subskills (or factors, see Hegarty & Waller, 2005). In their meta-analysis Linn and Petersen (1985) identified three broad categories within the main domain of spatial abilities: i) *spatial perception* (SP: the ability to perceive a relation between objects from one's perspective and despite distraction), ii) *spatial visualization* (SV: the ability to perform a multistep manipulation of complex information presented spatially) and, iii) *mental rotation* (MR: the ability to mentally rotate a two- or three-dimensional visual stimulus in space). A fourth aspect of spatial processing, *perspective-taking* (PT), was identified by Lohman (1988). It refers to the ability to imagine the appearance of an entity (someone or something) from a different perspective. These four spatial subskills are used to perform everyday activities. For example, SP helps one navigate in a furnished space without bumping into any surrounding objects; SV makes it possible to assemble multiple pieces of furniture to make a chair, as if completing a puzzle; MR makes it possible to read a map and identify the directions to a specific location without having to physically orient oneself geographically towards this direction; PT allows one to perceive appearance from someone else's point of view, this person being in a different position and orientation than the viewer. These processes are distinct from other aspects of cognition mediating spatial abilities, such as visuospatial memory, visuospatial learning and visuospatial attention. Spatial abilities are also known to rely on other cognitive processes, including speed of processing and central executive function (Hegarty & Waller, 2005).

Being visual-spatial in nature, sign languages rely on spatial mechanisms to produce and perceive language. The signer's space is used to express grammatical relations (e.g., verb

agreement, inflectional and derivational as morphological systems : Bellugi et al., 1990), to express spatial relationships among entities in a topographic relation (i.e., representation of distance on a reduced scale: Quinto-Pozos et al., 2013), or for depictive functions (i.e., representation of a distance on a life-size scale: Quinto-Pozos et al., 2013). In addition, syntax makes use of the spatial properties of sign language to associate referents denoted by lexical or grammatical elements (nominal, pronominal, anaphoric, etc.) to invisible spatial marks (loci) in the signer's space (Rinfret, 2009). The directionality of the verb movement between these loci provides information concerning the referents' role (Bellugi et al., 1990). Referents previously associated to a locus, sometimes as far back as a few sentences, may also be reactivated with a pronominal referent (e.g., pointing to the locus where the referent was associated). In other words, the physical space used in sign language production conveys meaning.

Related to the comprehension of sign language, engaging in a sign language conversation requires a considerable amount of cognitive spatial processing for the addressee. Because the message is conventionally produced from the signer's perspective (Pyers et al., 2015), the addressee must execute a shift in perspective to access the intended mental representation of the scene described by the signer (Brozdowski et al., 2019; Emmorey et al., 1998). In the case of a face-to-face conversation, the perspective shift requires a 180° rotation in order to obtain the signer's perspective as opposed to the addressee's own perspective. For example, consider the scene depicted in Figure 1. From the signer's point of view, the cat is located at the right side of the tree. However, due to the mirror effect of face-to-face communication, from the addressee's perspective, the cat is located to the left of the tree. To correctly comprehend the disposition of what is being signed, the addressee must execute a 180° mental rotation.

Figure 1

Mirror Effect of Face-to-Face Communication in Sign Language

Note. Signer producing the sign TREE with his left hand, and CAT with his right hand, with the addressee mentally mapping the disposition of signs by executing a 180° rotation the disposition of the signs.

Sign languages are also known to use constructed action structures (on the diversity of labels used, see : Cormier et al., 2015). These structures are expressed by multiple articulators such as the face, head, eye gaze and torso. The function of these structures is to represent the role, thoughts, affects or utterances of the referents (Cormier et al., 2015; Goswell, 2014). Janzen (2017) added that these constructions "contain overt markers of perspectivization in that the signer conceptualizes the perspective of a referent and has an embodied view of the space around her/[his] in which articulation takes place" (p.11). In other words, when these constructions are produced by the signer, the addressee must produce the 180° mental rotation required in a conventional face-to-face conversation and consider the perspective shift embodied by the signer to represent the referent. Therefore, users of a sign language need to create and manipulate mental images from diverse angles and perspectives to produce and comprehend sign language.

Based on this information, it has been argued that spatial cognition, which is dependent on language (Levinson, 2003; Majid et al., 2004), could be influenced by the use of a sign language.

Spatial processing could be expected to be superior among signers than among non-signers. However, investigators have failed to consistently show that there exists a relationship between performance on spatial ability tasks and sign language experience. More precisely, investigators have failed to show an advantage of signers in SP ability in terms of accuracy. For example, no difference in performance on SP tasks were reported between signer and non-signer children and adolescents (McDaniel, 1980; Robertson & Youniss, 1969). However, Emmorey et al. (1993) and Emmorey and Kosslyn (1996) showed an advantage of signers over non-signers in terms of response time. Using the same stimuli, both experiments showed that signers responded more quickly than non-signers when participants were required to identify if a X mark overlapped a memorized upper-case letter presented with block in a grid or between brackets. More precisely, signers had shorter response times in the complex condition (when the letters were formed of four or more segments in the grid [P, J, O, S, G] : Emmorey et al., 1993) and, when the stimuli were presented initially to the right hemisphere compared to the left (Emmorey & Kosslyn, 1996).

For SV, Blatto-Vallee et al. (2007) reported an advantage for non-signer students beginning in grade seven and extending to the bachelor's degree when compared to signers of the same educational level. In a more recent study, Marschark et al. (2015) compared the performance of two deaf groups (deaf users of a cochlear implant [CI]; deaf nonusers of CI) and two hearing groups (hearing non-signers; hearing signers) using the Spatial Relations task (subtest of the Woodcock-Johnson III [WJ-III] test of cognitive abilities: Woodcock et al., 2001) and an Embedded Figures task (Hauptman & Eliot, 1986). The results revealed no significant differences in performance between the two deaf groups, regardless of whether they used CIs or hearing aids. Similarly, there were no differences between the two hearing groups, regardless of whether or not they knew sign language. However, the results did show a significant difference between the hearing participants and the deaf participants. Specifically, the hearing participants outperformed deaf participants in SV ability. An absence of differences between signers and non-signers was also reported by Hauser et al. (2006) in a Paper Folding and Cutting test (Thorndike et al., 1986).

Because MR processes are intrinsically involved in sign language comprehension, it is assumed that signers would exhibit superior MR skills. Contrary to SP and SV abilities, more

studies have reported and advantage of signers over non-signers in MR tasks. MR has been shown to be influenced by general sign language use (Emmorey et al., 1993, 1998) or the time of exposure to a sign language for hearing signers (Talbot & Haude, 1993). Using the Mental Rotations test (Vandenberg & Kuse, 1978), Talbot and Haude (1993) tested three groups of students that differed in exposure to American Sign Language (ASL) through instructions (mean years of ASL instruction = group 1: 0 years; group 2: 0;8 years; group 3: 6;1 years). The investigators reported that both groups who had less than one year of exposure to ASL obtained similar scores and they both performed significantly more poorly than the group that was exposed to ASL for 6;1 years. Therefore, experience with ASL and formal instruction in learning sign language are predictive factors of performance on tasks that measure MR in hearing signers. Using a MR task like the one developed by Shepard and Metzler (1971), Emmorey et al. (1993) showed that the response times of deaf signers was shorter than the response times of hearing non-signers when making a decision requiring a 180° mirror rotation. Emmorey et al. (1998) reported that when MR tasks include linguistic stimuli, signers were more accurate in interpreting information displayed from the narrator's point of view (which require a 180° rotation) than when the interpretation was made from their own point of view (no rotation required). More recently Secora and Emmorey (2019) failed to show group differences between signers and non-signers in terms of accuracy using the revised version of the MR test initially developed by Vandenberg and Kuse (1978) and redrawn by Peters et al. (1995).

Using a PT task, Quinto-Pozos et al. (2013) reported a case study of a deaf adolescent with impaired sign language development. Cognitive, language and PT assessments showed evidence that an impairment in PT ability resulted in atypical ASL acquisition. This was especially so for perspective-dependent structures using space in a topographical function and role shifting. However, it didn't impact the adolescent's use of grammatical structures that didn't require adopting another person's perspective. On the Perspective-Taking Spatial Orientation Test (from Hegarty & Waller, 2004), the participant performed significantly more poorly than proficient deaf signers of her age. The results of this case study suggest that sign language use is partly dependent on PT processing. When testing a non-clinical sample, Secora and Emmorey (2019) reported no

differences in PT performance between adult signers and non-signers. Finally, Howley and Howe (2004) showed no differences between groups of deaf and hearing children on a PT test.

Previous findings suggest that the use of a sign language does not necessarily lead to superior spatial processing. In addition to the fact that there does not exist a consensual theoretical definition of the construct underlying spatial abilities (Borella et al., 2014), several factors related to the sample selection may contribute to the discrepancies observed across studies. They include hearing status and degree of impairment (e.g., deaf, hearing, hard of hearing), history of deafness (e.g., genetic, result of illness), age group (e.g., children, adolescents, adults), primary source of exposure to sign language (e.g., parents, friends, formal instruction), duration of exposure to sign language (e.g., from birth, acquired as a second language, before cochlear implantation), primary communication mode (e.g., signs, lipreading, cued speech, oral+signs), use of hearing devices (e.g., hearing aids, cochlear implants), cognitive abilities and brain health (e.g., impaired sign language development, aphasia, etc.). The experimental procedures used to measure spatial abilities (psychometric tasks, standardized tests, non-standardized experimental tasks) as well as the nature of test stimuli used (linguistic/non-linguistic, abstract/concrete) may also account for the discrepancies in the results reported across studies. A comprehensive review of the existing literature that takes into account all of these factors may provide a better understanding of spatial processing among signers.

It is widely documented that there is an effect of aging on cognition (Anderson & Craik, 2017; Blazer, 2017). Some cognitive skills are maintained and may even improve as a function of normal aging (Harada et al., 2013). This is particularly the case for language skills (Park & Reuter-Lorenz, 2009; Salthouse, 2010) and semantic memory (Rönnlund et al., 2005). Other cognitive skills tend to decline as a function of age, including episodic memory (Rönnlund et al., 2005), selective and divided attention (Carlson et al., 1995), executive function (Wecker et al., 2005) and speed of processing (Harada et al., 2013; Salthouse, 2010). Some investigators have argued that general spatial abilities deteriorate as a function of age (for a review: Techentin et al., 2014) while others have argued that it is not the case (de Bruin et al., 2016; Harada et al., 2013). As a multidimensional concept, it could be assumed that spatial abilities are mediated by other cognitive processes which may change as a function of aging. For example, to some extent,

visuospatial working memory (Kim et al., 2013; Zarantonello et al., 2019), visuospatial attention (Mazaux et al., 1995) and speed of processing (Carlson et al. 1995, Salthouse, 2010) are likely to have an effect on spatial processing as a function of aging (Techentin et al., 2014). In general, studies that have investigated the impact of age on the four subskills of spatial abilities (SP, SV, MR, PT) in hearing participants have shown a decrease in the level of ability and speed of processing of spatial information as a function of aging.

A decline in SP performance beginning early in the fifth decade of life has been reported (Panek et al., 1978; Schwartz & Karp, 1967). Specifically, there is a predominance of egocentric and field dependent determination of space among older adults (Comalli et al., 1959; Gruenfeld & MacEachron, 1975; Schwartz & Karp, 1967). Furthermore, investigators reported that older adults exhibit longer response times when making spatial judgments and when they process information for both categorial (i.e., broad directional relationships – “to the right”, “under”, “in”) and coordinate (i.e., exact location including distance and direction) spatial encoding (Bruyer et al., 1997; Meadmore et al., 2009).

Initially, SV ability declines as a function of age starting at approximately 60 years of age (Hertzog, 1989; Salthouse, 1990). This is followed by a more abrupt decrease in performance at around 70 years of age (Borella et al., 2014). Using a Paper-folding task, an age effect on performance and on metacognitive judgments of performance was reported by Ariel and Moffat (2017). Specifically, younger adults were more accurate on this task than older adults and they expressed a higher level of confidence regarding the accuracy of their responses.

An age-related decline in MR ability as been shown throughout the lifespan. Performance of younger adults on MR tasks are significantly better than those of adults aged 60 years or older (Hertzog, 1989; Hertzog & Rypma, 1991; Inagaki et al., 2002). Several studies have documented this age decline in MR regardless of the type of tasks used (paper-pencil tasks comparing accuracy [e.g., Berg et al., 1982; Inagaki et al., 2002]; chronometric tasks comparing response times [e. g., de Bruin et al., 2016; Devlin, 2001]). However, the performance of older adults showed discrepancies according to the type of task used (e.g., no age-related decline in Vandenberg and

Kuse's Mental Rotations [Borella et al. (2014)] vs age-related decline in Piaget's Three-Mountain Task [Inagaki et al., 2002]).

PT ability is also associated with an age-related decline, starting at about 50 years of age, with a more severe decline observed above approximately 60 years of age (Borella et al., 2014). However, Zancada-Menendez et al., (2016) reported that, compared to younger participants (mean age = 21.36 years), middle-aged participants (mean age = 41.95 years) displayed poorer performances on the simplest items of the Perspective Taking/Spatial Orientation Test (Kozhevnikov & Hegarty, 2001). Thus, it appears that PT ability decreases gradually across the complete adult lifespan and not only in later life. The age effect tends to diminish when the tests items are more complex and require a higher-level of cognitive processing (e.g., when the angle between the orientation of the stimulus and the perspective to be imagined is greater than 90°). This result suggests that there is a limit to the cognitive load induced by PT processing (Kozhevnikov & Hegarty, 2001; Zancada-Menendez et al., 2016).

As mentioned above, spatial abilities are used to manage day-to-day activities. An age-related decline in spatial abilities can have important implications on one's activities of daily living (Hegarty et al., 2006; Techentin et al., 2014). Inversely, life and social experiences lived during the lifespan can influence the cognitive functioning of older adults. The concept of cognitive reserve states that individual differences in cognitive functioning at an older age may result from factors intrinsic to the individual or from life experiences (Stern et al., 2018). When confronted with age-related changes, this diversity of factors has an effect on the ability to adapt or compensate to maintain efficient cognitive functioning (Stern, 2002; Stern et al., 2018). Investigators have highlighted several beneficial activities that contribute to cognitive reserve (Opdebeeck et al., 2016). Based on a series of studies that addressed the cognitive reserve concept, it was suggested that the constant switching between two languages involved in bilingualism helps maintain cognitive control among bilinguals through aging (e.g., Bak et al., 2014; Bialystok et al., 2004). To reach the right target in the desired language, the bilingual individual must control the choice of the correct lexical form in the target language and eliminate competing lexical forms (Bialystok, 2001). In addition, it has been argued that having a higher educational level has protective properties against the memory decline observed as a function of age (Angel et al., 2010; Lee et

al., 2012). A meta-analysis concluded that individuals with a higher level of education maintained their ability level on a wider range of cognitive domains, including visuospatial abilities, language and executive function (Opdebeeck et al., 2016). Also, Salthouse et al. (1990) reported that spatial skills used in a daily activity, like an occupation, tend to be protected against the process of normal cognitive aging. Specifically, the investigators observed that architects between 60 and 78 years of age outperform non-architect peers on five SV tests (Salthouse et al., 1990). Further, Uttal et al. (2013) showed that spatial abilities are subject to improvement through training in adulthood.

Could the lifelong use of a sign language as a primary mode of communication lead to an enhancement of the spatial abilities throughout the lifespan? Few studies have addressed the effect of aging on the cognitive abilities of deaf signers. Rudner et al. (2010) investigated the effect of linguistic modality on the temporal and spatial organization of working memory among older signers. The results revealed that, compared to age-matched hearing non-signers, older signers perform more poorly on tasks that require the retention of the order in which information is displayed temporally. This difference did not persist when the information was presented both spatially as well as temporally. In the clinical domain, investigators have stressed the importance of developing neuropsychological tests that would be suitable to evaluate the performance of older deaf signers (Atkinson et al., 2015; Dean et al., 2007, 2009). In their exploratory work, Spanjer et al. (2014) investigated changes in language among deaf signers with dementia. Other investigators have explored the impact of a cerebrovascular accident on sign language among aphasic deaf patients (e. g. Bellugi, 1983; Brentari et al., 1995; Hickok et al., 1997, 1998). To our knowledge, no other studies have reported results on cognitive functioning among older deaf signers.

Aim

The aim of this study is to investigate whether there are differences in spatial abilities among signers and non-signers of different age groups. Data on spatial processing were collected from three categories of participants that differed in linguistic experience: deaf signers, hearing signers and hearing non-signers. Within each category of linguistic experience, both younger and older participants were recruited. Thus, six groups of participants took part in the investigation.

First, the performances of younger and older deaf signers were compared to groups of aged-matched hearing non-signers. Then, to investigate whether the differences found are attributable to the neural reorganization associated with auditory deprivation or the use of a sign language, a second series of analyses compared the performances of younger and older hearing non-signers and age-matched hearing users of a sign language.

Method

Participants

A total of 40 prelingually deaf signers (DS: 20 older adults, 20 younger adults), 40 hearing signers (HS: 20 older adults, 20 younger adults) and 40 hearing non-signers (HNS: 20 older adults, 20 younger adults) were recruited for this study. The older adults were between 64 and 80 years of age, while younger participants were between 18 and 35 years of age. All participants had normal or corrected-to-normal vision assessed with a Snellen chart (GF #1240). Hearing participants were screened for cognitive impairment with the french version of the Addenbrooke's Cognitive Examination test (Bier et al., 2004). Deaf participants were screened with a translated and adapted version of the British Sign Language Cognitive Screening Test (Atkinson et al., 2015) in Quebec Sign Language[6] (LSQ). All participants holding or having held an occupation that might have improved their spatial skills (e.g., architects, pilots, taxi drivers) were excluded from the study. A summary description of the participants (i.e., age, gender, years of education and score on intelligence assessment) is provided in Table 1. To ensure that spatial processing differences were not due to differences in demographic factors, participants in the HS and HNS groups were matched to the participants in the DS group on the basis of years of education as well as performance on an intelligence test (measured with the Raven's Coloured Progressive Matrices [RCPM] – Raven, 1984). Groups were also matched for gender, due to reports of a potential gender effect on spatial abilities (Linn & Petersen, 1985; Voyer et al., 1995). Due to the general profile of the recruitment pool available in the province of Quebec an exception was made in recruiting participants in the older hearing signers group. Specifically, the

[6] The maximum score on the Québec Sign Language Cognitive Screening Test (LSQ-CST) is 110 points. The administration of this test is about 30 to 40 minutes in duration. It is divided in seven domains of cognition including orientation, attention, delayed recall, verbal fluency, language, visual-spatial abilities and executive function.

educational level of this group was 5 – 5½ years above the education level of the two other groups of older adults. All participants were paid 40 CAD$ for their participation.

Table 1

Summary Description of Participants

	DS			HS			HNS			
Variable	M	(SD)	rg	M	(SD)	rg	M	(SD)	rg	***p***
Older adults										
Age	71.5	(4.6)	66-80	68.1	(3.5)	64-78	71.5	(5.2)	65-80	.051
Yrs of education	11.4	(2.7)	6-15	17.1	(2.3)	10-21	12.2	(3.5)	4-18	.000*
RCPM	26.0	(4.9)	17-33	30.8	(4.1)	21-36	24.6	(4.2)	19-31	.000*
Gender †(Ma:F)		†10:10			†4:16			†10:10		
Younger adults										
Age	30.8	(3.5)	25-35	28.0	(4.1)	20-34	29.7	(3.7)	19-34	.073
Yrs of education	15.0	(3.0)	11-23	16.3	(2.7)	11-22	15.0	(2.1)	10-18	.236
RCPM	33.9	(2.3)	28-36	33.4	(1.8)	30-36	34.0	(1.9)	30-36	.568
Gender †(Ma:F)		†10:10			†10:10			†10:10		

DS = deaf signers. F = Female. HS = hearing signers. HNS = hearing non-signers. M = mean. Ma = Male. SD = standard deviation. RCPM = Raven's Coloured Progressive Matrices (Raven, 1984). rg = range. Yrs = years. * = significant.

All deaf signers (30 congenitally deaf, 10 deaf before age 2;6) had a bilateral severe to profound sensorineural hearing loss based on previous audiological reports or a hearing screening test conducted by the Experimenter. They reported using sign language as their primary mode of communication. To assess their language proficiency in LSQ versus in French, the following five subtests of the *Batterie d'Évaluation Cognitive du Language* (BECLA: Macoir et al., 2016) were administered to all deaf signers: i) pairing of images based on their semantic category, ii) object and verb naming, iii) repetition of words/signs, iv) repetition of non-words/non-signs, v) pairing of words/signs with images. A syntactic comprehension subtest from the *Batterie d'évaluation des troubles du langage dans les maladies neurodégénératives* (GRÉMOTs: Bézy et al., 2016) was

used to assess syntactic comprehension. All deaf participants obtained the passing score of the BECLA and GRÉMOTs in the adapted version in LSQ. As expected, all of them failed the same subtests when it was administered in spoken French. A summary of the participants scores on these measures is presented in Annex 1.

Hearing signers had hearing detection thresholds ≤30 dB HL in both ears, at audiometric test frequencies between 250 Hz and 3000 Hz. All participants self-reported being bilingual (LSQ-French); 11 were native-bilingual children of deaf parents, three were bilingual and had a close deaf family member, and 26 acquired LSQ in early adulthood. Most of this group (37 out of 40) were, or had been, LSQ-French interpreters or LSQ teachers. The other three worked in a deaf environment and used LSQ on a daily basis. On average the older hearing signers used LSQ for 47 years (*SD* = 10.45; range = 30–71) while younger hearing signers used LSQ an average of 15 years (*SD* = 8.98; range = 5–29). At the time the data were collected, older hearing signers self-reported a less frequent use of LSQ than their younger counterparts. This is attributable to the fact that they were retired or partly retired. For this group, the mean self-reported use of LSQ in their daily life was around 14,70% (*SD* = 15.95; range = 0.5–60). All the younger hearing signers reported a use of LSQ in daily life of around 45.75% (*SD* = 21.54; range = 10–90). Test results of the bilingual participants showed that they were successful on both French and LSQ version of the BECLA and GRÉMOTs subtests.

Hearing non-signers had hearing detection thresholds of ≤30 dB HL in both ears at audiometric test frequencies between 250 Hz and 3000 Hz. They all reported using French as their primary mode of communication and had no knowledge of LSQ. All the participants in this group obtained a passing score on the French version of the BECLA and GRÉMOTs subtest battery and failed the LSQ version of the same subtests.

Procedure

This study satisfied the ethical principles of the Helsinki Declaration and met the requirements of the Ethics Committee for Aging-Neuroimaging Research of the *Centre de recherche de l'Institut universitaire de gériatrie de Montréal* (CRIUGM). At the request of the participants, the experimental test sessions took place at their home, a private room in a public

place (e.g., a private room in a library, a private room designed for social activities in a residential home for older adults) or the CRIUGM. The time required to administer the complete protocol ranged from 2h30 and 4h30. Two test sessions were scheduled with each participant. Session 1 served to verify that the participant met all the recruitment criteria. All participants signed the consent form that was available in a paper format as well as in a video format in which the same information was presented in LSQ for deaf participants. All the experimental tests were administered during session 2. The participants were tested individually by a bilingual (LSQ-French) experimenter. Video-recorded standardized instructions were given in LSQ for deaf signers and in spoken French based on written instructions for hearing signers and hearing non-signers. The tests of spatial abilities were administered in a random order across all the participants. Each task included one to eight practice trials, depending on the complexity of the task. For each task, participants were informed that their response time was recorded.

Material and design

All participants completed seven computerized spatial tasks that covered the four subskills of spatial ability.

Spatial Perception

Water-Level Test (WLT: Piaget & Inhelder, 1956). This test was used to assess the constancy of horizontality related to gravity. Schematic water bottles were shown to participants at different angles of inclination. The participant is asked to draw the line showing where the water would be if the bottle was half-full. The test consists of eight stimuli that are presented in a predetermined order, with the bottle angle of inclination being 210°, 60°, 330°, 240°, 300°, 120°, 150° and 30°. Errors were calculated on the basis of the horizontality of the line. A response was scored as being correct if the line drawn was within ±10° of inclination.

Computarized Rod and Frame Test (CRFT: Docherty & Bagust, 2010). The CRFT (version 3.2) evaluates the subjective perception of verticality of lines. In this test a rod is shown alone on a dark background or embedded within a square frame. The participant is instructed to adjust the tilted linear rod until it is vertical. The square frame and the rod vary in their degree of orientation (frame: 0°, +18°, -18°, no frame; rod: +20°, -20°). The verticality judgments must be made

independently of the surrounding frame. The computer used to display the stimuli was placed at a distance of 70 centimeters in front of the participant. To limit the dependence on their visual field, participants wore goggles used to simulate low-vision (Low Vision Simulators – model R104) reducing their visual field to a tunnel vision of 20°. Illumination in the room was reduced to its minimum. Participants adjusted the rod using the right and left button of a computer mouse. The test contains 18 trials. Errors were scored by calculating the degree deviation of the rod relative to the expected response (i.e., ±2° inclination).

Spatial Visualization

Hooper Visual Organization Test (HVOT: Hooper, 1983). This test is designed to assess visual analytic and synthetic abilities. It consists of two-dimensional line drawings cut into two to four pieces. Each drawing represents a common object or animal such as an apple or a cat. The participant is instructed to name (in French or LSQ) what object is seen after reorganizing mentally the pieces. The test contains 28 items and each correct answer is awarded one point.

Revised Minnesota Paper Form Board Test (r-MPFBT: Likert & Quasha, 1941). This test is comprised of 64 multiple-choice items that require the manipulation of two-dimensional geometrical shapes cut into two to five fragments. For each item, the participant had to look at the target figure cut in fragments and touch on the tactile screen the option (one out of five) representing what the figure would look like if all the pieced were put together. The level of difficulty increases as the test progresses. Each correct answer is awarded one point.

Mental Rotation

Mental Rotation Test (MRT: Vandenberg & Kuse, 1978, redrawn by Peters et al., 1995). In this test, a three-dimensional target figure is presented next to four similar three-dimensional figures. Each figure consists of an abstract structure made of assembled cubes. The participant is instructed to identify, by touching the tactile screen, which of the four test figures are rotations of the target figure. For each test item, two of the four figures are correct matches (same structure as the target but rotated) and two are distractors (rotated mirror image of the target or rotated target from another item). Both correct matches need to be identified to obtain one point. The test is comprised of 24 test items.

Card Rotation Test (CRT: Ekstrom et al., 1976). In this test, a two-dimensional target figure is displayed, next to eight similar figures. The participant is instructed to identify, by touching the tactile screen, which of the eight figures represent a rotation of the target figure. A correct match is a representation of the target figure, as is or rotated. An incorrect match is a representation of a mirror version, or a mirror-rotated version, of the target figure. On any given trial, correct responses can vary between two to seven figures. The test is comprised of 20 items. One point in awarded for each correct identification and one point is retracted for each incorrect answer.

Perspective-taking

Perspective Taking/Spatial Orientation Test (PTSOT: Hegarty & Waller, 2004). For this test an arrangement of seven two-dimensional common objects are displayed on the left side of the computer monitor. A circle containing two of these objects appear on the right side of the screen. One object appears in the center of the circle while the second object is on the top of the circle. The two objects shown are different for each of the 12-test items. The following instructions are given to the participant: "Imagine you are standing at X (representing the object in the center of the circle) and facing Y (representing the object on the top of the circle). Draw a line to Z (representing another one of the seven objects on the left side of the monitor). While taking the perspective of the object X, looking at the object Y in the left display, use your finger to draw a line from the center to the edge of the circle that will point to the relative position of object Z. Six of the 12 items require a shift in perspective of more than 90° from the participants' frontal perspective. The other six require a shift in perspective of 90° or less. Scoring is based on the angular disparity between the answer produced and the expected response.

The stimuli for the CRFT were programmed with Python 2.7 software. E-Prime 3.0 software (Psychology Software Tools, Pittsburgh, PA) was used to program the stimuli for the other six tests. The computer used for data collection consisted of a 14'' tactile screen, Lenovo ThinkPad Yoga X1, enabling data collection through touchscreen and mouse devices. Techentin et al. (2014) have shown that for spatial tasks the test administration format (e.g., computerized, paper pencil, cards or slides) does not influence performance. Therefore, except for CRFT that had been programmed by Docherty & Bagust (2010), the test administration and scoring of all

tests were computerized. For all the test administered, both the responses provided by the participant as well as the response time were recorded by the computer, with the exception of HVOT in which the response provided by the participant was manually coded by the experimenter. There was no time restriction on any of the tasks. The automatic scoring generated by E-Prime or Python was manually checked by two independent persons.

Statistical analysis To simplify the data analyses, composite scores were calculated for each subdomain of spatial abilities (i.e.: SP = WLT & PRFT; SV = HVOT & r-MPFBT; MR = MRT & CRT). The *compute* function of SPSS (IBM SPSS Statistics, version 25) was used to transform the data which consisted of calculating the means of the two variables and creating a new computed variable. Using these composite scores, separate two-way ANOVAs were performed for each of the four spatial tests, namely SP, SV, MR and PT. One factor (non-repeated measure) was AGE (two levels: younger adults and older adults). The other factor (non-repeated measure) was LINGUISTIC EXPERIENCE (comparison 1 : deaf signers and hearing non-signers; comparison 2 : hearing signers and hearing non-signers). Two-way ANOVAs were used to analyze the data obtained for accuracy scores and response-time. The alpha-criterion level for all analyses is set to $p < .05$.

Results

Pearson correlations showed a significant relation between the two tests used to measure the same subdomain of spatial ability (WLT & PRFT, $r = .52$, $p < .000$; HVOT & r-MPFBT, $r = .56$, $p < .000$; MRT & CRT, $r = .68$, $p < .000$). In addition, separate ANOVAs were performed for each of the seven experimental tasks. The results of these analyses were not different from those obtained when the composite scores were used to analyze the data. Therefore, performances were analyzed in terms of accuracy (mean scores for SP, SV and MR tasks; mean angle disparity for PT) and response time (mean time for each item in milliseconds) for the composite scores. Performance on the practice trials were not included in the analyses.

Deaf signers vs. Hearing non-signers

First, the effect of sign language use on spatial abilities was investigated by comparing the performances of the deaf signers to those of the hearing non-signers. For each ability investigated and each dependent variable (accuracy and response time) a 2-way ANOVA was computed. The factors considered in the analyses were AGE (older adults vs. younger adults) and LINGUISTIC EXPERIENCE (sign language vs. no knowledge of sign language).

Accuracy

Accuracy results for all spatial skills are displayed in Figure 2. For the SP tasks, the AGE x LINGUISTIC EXPERIENCE interaction was not significant $F(1, 76) = 3.35$, $p = .071$, $r = .14$, 95% CI [6.95, 8.12]. There was a significant main effect of age, $F(1, 76) = 38.09$, $p < .000$, $r = .56$, 95% CI [8.16, 10.54], whereby the younger participants ($M = 9.35$, $SD = 2.00$) outperformed the older participants ($M = 5.73$, $SD = 3.17$). The LINGUISTIC EXPERIENCE effect was not significant $F(1, 76) = .002$, $p = .966$, $r = .09$, 95% CI [6.36, 10.54].

For the SV tasks, the AGE x LINGUISTIC EXPERIENCE interaction was significant $F(1, 76) = 7.16$, $p = .009$, $r = .19$, 95% CI [30.53, 32.54]. More precisely, the older deaf signers performed significantly better ($M = 29.25$, $SD = 5.12$) than the older hearing non-signers ($M = 24.96$, $SD = 5.51$), $F(1, 76) = 9.03$, $p = .004$, $\eta 2 = .11$, 95% CI [27.87, 33.63]. However, there was no difference in terms of performance between the two younger groups of participants ($p = .438$). Considering the AGE factor, the results indicate that the younger deaf signers ($M = 35.41$, $SD = 4.19$) performed better than their older peers ($M = 29.25$, $SD = 5.12$), $F(1, 76) = 18.65$, $p < .000$, $\eta 2 = .20$, 95% CI [33.87, 38.07]. Similarly, older hearing non-signers ($M = 24.96$, $SD = 5.51$) performed more poorly than younger hearing non-signers ($M = 36.52$, $SD = 2.70$), $F(1, 76) = 65.66$, $p < .000$, $\eta 2 = .46$, 95% CI [33.87, 38.07].

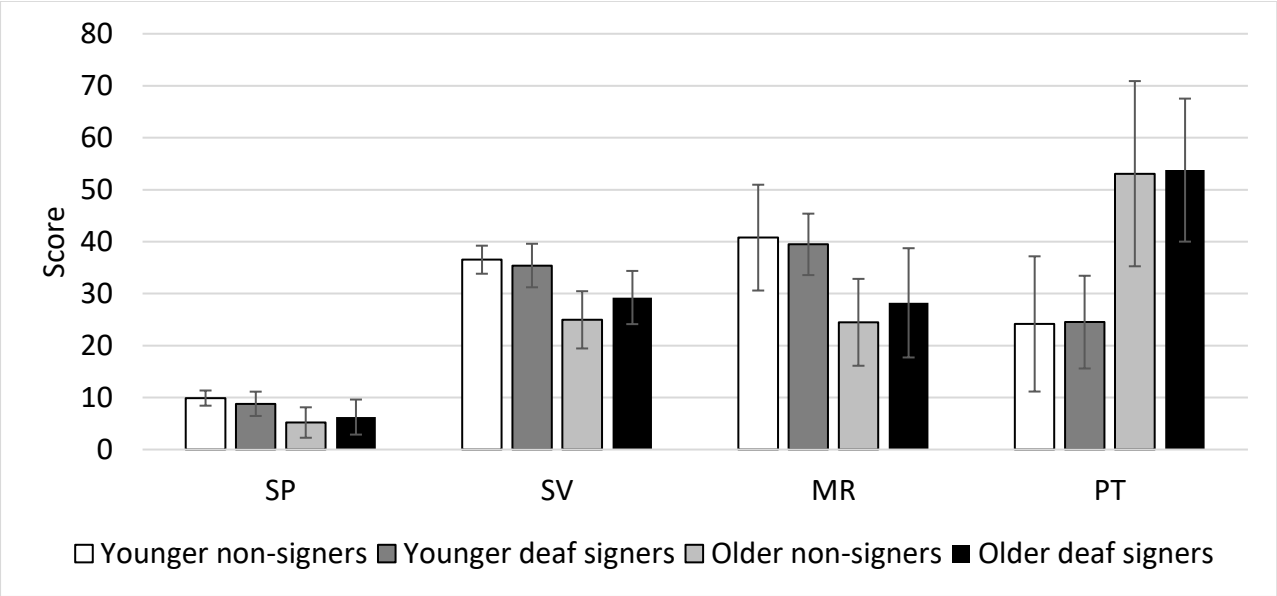
For the MR tasks, no significant AGE x LINGUISTIC EXPERIENCE interaction was observed, $F(1, 76) = 1.60$, $p = .210$, $r = .07$, 95% CI [31.25, 35.23]. There was a significant main effect of AGE, $F(1, 76) = 47.61$, $p < .000$, $r = .61$, 95% CI [36.13, 44.11], showing a large effect size based on Cohen's (1988, 1992) criteria. Significantly better performances were observed for the groups of

younger adults (*M* = 40.13, *SD* = 8.24) compared to the groups of older adults (*M* = 26.35, *SD* = 9.56). The main effect of LINGUISTIC EXPERIENCE was not significant, *F(*1, 76) = 3.77, *p* = .541, *r* = .07, 95% CI [28.63, 36.61].

For the PT task, there was no significant AGE x LINGUISTIC EXPERIENCE interaction, *F(*1, 76) = .003, *p* = .956, *r* = .08, 95% CI [35.82, 41.95]. There was a significant main effect of AGE, *F(*1, 76) = 89.46, *p* < .000, *r* = .73, 95% CI [18.27, 36.43], which corresponds to a large effect size. The mean angle of disparity from the expected responses was lower for the younger adults (*M* = 24.35, *SD* = 11.01) than did the older adults (*M* = 53.42, *SD* = 15.73). The main effect of LINGUISTIC EXPERIENCE was not significant, *F(*1, 76) = .03, *p* = .867, *r* = .07, 95% CI [32.54, 44.71].

Figure 2

Overall Accuracy Scores on SP, SV, MR and PT Tasks: Deaf Signers and Hearing Non-Signers



Note. Mean accuracy scores for SP, SV, MR and mean of angle disparity from expected responses in PT task. Data are shown for two groups of deaf signers and two groups of hearing non-signers. The error bars represent ± 1 standard deviation.

Response Time

As shown in Table 2, statistical analyses revealed that the deaf signers and hearing non-signers did not differ in their performance in terms of response time, on all the experimental tasks. The mean response time recorded for all spatial tasks are shown in Figure 3.

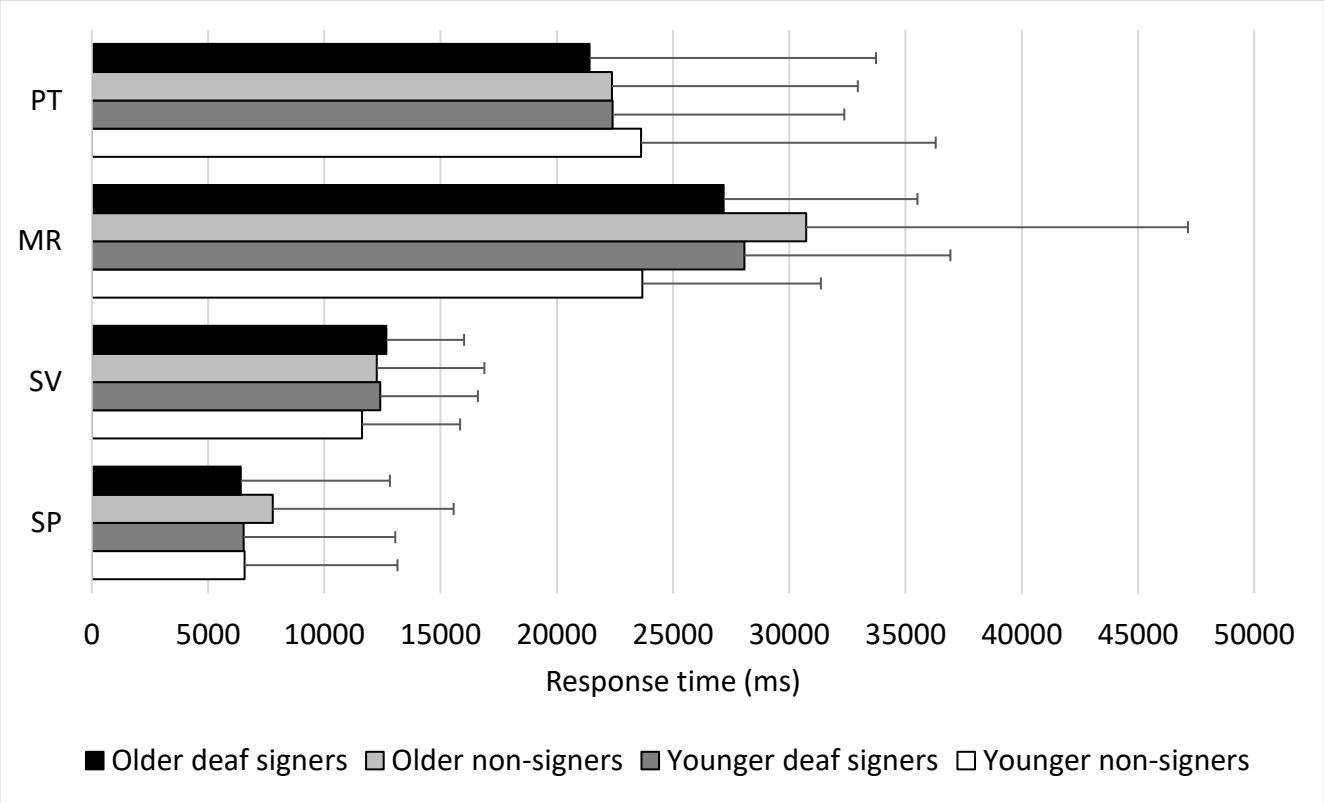
Table 2

Summary of Two-Way ANOVAs analyses comparing Deaf Signers and Hearing Non-Signers on the SP, SV, MR and PT tasks.

	Interaction			Age			Linguistic experience		
	F(1,76)	*p*	*r*	*F*(1,76)	*p*	*r*	*F*(1,76)	*p*	*r*
SP	1.48	.228	.08	1.00	.319	.01	1.70	.197	.09
95% CI	[6281.08, 7366.20]			[5462.37, 7638.85]			[6090.30, 8266.78]		
SV	.04	.840	.11	.24	.628	.10	.41	.523	.09
95% CI	[11323.46, 13159.22]			[10193.23, 13841.05]			[10121.57, 13769.39]		
MR	2.64	.108	.14	1.59	.212	.08	.03	.865	.11
95% CI	[24983.20, 29845.51]			[20963.67, 30789.24]			[22293.57, 32119.14]		
PT	.003	.958	.11	.19	.670	.10	.18	.670	.10
95% CI	[19900.71, 24997.77]			[17948.55, 28074.31]			[17933.91, 28059.67]		

Figure 3

Overall Response Time on SP, SV, MR and PT Tasks: Deaf Signers and Hearing Non-Signers



Note. The mean response time (in ms) recorded for each of the four spatial processing tasks (SP, SV, MR and PT). Data are shown for the two groups of deaf signers and the two groups of hearing non-signers. The error bars represent ± 1 standard deviation.

Hearing signers vs. Hearing non-signers

To investigate the potential effect of sign language use on spatial ability in hearing individuals, the performances of hearing signers and hearing non-signers were compared. In these analyses, the two levels of LINGUISTIC EXPERIENCE considered were hearing participants who were users of sign language and hearing participants who did not use sign language. The AGE factor consisted of comparing the results obtained from the older adults to those obtained from the younger adults.

Accuracy

Accuracy performance for all spatial skills are displayed in Figure 4. For the SP tasks, the AGE x LINGUISTIC EXPERIENCE interaction was significant, $F(1, 76) = 6.31$, $p = .014$, $r = .63$ 95% CI [6.95, 8.12]. This result implies that younger and older adults performed differently on SP tasks based on their respective language experience. Specifically, the older hearing signers performed significantly better ($M = 8.15$, $SD = 2.37$) than older hearing non-signers ($M = 5.20$, $SD = 2.94$) on tasks involving SP, $F(1, 76) = 15.36$, $p < .000$, $\eta^2 = .17$, 95% CI [6.12, 8.98]. This significant difference was not observed when the results obtained from the two younger groups of participants were compared ($p = 0.716$). The analyses revealed that older hearing non-signers ($M = 5.20$, $SD = 2.94$) performed more poorly than younger hearing non-signers ($M = 9.90$, $SD = 1.46$), $F(1, 76) = 38.98$, $p < .000$, $\eta^2 = .34$, 95% CI [8.17, 10.53]. Similarly, younger hearing signers ($M = 10.18$, $SD = 2.51$) outperformed older hearing signer adults ($M = 8.15$, $SD = 2.37$), $F(1, 76) = 7.24$, $p = .009$, $\eta^2 = .09$, 95% CI [8.17, 10.53].

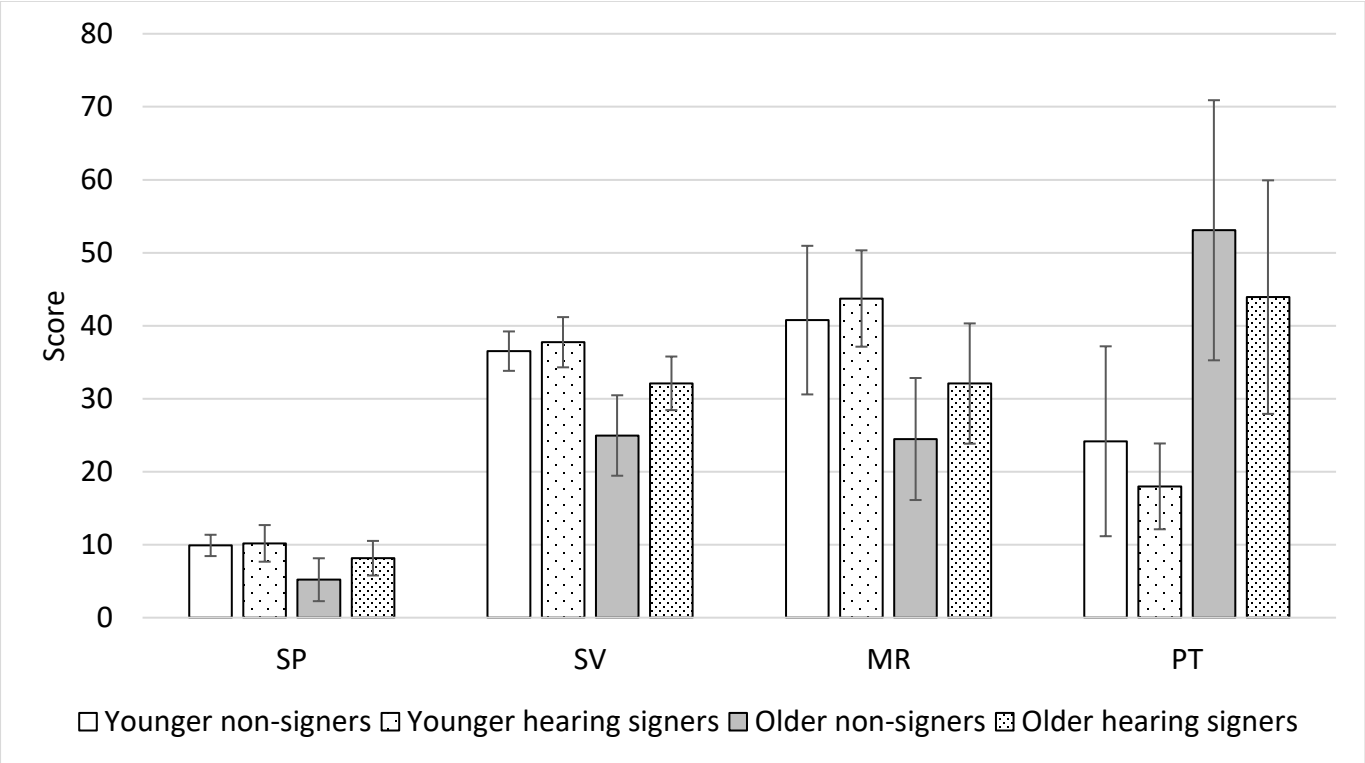
For the SV tasks, the AGE x LINGUISTIC EXPERIENCE was a significant, $F(1, 76) = 11.20$, $p = .001$, $r = .22$, 95% CI [30.53, 32.54]. Specifically, the older hearing signers performed significantly better ($M = 32.11$, $SD = 3.67$) than the older hearing non-signers ($M = 24.96$, $SD = 5.51$), $F(1, 76) = 32.49$, $p < .000$, $\eta 2 = .30$, 95% CI [27.87, 33.62]. No difference was found between the two groups of younger participants ($p = .337$). The younger hearing signers ($M = 37.74$, $SD = 3.44$) outperformed the older hearing signers ($M = 32.11$, $SD = 3.67$), $F(1, 76) = 20.11$, $p < .000$, $\eta^2 = .21$, 95% CI [33.87, 38.07]. Similarly, younger hearing non-signers ($M = 36.52$, $SD = 2.70$) performed better than older hearing non-signers ($M = 24.96$, $SD = 5.51$), $F(1, 76) = 84.95$, $p < .000$, $\eta^2 = .53$, 95% CI [33.87, 38.07].

For the MR tasks, the AGE x LINGUISTIC EXPERIENCE interaction was not significant, $F(1, 76) = 1.52$, $p = .222$, $r = .06$, 95% CI [31.25, 35.23]. There was a main effect of AGE, $F(1, 76) = 54.86$, $p < .000$, $r = .62$, 95% CI [36.13, 44.11]; the older adults ($M = 28.28$, $SD = 9.05$) performed more poorly than the younger adults ($M = 42.25$, $SD = 8.60$). Similarly, there was a main effect of LINGUISTIC EXPERIENCE, $F(1, 76) = 7.82$, $p = .007$, $r = .22$, 95% CI [28.64, 36.61]; hearing signers ($M = 37.90$, $SD = 9.44$) outperformed the hearing non-signers ($M = 32.63$, $SD = 12.35$).

For PT task, the AGE x LINGUISTIC EXPERIENCE interaction was not significant, $F(1, 76) = .23$, $p = .635$, $r = .07$, 95% CI [35.82, 41.95]. The main effect of AGE was significant, $F(1, 76) = 77.33$, $p < .000$, $r = .69$, 95% CI [18.26, 30.44]; older adults ($M = 48.50$, $SD = 17.35$) produced a greater angle of disparity errors than younger adults ($M = 21.08$, $SD = 10.45$). Similarly, the main effect of LINGUISTIC EXPERIENCE was significant, $F(1, 76) = 7.82$, $p = .007$, $r = .22$, 95% CI [32.54, 44.71]; hearing sign language users ($M = 30.95$, $SD = 17.72$) outperformed the hearing non-signers ($M = 38.63$, $SD = 21.72$).

Figure 4

Overall *Accuracy scores* on SP, SV, MR and PT Tasks: Hearing Signers and Hearing Non-Signers



Note. Mean accuracy scores for SP, SV, MR tasks and mean of angle disparity from expected responses in PT task. Data are shown for two groups of non-hearing signers and two groups of hearing signers. The error bars represent ± 1 standard deviation.

Response Time

The mean response times observed for each spatial task are displayed in Figure 5. For the SP tasks, the AGE x LINGUISTIC EXPERIENCE interaction was not significant, $F(1, 76) = 1.73$, $p = .193$, $r = .09$, 95% CI [6281.08, 7366.20]. Similarly, the main effect of AGE, $F(1, 76) = 1.45$, $p = .232$, $r = .07$, 95% CI [5462.37, 7638.85], and LINGUISTIC EXPERIENCE, $F(1, 76) = .05$, $p = .821$, $r = .11$, 95% CI [6090.3, 8266.78], were not significant.

For SV tasks, the AGE x LINGUISTIC EXPERIENCE interaction was significant, $F(1, 76) = 4.58$, $p = .036$, $r = .20$, 95% CI [11323.46, 13159.22]. Specifically, the mean response time of the older hearing non-signers ($M = 12263.21$, $SD = 4622.29$) was shorter than the mean response time of the older hearing signers ($M = 16437.94$, $SD = 6852.51$), $F(1, 76) = 6.79$, $p = .011$, $\eta^2 = .08$, 95% CI [10130.85, 13760.11]. This significant difference did not hold between the two groups of younger participants ($p = .675$). Also, a significant difference was observed between the younger hearing signers and the older hearing signers $F(1, 76) = 11.70$, $p = .001$, $\eta^2 = .13$, 95% CI [10200.43, 13833.85]. Specifically, the mean response time of the older hearing signers ($M = 16437.94$, $SD = 6852.51$) was longer than that of the younger hearing signers ($M = 10952.60$, $SD = 4092.20$). This difference did not hold between older and younger hearing non-signers ($p = .693$).

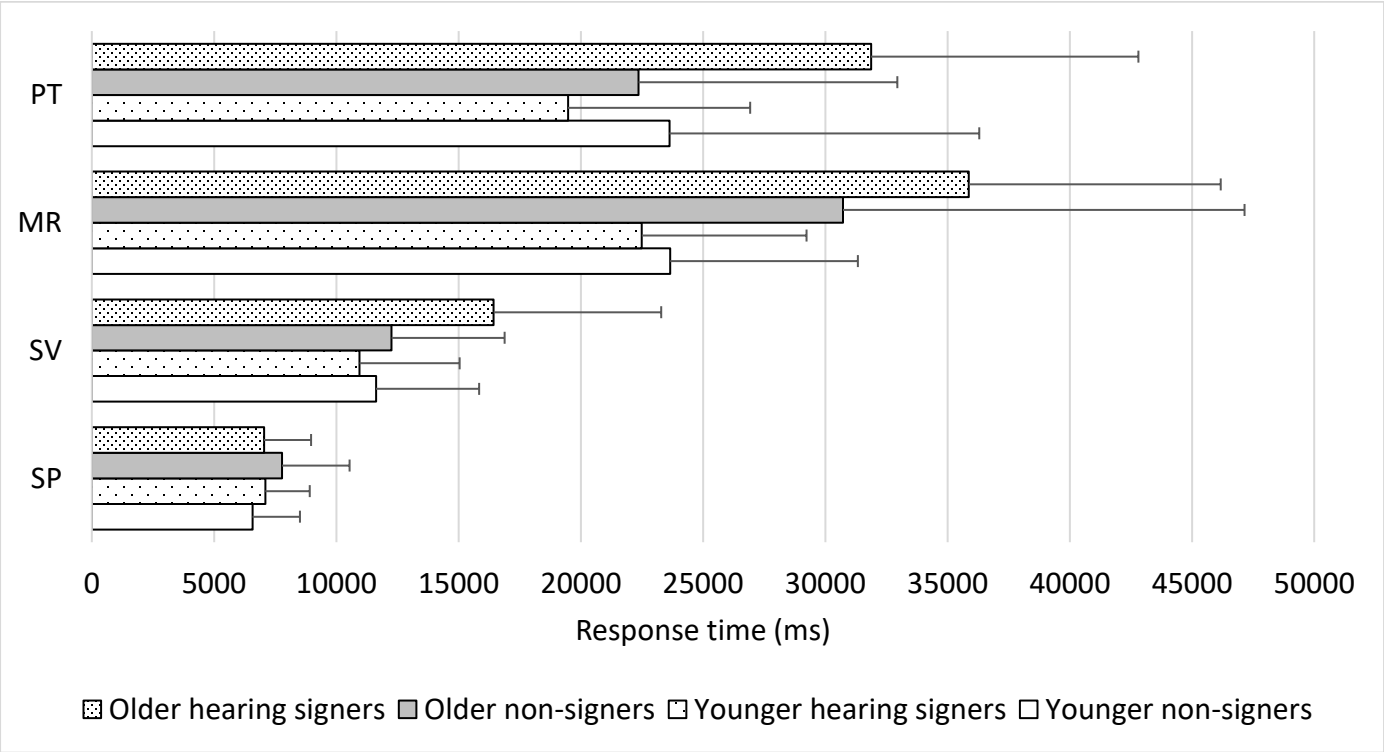
For the MR tasks, the AGE x LINGUISTIC EXPERIENCE interaction was not significant, $F(1, 76) = 1.67$, $p = .200$, $r = .08$, 95% CI [24983.20, 29845.51]. There was a significant main effect of the AGE, $F(1, 76) = 17.37$, $p < .000$, $r = .41$, 95% CI [20962.70, 30789.24]. The mean response time of the older adults ($M = 33301.66$, $SD = 13780.31$) was significantly longer than the mean response time of the younger adults (younger adults, $M = 23091.85$, $SD = 7153.93$). The main effect of LINGUISTIC EXPERIENCE was not significant, $F(1, 76) = .65$, $p = .421$, $r = .06$, 95% CI [22293.56, 32119.14].

Lastly, for PT task, there is a significant AGE x LINGUISTIC EXPERIENCE interaction, $F(1, 76) = 8.31$, $p = .005$, $r = .28$, 95% CI [19900.71, 24997.77]. The mean response time of the older hearing signers ($M = 31875.46$, $SD = 10933.69$) was longer than the mean response time of the older hearing non-signers ($M = 22367.57$, $SD = 10581.13$), $F(1, 76) = 8.05$, $p = .006$, $\eta^2 = .09$, 95% CI [17961.12, 28032.46]. This significant difference was not observed when the mean response time

of the younger hearing signers and younger hearing non-signers were compared (p = .220). In addition, there was a significant difference between older and younger hearing signers $F(1, 76)$ = 13.69, p < .000, η^2 = .15, 95% CI [17976.07, 28046.77]. The mean response time of the older hearing signers (M = 31875.46, SD = 10933.69) was longer than the mean response time obtained from the group of younger hearing signers (M = 19479.02, SD = 7540.63). There was no significant difference between the two groups of hearing non-signers (p = .708).

Figure 5

Overall Response Time on SP, SV, MR and PT Tasks: Hearing Signers and Hearing Non-Signers



Note. The mean response time (in ms) recorded for each of the four spatial processing tasks (SP, SV, MR and PT). Data are shown for the two groups of hearing non-signers and the two groups of hearing signers. The error bars represent ± 1 standard deviation.

Discussion

The main goal of this study was to investigate whether there are differences in spatial abilities among signers (deaf and hearing) and hearing non-signers of different age groups. Seven tasks that covered four subskills of spatial abilities (SP, SV, MR and PT) were administered to six groups of participants. Based on the premises of the cognitive reserve concept, the results of the investigation served to further elucidate what is known about the effect of sign language use on spatial cognition among older adults. Globally, the results showed that older signers outperformed older non-signers in terms of accuracy on SV tasks. This result suggests that sign language use, as a significant life experience, may have a beneficial effect on this specific subskill as a function of aging. In addition, both younger and older hearing signers showed enhanced MR and PT abilities compared to hearing non-signers. Together these results indicate that the effect of sign language use cannot be generalized to all spatial subskills and that a more thorough investigation for each subskill is necessary.

Consistent with previous literature on the effect of age on spatial abilities (e.g., Akiyama et al., 1985; Ariel & Moffat, 2017; Hertzog, 1989; Zancada-Menendez et al., 2016), accuracy results revealed that the younger participants constantly performed better than the older participants across all tasks. For the SV tasks, the effect size revealed a smaller effect of aging among the signers (deaf and hearing) than among their non-signer peers. This suggest that sign language use mitigated the effect of aging in SV processing. Previous investigators have provided evidence that aging leads to a general decrease in speed of processing (Park & Reuter-Lorenz, 2009; Salthouse, 1996, 2000) resulting in longer response times. In contrast to the conclusion of the meta-analysis on spatial abilities reported by Techentin et al. (2014), response time measures obtained in the present study did not reveal a generalized aging effect on performance. For example, for all four subskills of spatial abilities, the response time data obtained did not reveal an age difference between the two groups of deaf signers. Nonetheless, in line with Berg et al. (1982), on the MR tasks the mean response time of the older hearing non-signers were significantly longer than those of their younger peers. The older hearing signers displayed significantly longer response times than the younger hearing signers on the SV, MR and PT tasks. Consequently, the pattern of results that emerged from the present study only partly supports

the general assumption (supported, among others, by Starns & Ratcliff, 2010) that older adults value accuracy at the expense of speed in cognitive tasks.

Considering linguistic experience, both sets of data (1: deaf signers vs. hearing non-signers; 2: hearing signers vs. hearing non-signers) suggest that spatial abilities are influenced differently by age and language experience. For SP ability, no differences in the accuracy and response time data were observed between deaf signers and hearing non-signers. Whereas the older hearing signers outperformed older hearing non-signers in terms of accuracy performance, no differences emerged between these two groups in the response time data. Both the accuracy and the response time data revealed that the younger hearing signers and younger hearing non-signers performed similarly on the SP tasks.

On the SV tasks, in terms of accuracy, older signers (deaf and hearing) performed significantly better than older hearing non-signers. In other words, older users of a sign language are better than older users of a spoken language for tasks that require the manipulation of complex information presented spatially. The advantage of signers (deaf and hearing) over hearing non-signers wasn't observed among the younger groups. These results provide additional evidence that long-life exposure to a mentally stimulating activity may contribute to cognitive reserve of certain abilities. Compared to the non-signers, the older participants who used signs appear to benefit from the long-term practice of a sign language to maintain their SV processing abilities. However, the effect size is small to medium (Cohen: 1988, 1992). This suggests that other factors may account for the differences observed between signers and non-signers. Also, the response time data for the SV tasks did not reveal a group difference between the deaf signers and the hearing non-signers. Conversely, the older hearing signers displayed longer response time results than the older hearing non-signers.

Overall, the deaf signers and hearing non-signers obtained similar accuracy scores and response time results on the PT and MR tasks. The accuracy results are in line with the results of a study that investigated the same spatial subskills among young adults who were deaf signers with an aged-matched group of hearing non-signers (Secora & Emmorey, 2019). Further, the accuracy data of the current study revealed that both groups of hearing signers (younger and

older adults) outperformed the hearing non-signers. This result corroborates those of Talbot and Haude (1993) who obtained similar results with young adults in a MR task. It appears as though hearing adults who use signs to communicate exhibit an advantage in MR ability compared to hearing non-signers. This advantage is not observed for deaf signers. For the response time data, the only difference in performance on MR and PT tasks is that older hearing signers had longer response times than the older hearing non-signers on the PT. No difference in response time or the correct response data was observed between the deaf signers and the hearing non-signers, in both age groups. This result appears to be in contradiction with previous findings showing shorter response times on MR tasks for signers over non-signers in younger adults (Emmorey et al., 1993; Le et al., 2018).

One way to rule out the possibility that a potential advantage in spatial abilities is influenced by auditory deprivation is to include data obtained from hearing signers. If the results obtained from a group of hearing signers are similar to the performances observed from deaf signers, and better than those of hearing non-signers, it would indicate that experience with sign language has a positive effect on of the spatial abilities investigated. In the present study, an equivalent pairing of older hearing signers with the other groups of older participants was not possible. As shown in Table 1, older hearing signers had a statistically significantly higher education level (M = 17.1) than the older hearing non-signers (M = 12.1) and the older deaf signers (M = 11.4). During their active working career, most of the older hearing signers worked in deaf elementary or high schools as teachers, or they were educational advisors, speech-language pathologists, interpreters, etc. All of these occupations require a college or university degree. Based on their age, the older deaf signers recruited for this study, would have started their post-secondary education between 1955 and 1970. In Quebec, sign language interpretation services for college and university-level students were not available before the early 80s. Thus, most of the older deaf adults who took part in the investigation did not have the opportunity to attend a higher-level educational institution. Because the older hearing non-signers, were matched for educational level with the older deaf signers, they also exhibited a lower level of education than the older hearing signers. Higher level of education is known to have a positive impact on scores obtained on tasks that measure spatial abilities (Opbdebeeck, 2016). Therefore, in the present

study higher accuracy scores were expected from the older hearing signers than for the hearing non-signers.

Notwithstanding the difference in their educational level, it is possible that the higher scores obtained from the older hearing signers on the SV and PT tasks were the result of an accuracy-response trade-off. Indeed, the response times of the older hearing signers were significantly longer than those of the older hearing non-signers on these tasks. Salthouse (1990) reported that older architects, who had long-life practice of SV skills due to their occupation, took significantly longer to complete test trials than non-architect older adults who were not expected to have enhanced SV processing. These results indicate that older adults who feel (or know) that they have the cognitive resources required to successfully perform the task tend to prioritize optimizing the results rather than complying with instructions stating that their responses time would be considered. In the present study a higher educational level associated with superior analytical skills available to resolve cognitive tasks might have benefited the older hearing signers. However, the use of these additional resources had an important accuracy-response time trade-off.

Education level alone cannot account for the differences between younger hearing signers and their hearing non-signer peers because these groups were matched for educational level. It is worth noting that the younger hearing signers outperformed their hearing non-signer peers in terms of accuracy of responses on the MR and PT tasks. Also, additional analyses revealed that the younger deaf signers and younger hearing signers had a significantly different level of performance on the MR and PT task (MR : F [1, 38] = 4.60, p = .038, ω^2 = .29, 95% CI [39.71, 47.74]; PT: F [1, 38] = 7.49, p = .009, ω^2 = .37, 95% CI [13.14, 22.82], both revealing a large effect size [Kirk, 1996]). Hearing signers outperformed deaf signers on both subskills. Additionally, the hearing signers displayed a significantly shorter response time than the deaf signers in MR, F(1, 38) = 5.00, p = .031, ω^2 = .30, 95% CI [17458.15, 27539.13] but not in PT, F(1, 38) = 1.09, p = .303, ω^2 = .05, 95% CI [13819.94, 25138.12] (see Table 2). These results suggest that the use of a sign language to communicate might not be the only factor that moderates spatial skills. The scores obtained for the younger deaf and hearing signers on the MR and PT tasks are summarized in Table 2.

Table 3

MR and PT mean (standard error) for younger deaf and hearing signers

	YDS	YHS	*p*
MR			
Accuracy	39.48 (1.32)	43.73 (1.48)	.038*
Response time (ms)	28067.82 (1982.50)	224908.64 (1506.38)	.031*
PT			
Accuracy	24.52 (1.99)	17.99 (1.32)	.009*
Response time (ms)	22396.84 (2229.68)	19479.03 (1686.14)	.303

YDS = younger deaf signers. YHS = younger hearing signers. MR = Mental rotation tasks. *ms* = milliseconds. PT = Perspective-taking task. * = significant.

One advantage of unimodal bilingualism in a hearing population (e.g., the ability to understand and speak two spoken languages) is that it improves cognitive control among bilingual individuals (Bialystok, 2001). Unimodal bilinguals exhibit enhanced cognitive control due to the constant engagement of cognitive mechanisms required to manage the two known languages (Macnamara & Conway, 2014). More precisely, to retrieve the correct target in the desired language, the bilingual speaker must control the choice of the correct lexical entry in the appropriate language and eliminate competing lexical forms (Bialystok, 2001). Research on working memory have shown cognitive advantage of unimodal bilinguals over unilingual among children (Purić et al., 2017), younger adults and older adults (Bialystok et al., 2014). Also, Greenberg et al. (2013) revealed an advantage of bilingual children over monolingual children on PT tasks. In the present study, it can be speculated that bimodal bilinguals (i.e., participants who use one spoken language and one sign language: hearing signers) displayed a cognitive advantage over the other groups. However, bimodal bilinguals might not have the same cognitive advantage as unimodal bilinguals because the two languages employed access different sensory-motor systems (Emmorey & McCullough, 2009). In fact, because accessing a lexical form in sign-specific and speech-specific regions of the brain is non-competitive (Evans et al., 2019) and because there is less overlap in the neural systems when processing the two languages (Emmorey et al., 2016),

bimodal bilingualism may not require as much cognitive control as unimodal bilingualism (Williams et al., 2016). Few investigators have tested this hypothesis explicitly. It has been established that unimodal bilinguals perform better than bimodal bilinguals and monolinguals, and that the performances of the two latter groups are similar to each other in terms of executive function (Emmorey et al., 2008) and in attention (Mercure et al., 2018). Therefore, it is difficult to establish if the difference observed for PT and M tasks are the results of bimodal bilingualism or the results of another factor of influence.

The present results may stimulate discussions on the effect of sign language use on spatial subskills and specifically on how this effect may be influenced by linguistic experience (i.e., bimodal bilingualism) as well as by age. The underlying skills involved in performing MR and PT tasks may be sensitive to sign language use in the deaf population (e.g., Emmorey et al., 1993; Emmorey et al., 1998; Secora & Emmorey, 2019). However, the present results revealed that only hearing users of a sign language exhibit a cognitive enhancement due to sign language use. Is it the result of an enhancement due to bimodal bilingualism or the result of a reinforcement of spatial skills due to the regular cognitive demands inherent in simultaneous interpreting? The current data did not allow to address this hypothesis. As proposed by Emmorey (1998), deaf signers might use reverse imagery mechanisms instead of an array of mental rotation to interpret a sign language message. In most cases, sign language conversations are face-to-face, thus requiring a 180° perspective shift. Therefore, the potential advantage of deaf signers may simply be their ability to make a 180° mental rotation. The present study does not make it possible to address this specific issue. As for hearing signers, who are mainly exposed to linguistic input of spoken language, they are required to master two typologically distant languages. The spatial transformations that are required when communicating in a visual-spatial language are not necessary when communicating in a linear mode of communication like spoken language. Therefore, using a language in another modality such as sign language may also enhance MR and PT abilities in hearing signers. The constant switch that takes place between languages of different modalities could contribute to the maintenance of these spatial subskills in older age. On the other hand, the advantage of older deaf signers on SV tasks suggests that lifelong use of a sign

language contributes to the processing of complex segmented elements that can be reorganized into an image or a scene that conveys meaning.

Conclusion

In summary, this cross-linguistic study provides evidence that spatial abilities vary as a function of age and linguistic experience. The results revealed that older signers outperformed older non-signers in terms of accuracy on SV tasks suggesting a potential lifelong beneficial effect of sign language use for this spatial subskill. In addition, both younger and older hearing signers showed enhanced MR and PT abilities compared to hearing non-signers. This indicates that managing two languages of distinct modalities might enhance these two spatial subskills. Further research is needed to better understand the functional impact of these findings on the real-world daily activities of deaf and hearing signers.

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Annex 1

Summary of scores on language measures for deaf signers and hearing signers: Quebec Sign Language version

Variable	DS			HS		
	M	(SD)	rg	M	(SD)	rg
Older adults						
Pairing of images (/20)	19.0	(0.9)	17-20	19.9	(0.5)	18-20
O and V naming (/20)	19.9	(0.2)	19-20	20.0	(0.0)	-
Rep. of signs (/15)	15.0	(0.0)	-	15.0	(0.0)	-
Rep. of non-signs (/10)	9.9	(0.4)	8-10	10.0	(0.0)	-
Pairing sign-image (/20)	19.7	(0.5)	19-20	19.9	(0.4)	18-20
Syntactic compreh. (/24)	16.2	(2.5)	14-22	19.6	(2.3)	15-22
Younger adults						
Pairing of images (/20)	19.9	(0.2)	19-20	19.9	(0.3)	19-20
O and V naming (/20)	19.9	(0.2)	19-20	20.0	(0.0)	-
Rep. of signs (/15)	15.0	(0.0)	-	15.0	(0.0)	-
Rep. of non-signs (/10)	10.0	(0.0)	-	10.0	(0.0)	-
Pairing sign-image (/20)	20.0	(0.0)	-	19.9	(0.4)	18-20
Syntactic compreh. (/24)	21.2	(2.0)	16-24	20.2	(2.8)	15-24

DS = Deaf signers. HS = Hearing signers. O and V images = object and verb naming. Pairing of images = pairing of images based on their semantic category. Pairing sign-image = pairing of signs with images. Rep. of signs = repetition of signs. Rep of non-signs = repetition of non-signs. Syntactic compreh. = Syntactic comprehension.

Summary of scores on language measures for hearing signers and hearing non-signers: French version

Variable	HS			HNS		
	M	(SD)	rg	M	(SD)	rg
Older adults						
Pairing of images (/20)	19.9	(0.5)	18-20	19.5	(0.8)	18-20
O and V naming (/20)	19.9	(0.2)	19-20	19.9	(0.3)	19-20
Rep. of words (/15)	15.0	(0.0)	-	15.0	(0.0)	-
Rep. of non-words (/10)	10.0	(0.0)	-	10.0	(0.0)	-
Pairing word-image (/20)	20.0	(0.0)	-	19.8	(0.6)	18-20
Syntactic compreh. (/24)	21.2	(2.5)	15-24	17.6	(2.1)	14-20
Younger adults						
Pairing of images (/20)	19.9	(0.3)	19-20	19.8	(0.8)	17-20
O and V naming (/20)	19.9	(0.2)	19-20	19.9	(0.2)	19-20
Rep. of words (/15)	15.0	(0.0)	-	15.0	(0.0)	-
Rep. of non-words (/10)	10.0	(0.0)	-	10.0	(0.0)	-
Pairing word-image (/20)	20.0	(0.0)	-	19.9	(0.2)	19-20
Syntactic compreh. (/24)	21.8	(1.9)	18-24	21.75	(1.9)	17-24

HS = Hearing signers. HNS = Hearing non-signers. O and V images = object and verb naming. Pairing of images = pairing of images based on their semantic category. Pairing word-image = pairing of word with images. Rep. of words = repetition of words. Rep of non-words = repetition of non-words. Syntactic compreh. = Syntactic comprehension.

Chapter 5 – Discussion

The discussion is divided into six sections. Section 5.1 provides a reminder of the main objectives of this thesis. Section 5.2 summarizes the general results in relation to the exploratory hypotheses proposed in Chapter 1. Section 5.3 presents the particularities of HS in light of the results obtained from older HS. Section 5.4 summarizes the contribution of the current findings on spatial cognition to the concept of cognitive reserve. Section 5.5 outlines the limits of this thesis and section 5.6 addresses future research perspectives.

5.1 Reminder of the main objectives

The main objectives of this cross-sectional study were to:

1) synthesize, based on the previous literature, the impact of sign language use on spatial abilities in children and adults
2) empirically investigate the effects of aging on spatial abilities in deaf sign language users;
3) empirically investigate whether there are differences in performance on tasks of spatial abilities in terms of accuracy and response time based on language experience and age.

This thesis documents the effects of normal cognitive aging on spatial abilities (SP, SV, MR, and PT) among older DS in order to shed a light on age-related cognitive changes of this population (Paper 2). In addition, it presents evidence of the effects of language experience (DS/HS/HNS) concerning the performance of older and younger adults on tasks of spatial abilities among (Paper 3). To our knowledge, this is the first research program to investigate spatial cognition of signers (DS and HS) in relation to the age-related changes occurring in older age.

5.2 General results of the scoping review

The scoping review presented in Chapter 2 aimed to synthesize and summarize studies that investigated the relationship between sign language use and spatial abilities. In the scoping review, 11 factors were documented in 22 experimental papers in order to better understand the potential effect, if any, on the long-term use of a visual-spatial language on spatial cognition. These factors covered year of publication, country of the study, sample size, age, sex, hearing

status, age of sign language acquisition, age of onset of deafness, spatial subskill targeted, task description and main outcome measure.

The results of the scoping review showed a great level of diversity across studies in sample description, measure used to assess a spatial subskill and the labels used to define the spatial ability targeted. Therefore, general tendencies on the performance of signers compared to non-signers in tasks requiring spatial cognition did not emerge from this scoping review. However, what the scoping review was able to highlight is the important impact that various experiential factors can have on cognitive development. The factors of the age of acquisition of sign language as well as the age of deafness are particularly crucial in studies including deaf people. For example, a congenital deaf person who learned sign language at 6 years old (e.g., following unsuccessful cochlear implantation procedures and rehabilitation) was exposed to few linguistic inputs in the early stages of life. This lack of language stimulation in early age modulates the cognitive development and differences in terms of performance on cognitive tasks can be expected when compared to a deaf person that was exposed to sign language from birth. Studies prior to the 1990s rarely considered these factors in their research on the spatial cognition of deaf signers. In particular, some of these investigations were conducted with deaf children attending deaf schools. These environments, in addition to varying in terms of policies regarding language teaching (signs vs oral), accommodated a variety of students with distinct language acquisition experiences (age of diagnosis of deafness, development of house signs with family members, age of entry in the educational institution, etc.). Future research should recognize the importance of documenting these types of factors in all research on the cognitive processing among signers.

To our knowledge this scoping review constitutes the first paper that collated the evidence of all research on the relationship between the use of a sign language and spatial skills. What has become obvious from this work is that no research to date has investigated this relationship i) in a group of older adults, and ii) taking into account the effect of aging. Paper 2 and paper 3 provide the first piece of evidence on this matter.

5.3 General results in relation to hypotheses

This section will summarize the general results from Paper 2 and Paper 3 based on the exploratory hypotheses proposed in Chapter 1.

Hypothesis 1

Spatial abilities tend to decrease with age for all adults, including deaf signers.

Prediction 1.1

In terms of accuracy, younger deaf signers will outperform their older peers on all tasks of spatial abilities (SP, SV, MR, PT) (Paper 2).Paper 2 revealed a global effect of age on performance on all tasks of spatial abilities. As expected, older DS performed significantly more poorly than younger peers with, in most cases, a large effect size (Cohen, 1988, 1992). In that sense, compared to the use of spoken language, the use of a language based on a different sensory-motor modality did not show a specific effect on the aging on cognition.

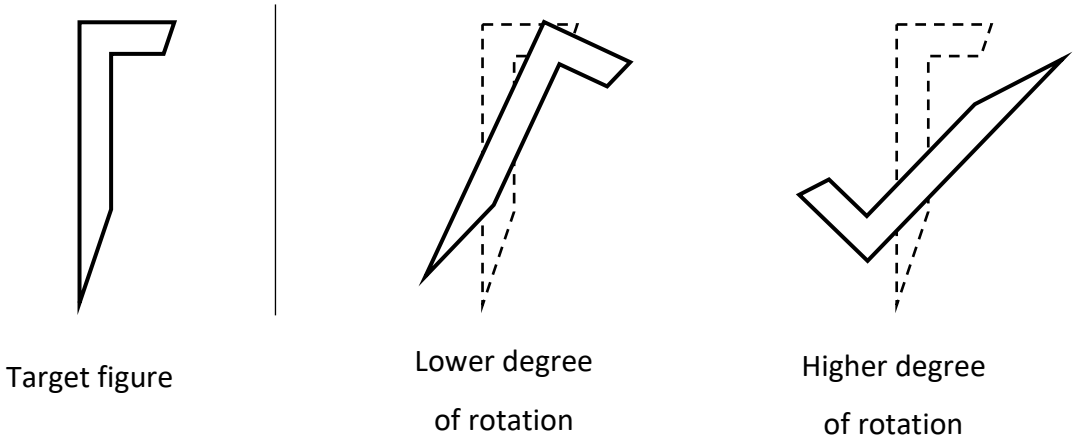
On the PT tasks, older DS exhibit a higher mean of angle disparity from the expected response compared to younger deaf adults. This suggests that age-related changes in the older DS population lead to less efficient processing of subjective spatial transformation. These results are consistent with what has been reported for the older HNS population. More precisely, an age-related decline is noticeable in HNS at approximately age 60 (Borella et al., 2014; Herman & Coyne, 1980; Inagaki et al., 2002). Additionally, a more detailed analysis (see Study 1) revealed that the angle of disparity between the response produced and the expected response increases in older DS when the new perspective to adopt is ≥ 91° from their actual perspective. This pattern of response was not observed in younger signers. Their performance did not significantly differ between items requiring the adoption of a new perspective of 91° or greater from their actual perspective compared to items requiring a perspective shift of 90° or less. Finally, younger DS performed significantly better than older DS, regardless of the new perspective to adopt (e.g. ≤ 90° or ≥ 91°). This finding differs from the results of Zancada-Menendez et al. (2016) who investigated PT ability in a HNS population. They showed a difference between age groups for

items requiring a perspective change of less than 90°, but not for items requiring a perspective change of more than 90°. In other words, the gap between performance of older and younger adults decreases when the test items are more complex items and thus require a higher-level of cognitive processing. This discrepancy between their results and the results of Study 1 suggests that younger DS may be less affected by the level of complexity of items compared to younger HNS. The adoption of a non-egocentric perspective, which is a common process in sign language comprehension, may improve the ability of younger DS to process information that requires important perspective change.

Results from the SP tasks revealed that older DS, just as older HNS (Gruenfeld & MacEachron, 1975; Panek et al., 1978; Schwartz & Karp, 1967), are more field-dependent than younger signers. When a confounding frame of reference was presented, or when no frame provided spatial reference, younger DS performed significantly better than the older DS. These results indicate that the age-related impact on SP found in the HNS population can be generalized to the DS population.

Regarding the MR ability, results from Paper 2 showed that, when the task involved two-dimensional stimuli, the older DS obtained a lower score than younger DS. Similar results were found in the older HNS population (Borella et al., 2014; Hertzog & Rypma, 1991; Inagaki et al., 2002; Jansen & Heil, 2009; Meneghetti et al., 2011). Detailed analysis revealed that the two age groups produced a similar number of incorrect matches between the items and the target figures. Their differences in performance were due to the number of correct matches; the younger DS selected more figures that were good matches with the target figure compared to older DS. Two possibilities are proposed to account for this pattern of responses. First, knowing that an incorrect match resulted in the subtraction of one point, older DS may have refrained from selecting figures for which they had certain doubts. This strategy avoids the risk of having points subtracted from their score. Second, older DS may not have selected figures that would have been good matches due to the cognitive effort required to mentally rotate the figure. As shown in Figure 13, some figures had a greater degree of rotation from the target figure (≥ 91° rotation on the left or the right) while others have a lower degree of rotation (≤ 90° rotation on the left or the right). As shown in the discussion of Study 1, the non-response pattern of older DS compared to younger

DS does not support the first proposed hypothesis. However, additional repeated-measure analyses have shown that the ratio of response of older DS for items requiring a rotation of ≥ 91° was significantly lower than the ratio of response for items requiring a rotation of ≤ 90° rotation,



$F(1,19) = 21.69$, $p < .001$, $r = .72$. In contrast, younger DS had similar ratios of response regardless of the degree of rotation required to analyze the item, $F(1,19) = .885$, $p = .359$, $r = .21$. This indicates that older adults are sensitive to the degree of rotation, and that the cognitive effort or other cognitive abilities required to analyze items with a higher degree of rotation may have been too important.

Figure 4. – Examples of two-dimensional stimuli of lower and greater angle disparity from the target figure (on the left).

Finally, older DS performed more poorly than younger DS in the SV tasks composed of abstract stimuli. This finding is congruent with what has been found in previous investigations regarding the effect of age on performance on SV tasks in older HNS (Ariel & Moffat, 2017; Hertzog, 1989; Meneghetti et al., 2011; Salthouse et al., 1990). Although younger DS consistently outperformed the older DS, the effect size revealed a larger effect of age for items of a higher level of complexity ($r = .54$) compared to items of a lower level of complexity ($r = .32$). This suggests that the ability to manipulate four or five segments in order to mentally reproduce a complex targeted figure is more impacted by age than by the complexity of the figures to be reproduced. Additionally, the results of Study 1 showed that both age groups performed better with items of a lower level of complexity (2–3 segments) compared to items of higher levels of

complexity (4–5 segments). This indicates that both groups were sensitive to the level of difficulty imposed by the task.

> *Prediction 1.2 :* In terms of response time, younger adults (DS, HS, and HNS) will outperform their older peers on all tasks of spatial abilities (SP, SV, MR, PT) (Paper 3).

Results showed no difference in performance in terms of response time between older DS and younger DS, as well as between older HNS and younger HNS on all spatial tasks.[7] For older and younger HS, no significant difference in response time for SP tasks was found between the two age groups. However, older HS did respond significantly more slowly than their younger peers on the SV, MR, and PT tasks. Additionally, when the language experience factor is considered, the only difference found between groups was that older HS performed more slowly than older HNS in SV and PT tasks. No other difference based on language experience was reported in terms of response time for both older adults and younger adults. To our knowledge, the findings reported for the SV and PT are the first to compare results from signers and non-signers using response time data (see Chapter 1).

These patterns of response time between older and younger adults, especially in DS and HNS, do not represent what is commonly described as a robust effect of age on response time across spatial tasks (Techentin et al., 2014). Older adults generally exhibit longer response time compared to younger peers, suggesting a generalized cognitive slowing in the spatial domain (Techentin et al., 2014). We proposed an interpretation for the similar performance of younger and older adults in DS and HNS, and for the differences between age groups of HS.

As summarized in Chapter 1, performances of older participants in terms of accuracy have been shown to be highly influenced by the time pressure imposed to accomplish the task (Hertzog et al., 1993; Starns & Ratcliff, 2010). Older adults tend to prioritize a greater level of accuracy at the expense of response time, whereas younger adults adjust more adequately to the instructions to respond as quickly as possible (Forstmann et al., 2011; Starns & Ratcliff, 2010; Touron &

[7] A main effect of age was found in the ANOVA comparing data from HS and HNS, reporting that older adults (HS and HNS) performed more slowly on MR tasks. It is proposed that this inconsistency from the ANOVA results of the comparison of DS and HNS is due to the atypical performance of older HS having influenced the profile of performance of older adults when considered as one group (older adults = HS + HNS).

Hertzog, 2009). This is traditionally referred to as the *speed-accuracy trade-off*. Interestingly, the results of Study 2 seem to show a reverse pattern. Participants (DS and HNS), who were all informed that response time was an outcome measure, performed as fast as their younger peers but at the expense of accuracy scores. Younger DS and younger HNS consistently outperformed their older peers. Therefore, DS and HNS older adults did not prioritize a greater level of accuracy. The speed-accuracy trade-off that was observed in older DS and HNS seems to indicate that these participants valued response time over accuracy. These patterns of response led to the following speculative interpretation.

As discussed in Chapter 1, the efficiency of cognitive processes has been shown to decrease as a function of time. Concretely, it has been proposed that older adults need to deploy more effort to maintain the same cognitive performance as the level of performance displayed by younger adults (Ennis et al., 2013). Multiple studies have provided evidence that, compared to their younger peers, older adults exhibit longer response time on cognitive tasks due to the supplemental effort required to accomplish the task (e.g. Forstmann et al., 2011; Touron & Hertzog, 2009). The effort deployed in cognitive tasks has been measured and observed in previous studies using physiological measures. Investigations using physiological responses to cognitive tasks have shown that there is an increasing systolic blood pressure during the accomplishment of a cognitive task that reflects the level of difficulty of the task (Wright & Dill, 1993). The systolic blood pressure increases up to the point where older adults are still able to perform successfully at the task. Interestingly, when the task is perceived by the older adults as unfeasible, or not worthwhile, they disengage from the task, and systolic blood pressure decreases (Wright & Drill, 1993). Along this line, Wright et al. (1998) observed that engagement on a task is correlated with the meaning associated to this task. Therefore, when the effort deployed in order to attain a successful performance level of a difficult task increases, motivational factors are a crucial determinant in the task engagement (Ennis et al., 2013). The FUEL model (Framework for Understanding Effortful Listening: Pichora-Fuller et al., 2016) also states that cognitive demand and intrinsic motivation interact with the effort deployed to accomplish a task.

Based on this knowledge, the absence of difference found between older and younger adults might be due to the fact that there was a lack of motivation when having to accomplish the spatial tasks that required an important cognitive effort. If they initially tried to accomplish the task correctly, it is conceivable that the older signers and the older HNS responded more quickly due to the important effort required to complete the task and the lack of intrinsic motivation. As an example, Jansen and Heil (2009) proposed that MR tasks might just be too difficult for older adults, which in that case would not allow them to attain a better score even when sacrificing time. Older DS and older HNS may have conceived that the level of difficulty of the tasks would have a certain impact on their accuracy score. Therefore, they might have chosen to adopt the strategy of prioritizing speed of response over accuracy. This interpretation makes it possible to explain the difference in the pattern of response between older HS compared to DS and HNS. Older HS had longer response times than their younger peers in SV, MR, and PT tasks. This result might be an artifact of sociodemographic differences among older groups. As shown in Table 2, older HS are statistically significantly younger (~3 years), had more years of education (~5 years), and had a higher level of general intelligence based on the RCPM (~5 points) than the two other older groups. It may be assumed that the higher the intelligence of a person is, the better they will be at solving problems (for a review, refer to Beckmann & Guthke [2014]). Therefore, the higher score on the RCPM and the higher educational level of the older hearing signers may have led them to perceive that they had the cognitive capacity to accomplish the task successfully, and henceforth increased their intrinsic motivation. Conceiving it as a challenge in which they can perform successfully, they might have opted for the strategy of valuing accuracy at the expense of response time. Even though they obtained significantly higher accuracy scores, the Older HS did show significantly longer response times than HNS on the SV and PT tasks. It is possible that the attitude towards the difficulty of the tasks differed between older DS and older HNS compared to HS. If all participants initiated the tasks with motivation, the difficulty and the duration of certain tasks may have caused more fatigue among the DS and the HNS participants. Additional analyses were performed to investigate the level of prediction of response time and accuracy in older adults The results of those analyses failed to reveal a significant relationship (SV:

$F[1,59] = 2.63$, $p = .110$, $R^2 = 0.043$; PT: $F[1,59] = 1.18$, $p = .281$, $R^2 = 0.020$). More research is needed on the impact of motivation on the performance at difficult cognitive tasks in signers.

Hypothesis 2

Due to their signing experience, there are differences on how signers (deaf and hearing) and non-signers process spatial information and spatial transformations.

Prediction 2.1: In terms of accuracy, HS (older adults, young adults) will perform better on MR tasks compared to their HNS peers of the same age group. This difference will not be observed between the DS and the HNS, in their respective age group (Paper 3).

Results from Paper 3 supported Hypothesis 2. Analysis comparing performance of HS and HNS revealed a general effect of linguistic experience in terms of accuracy. HS of both age groups outperformed the HNS peers of the same age group. Previous studies have shown similar results in younger HS (Keehner & Gathercole, 2007; Talbot & Haude, 1993). Paper 3 provided the first results involving older HSs. As noted earlier, older HS may have had some characteristics that might have been advantageous when performing spatial tasks (i.e., higher educational level—refer to discussion in Paper 3). It is possible that the higher performance level of older HS was due to their higher educational background. However, the apparent advantage of younger HS compared to younger HNS that were matched on the educational level suggests that the advantage of older HS cannot be attributable solely to this difference in socio-demographic characteristics.

Concerning the MR tasks, no difference in performance was observed between DS and HNS of both age groups. These results are consistent with findings of several studies that have used similar abstract mental rotation stimuli to assess adult populations (Chen & Chen, 1990; Emmorey et al., 1993; Le et al., 2018; Secora & Emmorey, 2019; Youniss & Robertson, 1970). The absence of a difference was found based on the computation of a composite score for MRT and CRT tasks. However, the same conclusion was reached when a separate analysis was conducted

for each task (main effects for language experience in MRT: $F[1, 76] = .08$, $p = .781$; CRT: $F[1, 76] = .49$, $p = .487$).

The advantage of HS over HNS on the same tasks that also revealed that DS did not outperform HNS suggests that sign language might not be the unique influential factor of performance on MR tasks. The specific attributes of HS relative to performance on spatial tasks are discussed in section 5.4.

> *Prediction 2.2*: In terms of accuracy, younger HNS will perform better on SV tasks compared to their DS peers of the same age group, but not compared to HS. Given the general effect of age on SV ability, this difference will not be observed in the older groups (Paper 3).

As expected, no difference in performance on SV tasks was observed between the younger HS and the younger HNS. Regarding the difference between younger DS and younger HNS, the results of Paper 3 did not reach a statistically significant level of difference. These findings are different from the results of previous studies (Blatto-Vallee et al., 2007; Marschark et al., 2013, 2015) who showed an advantage of HNS over DS. However, the results are consistent with the findings of other studies (Hauser et al., 2006; Tomlinson-Keasey & Smith-Winberry, 1990) who failed to show an advantage of HNS. Most studies that have investigated SV ability in signers and non-signers are based on data obtained from adolescents and young adults (~age 20: see Chapter 2). The inconsistencies between the results of previous investigations and the present findings may be due to the differences in the characteristics of the deaf group studied. As discussed in section 1.2.1, DS represent a particularly heterogeneous group of individuals. It is important to consider this factor when comparing results across studies. For example, onset of deafness and exposure to a sign language as a primary language within the sensitive period of language acquisition is known to have an impact extending beyond language development (discussed in Mayberry, 2002). This fact may account for some of the differences observed across studies. For example, concerning the age of deafness, neither Blatto-Vallee et al. (2007) or Marschark et al. (2013, 2015) provided information on the age of deafness of their participants. On the other hand, Hauser et al. (2006) and Tomlinson-Keasey and Smith-Winberry (1990),

specified that their participants were congenitally deaf (all born from deaf parents in the case of Hauser et al., 2006). As stated in Marschark et al. (2015), selecting a sample of congenital deaf individuals born from deaf parents presents the inconvenience of generating research results that are not generalizable to the vast majority of the deaf population. Congenital deaf individuals born from deaf parents represent only a small percentage of individuals who identify themselves as deaf (5% to 10% based on Mitchell & Karchmer, 2004). Perhaps if Blatto-Vallee et al. (2007) and Marschark et al. (2013, 2015) would have provided more detailed information concerning the deafness of their respective participants, it would have made it possible to better explain the effect of this factor on the cognitive development of DS. In Study 2 results from 30 congenitally deaf and 10 prelingual deaf adults (before age 2.5) were presented. Similarly to the results of Hauser et al. (2006) and Tomlinson-Keasey and Smith-Winberry (1990), no difference was found between the DS and the HNS. Based on this information, it is possible that congenital deafness or deafness acquired during the prelingual phase results in the development of similar SV abilities among DS and HNS. Since studies never provided evidence of a relationship between late-acquired deafness and a disadvantage in SV processing among DS, this interpretation remains speculative. In future research, it may be of interest to compare the effects of early-acquired vs. late-acquired deafness on spatial processing.

In addition, regarding sign language experience, previous studies describe their participants' experience either in terms of period of sign language acquisition or in terms of sign language proficiency. Several measures in studies addressing SV ability have been used to characterize sign language acquisition or sign language proficiency. Most of the measures reported are subjective in nature; the information is obtained from self-reported questionnaires answered by the participants. The information reported may consist of when sign language was acquired (e.g. from birth: Hauser et al., 2006), on the source of sign language acquisition (e.g. from deaf parents: Hauser et al., 2006), of the predominance of sign language use related to the potential use of another language (e.g. American Sign Language as a primary language: Tomlinson-Keasey & Smith-Winberry, 1990), of one's preferences of mode of communication (e.g. preference for sign language over spoken language: Marschark et al., 2013), of a self-rated scale of ASL proficiency (Marschark et al., 2015), or a combination of these measures. The only

study in which both a standardized test that assesses language skills (i.e. the Sign Language Proficiency Interview [SLPI]) as well as other subjective measures were administered to the participants was reported by Marschark (2015). As mentioned earlier, Blatto-Vallee et al. (2007) and Marschark et al. (2013, 2015) reported an advantage of HNS over DS at SV tasks. As reported in the scoping review (refer to Paper 1), Blatto-Vallee et al. (2007) made no mention of how or when their participants acquired sign language, nor did they report the level of sign language proficiency of their participants. Marschark et al. (2013) reported that their participants preferred sign language over spoken language, which does not indicate the actual level of reliance on spoken language of their participants. Marschark et al. (2015) indicated that their deaf participants acquired sign language at a mean age of 6.66 years old for participants with a cochlear implant and 2.91 years old for participants without a cochlear implant (in which 24/55 participants were native signers). Further, the language proficiency of these two groups of participants was assessed using the SLPI (ranking from 0 [no knowledge of sign language or few bases] to 5 [highly skilled signers]) and their mean rate were respectively of 1.98 for deaf participants with a cochlear implant and 2.90 for deaf participants without a cochlear implant. As mentioned by Marschark et al. (2015), a level of 2 on the SLPI would be considered as the lowest level at which someone may be considered to be a sign language user. Given these low scores, it is possible that part of the deaf participants relied on a primary mode of communication other than sign language to communicate in their daily life. Hauser et al. (2006) and Tomlinson-Keasey and Smith-Winberry (1990) found no difference between DS and HNS on SV tasks. In both studies, only native DS were recruited as participants. The differences in sign language experience observed across studies suggest that age of sign language acquisition and sign language proficiency may influence performance at SV tasks. Future studies should consider investigating the separate effect of age of sign language acquisition and sign language proficiency on cognitive performance. Acknowledging the fact that sign language proficiency can be highly variable, six language assessment subtests were administered in Study 2 to the DS so that the level of LSQ knowledge of the participants could be described quantitatively. The syntactic comprehension subtest of the GRÉMOTs (Bézy et al., 2016) adapted to LSQ confirmed that participants were sufficiently skilled in LSQ to interpret sentences including a verb (either directional or locative),

two or three referents, as well as singular or plural information (e.g. “The two girls showed the boy to the two other girls”). Complementarily, the administration of the test in French confirmed that DS were not sufficiently proficient in French to rely on this mode of communication. In terms of sign language experience, the sample of Paper 3 is similar to the participants who took part in the study reported by Hauser et al. (2006) and to those investigated by Tomlinson-Keasey and Smith-Winberry (1990). From that perspective it is not surprising that the results of Paper 3 are consistent with the results of those two investigations.

Interestingly, for the older adult groups the results presented a completely different pattern from those specified in Hypothesis 2. Both groups of older signers (DS and HS) outperformed their hearing peers of the same age group. Whereas no differences in performance on SV tasks were observed among the younger participants, it would appear that the long-life use of a sign language contributes to the cognitive reserve in the spatial domain. In that sense, use of a sign language might not provide a measurable advantage in terms of SV ability at a younger age, but it may be an asset with the age-related changes that occur in later life. The suggestion that sign language use may have some direct implications on the performance at SV tasks is still somewhat speculative. Although spatial mechanisms are unquestionably required in sign language production and comprehension, only careful interpretation can be made on how the practice of a sign language is directly linked to SV processing. More research is needed to elucidate the relationship between SV ability and sign language production and comprehension.

<u>Hypothesis 3</u>

Due to their signing experience, there are differences in terms of speed of processing of spatial information and spatial transformations between signers (deaf and hearing) and non-signers.

Prediction 3.1: In terms of response time, DS and HS (older adults, younger adults) will perform better on MR and SP tasks compared to the HNS of the same age group (Paper 3).

Results from Paper 3 did not support the assumption of Hypothesis 3. For both spatial subskills (MR and SP), there was no significant difference in terms of response time between DS and HNS peers, as well as between HS and HNS of the same age group. Specific to the SP subskill, for the younger adults, the recent results are in contrast to those of Emmorey et al. (1993) and Emmorey and Kosslyn (1996). It is worth noting that these last two studies used the same experimental design to assess spatial perception. Therefore, the difference between the recent results and the results of these two studies may be due to the differences in the nature of the tasks. Emmorey et al. (1993) and Emmorey and Kosselyn (1996) used a task that assessed the relative position of apparent entities (e.g. a letter drawing) within grids or between brackets (Podgorny & Shepard [1978], modified by Kosslyn et al. [1988]). Study 2 used two tasks of SP in relation to relative verticality (CRFT: Docherty & Bagust, 2010) and relative horizontality (WLT: Piaget & Inhelder, 1956). Since performance on SP ability appears to be sensitive to the nature of the task administered (refer to section 1.1.1.1 of the thesis and results of Comalli and Schmidt [1976]), it is suggested that the different tasks used in the present study and the one used by Emmorey and colleagues may explain the different outcome.

The results of Paper 3 revealed no differences in MR tasks as a function of language experience for both age groups. Both Le et al. (2018) and Emmorey et al. (1993) reported a shorter response time for signers (DS and HS for Emmorey et al., 1993; DS for Le et al. 2018) compared to HNS. Since performance at MR tasks in Paper 3 represents the CRT and MRT composite score, additional analyses were conducted to investigate the effect of language experience on the two tasks (see Table 3). No difference between groups was found for either CRT or MRT.

	CRT		MRT	
	F(1,39)	*p*	*F*(1,39)	*p*
Older adults				
DS vs. HNS	1.63	.210	.07	.791
HS vs. HNS	.37	.546	3.17	.079
Younger adults				
DS vs. HNS	.94	.339	3.29	.078
HS vs. HNS	1.00	.325	.00	.990

CRT = Card Rotation Test; DS = deaf signers; HNS = hearing non-signers; HS = hearing signers; MRT = Mental Rotations Test.

Table 1. – Scores on CRT and MRT tasks between DS and HNS, and HS and HNS for each age group

These discrepancies between previous results and the results obtained in Paper 3 may be due to the different adaptations of Shepard and Metzler's (1971) Mental Rotations Task[8]. Although Le et al. (2018), Emmorey et al. (1993), and the MRT used in Paper 3 were all inspired to some extent by Shepard and Metzler's (1971) Mental Rotations Task, the adaptations differ in terms of test administration procedure and the nature of the stimuli. Le et al. (2018) used the conventional three-dimensional stimuli developed by Shepard and Metzler, but created two versions of the tasks in which participants were required to indicate if the two figures were the same or different: the experimental (comparing two figures with one rotated on a vertical axis) and the control (comparing two figures that are identical or with one in mirror image). Emmorey et al. (1993) used a similar design, but with two-dimensional stimuli. The version of Vandenberg and Kuse (1978) used in Paper 3 reproduced the three-dimensional stimuli of Shepard and Metzler's test, but in a setup requiring the participants to identify two figures out of four

[8] The Mental Rotations Task of Vandenberg and Kuse (1978) used as an experimental task in Study 2 is based on Shepard and Metzler's (1971) Mental Rotations Task.

(presented in a row) that are the same as the target figure (for a visual, see Figure 9). It is possible that the multiple figures (one target figure and four stimuli figures) used in the Vandenberg and Kuse (1978) version require additional attentional and inhibition resources in order to discriminate the bad matches (mirror image or mirror-rotated image) from the good matches. These differences may account for the discrepancies observed in terms of response time between results from Study 2 and results from previous studies.

Exploratory findings on SP and PT

As was expected based on the current knowledge on cognitive aging, the analysis revealed that there is a general effect of age across all language experience groups (DS, HS, and HNS). Older adults performed more poorly than younger adults in terms of accuracy. No difference in performance was found on tasks of both subskills between DS and HNS. These results reflect what had been observed in previous research among children and younger deaf adults (SP: Emmorey et al., 1993; Emmorey & Kosslyn, 1996; McDaniel, 1980; PT: Howley & Howe, 2004; McDaniel, 1980; Secora & Emmorey, 2019; Youniss & Robertson, 1970). Older HS did perform better than older HNS on SP tasks. This pattern of results was not observed in the groups of younger adults. On the PT tasks, both groups of HS (older and younger adults) outperformed their HNS peers from the same age group.

The results revealed a difference in performance on spatial tasks between HS and DS compared to the control group of HNS. This result suggests that sign language use by itself may not be sufficient to explain the observed differences. Alternatively, these results suggest that a visuo-spatial language modality (e.g., sign language) may impact cognition differently in HS and DS. This issue is discussed further in section 6.3.

This thesis aimed to generate new evidence on the potential effect of sign language use within the perspective of cognitive age-related changes. Results showed that the effect of age on spatial abilities is subdomain-specific, and that as a single factor sign language use may not be sufficient to explain the differences observed among the participants. A visual display of the performances in terms of accuracy and response time for the three groups of language

experience, separated by age groups, is displayed in Figure 14. This figure highlights the significant differences (marked with an asterisk) between language experience groups through age groups.

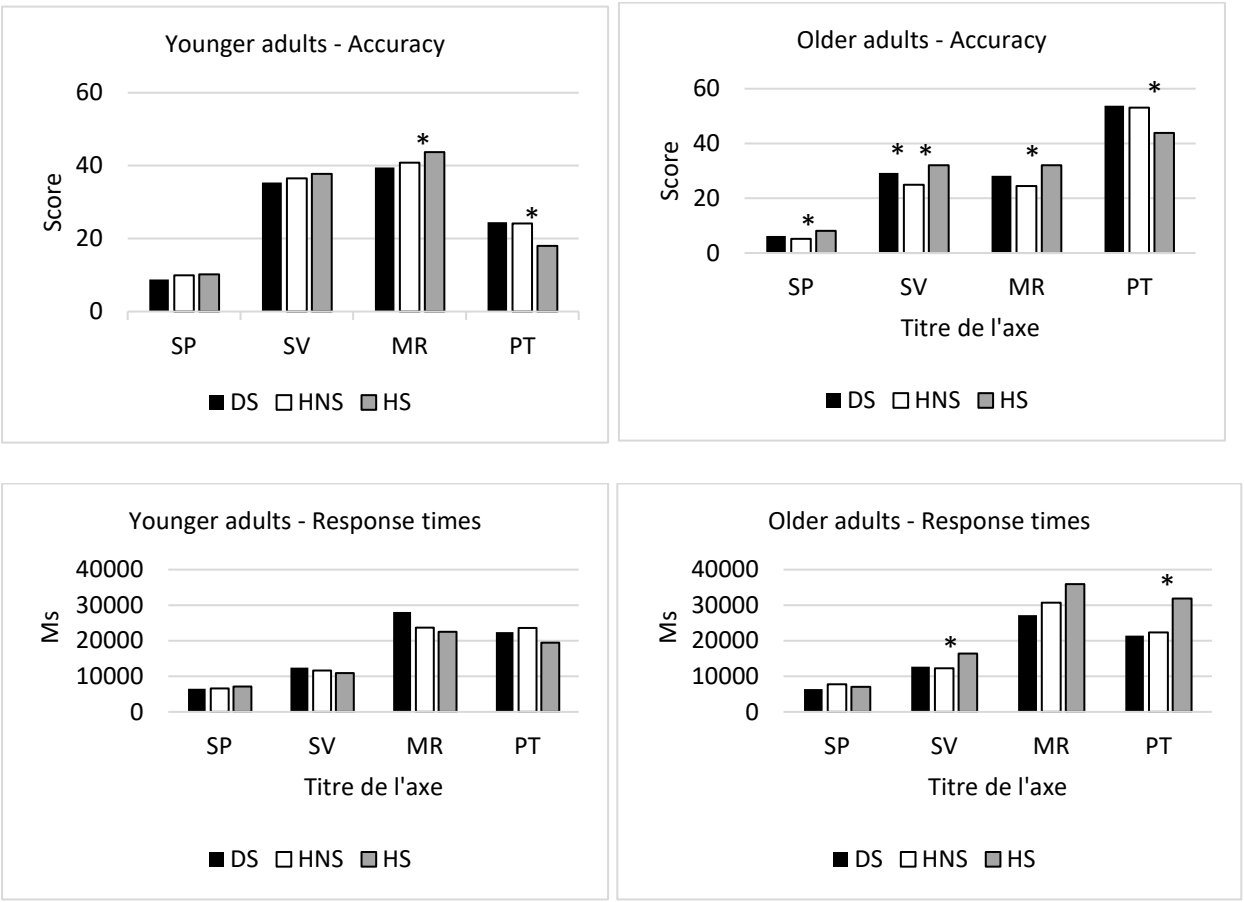


Figure 5. – Performance in terms of accuracy and response time of the three groups of language experience, by age groups.

5.4 The unique profile of hearing signers

Research that investigates the impact of sign language use on cognition faces important challenges. One of them is related to the ability to differentiate the effect of auditory deprivation and brain plasticity from the effect of the long-term use of a sign language (Bavelier et al., 2006). Methodologically, one option that makes it possible to distinguish these confounding factors is to include a group of HS in the experimental design. This choice presents the advantage of investigating the effect of sign language use apart from the effect of deafness per se (i.e. comparing HS to HNS). However, one characteristic of HS is that they are bimodal bilinguals (i.e.

sign–speech bilingualism). The perceptual and motoric systems used to perceive and produce speech and signs are different (i.e. perception: audition vs. vision; production: vocal tract vs. hands, face, and body in space: Emmorey, Luk, et al., 2008). It has been argued that bimodal bilinguals do not have the same cognitive advantage in terms of executive control as unimodal bilinguals (Emmorey, Luk, et al., 2008). The advantage of unimodal bilinguals in terms of cognitive control has been proposed to be the result of the constant engagement of cognitive mechanisms required to manage the two languages in competition (Macnamara & Conway, 2014). In order to retrieve the correct target in the desired language, the unimodal bilinguals must control the choice of the correct lexical entry of the targeted language and eliminate competing lexical forms (Bialystok, 2001). The management of attention on the target language and the monitoring of different languages' interference engage executive control processes of unimodal bilinguals, such as inhibition, updating, and shifting (Bialystok et al., 2006).

When it comes to bimodal bilingualism, accessing a lexical form in sign-specific and speech-specific regions of the brain is non-competitive (Evans et al., 2019) and there is less overlap in the neural systems when processing the two languages (Emmorey et al., 2016; Zou et al., 2012). Bimodal bilinguals need to suppress the production of sign language when a spoken language is used. However, they may not require the same degree of cognitive control as is the case for unimodal bilingualism given the fact that unimodal bilinguals need to discriminate two languages from the same modality (Emmorey et al., 2016). In addition, bimodal bilinguals have the particularity of being able to articulate the two languages simultaneously (Emmorey, Borinstein, et al., 2008). Evidence from Emmorey, Borinstein, et al. (2008) indicates that HS have a predominant preference for *code-blending* (i.e. the simultaneous production of sign and spoken work) over *code-switching* (i.e. changing from one language to another) when they are in the presence of other HS. These findings suggest that the dual lexical retrieval implied in code-blending is less costly in terms of cognitive resources than the language inhibition implied in code-switching (Emmorey et al., 2016; Green, 1998). Therefore, the sensory-motor differences in bimodal bilingualism may not require such effort of inhibition resulting in the enhancement of cognitive control. To our knowledge, studies on the cognitive differences between bimodal bilinguals and unimodal bilinguals are limited to investigations involving the executive function

(Emmorey, Luk, et al., 2008) and attention (Mercure et al., 2018). Flanker tests of executive function have shown that unimodal bilinguals perform better in terms of response times than bimodal bilinguals or monolinguals, the two latter performing similarly (Emmorey et al., 2008). In terms of attention, Mercure et al. (2018) compared unimodal bilingual, monolingual, and bimodal bilingual (i.e. with Deaf mothers) infants on tasks of attention capture and attention maintenance, using faces as stimuli. Contrary to what was expected by the investigators, bimodal bilinguals did not differ in terms of response times from monolinguals in orienting their gaze in the direction of faces (Mercure et al., 2018). These findings suggest it is not the bilingualism *per se* that provides an advantage in terms of cognitive control, executive function, and attentional mechanisms. Rather it is the higher degree of control between two unimodal languages compared to two languages of different modalities.

Study 2 was not designed to isolate the potential effect of bimodal bilingualism compared to unimodal bilingualism. In an attempt to investigate the effect of sign language use on cognition, the current findings have their own limits. In order to investigate whether DS and HS process spatial tasks similarly, which would have supported the hypothesis that the advantage observed in HS is due to sign language experience, additional analyses have been conducted to compare the two groups. Results showed that HS consistently outperformed DS in terms of accuracy on all spatial tasks (see Table 4). Caution must be applied when interpreting these results given the socio-demographic differences between the two older groups of participants. In terms of response time, older HS had significantly longer responses times than older DS on the SV, MR, and PT tasks. As a reminder, older HS had significantly longer response times in SV and PT compared to older HNS. In addition, younger HS had shorter response times than younger DS on the MR tasks. These findings suggest an effect of bimodal bilingualism in spatial processing or a different cognitive treatment of sign language that may influence the cognitive functioning of HS.

	ODS	OHS	YDS	YHS	*p*
	M (*SD*)		*M* (*SD*)		
SP					
ACC	6.25 (3.37)	8.15 (2.37)	8.80 (2.34)	10.18 (2.51)	.008*
RT (ms)	6410.87 (2573.38)	7043.61 (1924.57)	2386.52(1675.03)	2200.76 (1031.05)	.597
SV					
ACC	29.25 (5.12)	32.11(3.67)	35.41(4.19)	37.74(3.44)	.007*
RT (ms)	12667.88 (3346.24)	16437.94 (6852.51)	12406.53 (4200.04)	10952.60 (4092.20)	.285[a]
MR					
ACC	28.22 (10.51)	32.08 (8.24)	39.48 (5.91)	43.73 (6.60)	.027*
RT (ms)	27176.89 (8339.47)	35875.29 (10301.31)	28067.83 (8866.01)	22498.64 (6736.72)	.421[b]
PT					
ACC	53.77 (13.76)	43.92 (16.00)	24.52 (8.92)	17.99 (5.88)	.003*
RT (ms)	21406.54 (12326.77)	31875.48 (10933.69)	22396.84 (9971.45)	19479.03 (7540.63)	.107[c]

ACC = accuracy. *M* = mean. MR = mental rotation. ms = milliseconds. ODS = older deaf signers. OHS = older hearing signers. PT = perspective taking. RT = response time. *SD* = standard deviation. SP = spatial perception. SV = spatial visualization. YDS = younger deaf signers. YHS = younger hearing signers.

[a] Interaction was significant, $F(1,76) = 5.90$, $p = .018$. Simple effects showed OHS had longer response times compared to ODS.

[b] Interaction was significant, $F(1,76) = 13.59$, $p < .001$. Simple effects showed OHS had longer response times compared to ODS and that inversely YDS had longer response times compared to YHS.

[c] Interaction was significant, $F(1,76) = 8.38$, $p = .005$. Simple effects showed OHS had longer response times compared to ODS.

Table 2. – Mean, *SD*, and statistical significance of language experience's main effect between HS and DS of both age groups for accuracy and response times.

Interestingly, the advantage of HS has also been reported in previous research investigating the relationship between sign language use and spatial abilities. Two studies included in the scoping review (refer to Chapter 2) obtained results from HS, DS, and HNS on spatial tasks (Emmorey et al., 1993; Marschark et al., 2015). Emmorey et al. (1993) showed that

HS and DS had shorter response times than HNS on an adapted version of the Mental Rotations Tasks (Shepard & Metzler, 1971). On the other hand, Marschark et al. (2015) reported that HS, as well as HNS, outperformed DS in terms of accuracy on SV tasks. In both cases, HS appeared to have an advantage independently of the group to which they are compared. It is worth noting that these two studies have important methodological differences (notably in terms of sample selection: see argument in Hypothesis 3) and that they did not target the same spatial subskills. Therefore, it is difficult to determine which factor provides an advantage in terms of performance on spatial tasks in bimodal bilinguals. Finally, studies that have compared HS to HNS have reported an advantage in favor of HS. Keehner and Gathercole (2007) and Talbot and Haude (1993) reported that HS outperformed HNS in terms of accuracy on MR tasks. The comparison between younger HS and younger DS clearly suggests that sign language use is not the unique factor contributing to the better performances of HS on some spatial tasks. Further research is needed to elucidate the effect of bimodal bilingualism on spatial processing.

5.5 Contribution to the current knowledge on cognitive reserve

The most important work showing what seems attributable to the cognitive reserve in this cognitive domain is attributable to Salthouse et al. (1990). This research investigated the impact of long practice of SV through occupational functions on cognitive function in older architects. Salthouse et al. (1990) showed that older architects, currently working or recently retired, outperformed non-architects of the same age group on a battery of five SV psychometric tests from the Ekstrom et al. (1976) Kit of Cognitive Reference Tests (i.e. Paper Folding, Surface Development, Form Boards, Cube Comparison, Block Design). These findings raise interesting issues on the explanation of such cognitive advantage: Do these architects achieve this occupational position due to their inherently higher aptitude in spatial processing? Or did they enhance their spatial skills as the result of longtime practice in their professional functions? Spatial abilities are sensitive to training (e.g. Meneghetti et al., 2018), but high-level spatial abilities have also been shown to be a good predictor of success in STEM fields (science, technology, engineering, and mathematics: Lubinski, 2010). With this regard, sign language users provide an interesting research perspective. Deaf users of a sign language do not choose sign language as a mode of communication due to their inherent good spatial abilities. For signers (at

least for deaf signers and CODAs), sign language use is a lifestyle, a mode of communication that is linked to their identity and shows their sense of belonging to the Deaf community. As pointed out by Talbot and Haude (1993), the remaining grey zone, concerns the hearing signers who choose to learn sign language without intrinsic motivation (e.g. no deaf parents, no deaf friend, no deaf partner).

The current results make it difficult to link cognitive activity related to sign language with a potential neuroprotective function. Spatial mechanisms recruited in sign language production and comprehension may, through time, not require as strong cognitive processes in DS as hearing signers due to the high frequency of their solicitation. Sign language for DS is their primary mode of communication. Consequently, DS may be accustomed to using their spatial cognition skills. The fact that HS alternate between environments either dominant in sign language (e.g. family) or dominant in spoken language (e.g. bank appointment) might not allow such accommodation. Therefore, HS are more regularly in a position where they engage higher cognitive processes. This may provide a possible interpretation of the advantage of younger HS over younger HNS on MR and PT tasks because these two subskills are frequently solicited in sign language production (as discussed in Chapter 1). In terms of older signers, it is difficult to determine if their apparent coping for task demand is attributable to the confounding factors of bimodal bilingualism, their education level, or their level of intelligence. Future research should investigate this issue.

5.6 Limits

This thesis presents six main limits. An important one concerns the scoping review. The objective of this type of review is to collate exhaustively all sources of evidence that are relevant to the main topic (here performance on small-scale tasks of spatial abilities in signers). The fact that a review of the state of knowledge on the spatial abilities of signers was deemed necessary implies that the sources of evidence on this topic are heterogeneous. In sum, the limited body of knowledge and the lack of consensual findings made it difficult to generate firm hypotheses (Daudt et al., 2013).

The impact of sign language on spatial cognition might not be completely measured by small-scale spatial abilities. Small-scale spatial abilities investigated in Study 1 and Study 2 may

be too static to capture the real representation of space as it is processed in sign language. Therefore, small-scale spatial abilities assessed with psychometric standardized measures may not be sufficiently sensitive to investigate the effect of sign language on spatial cognition. The fact that sign language processing involves a diversity of visuospatial processes that exceed small-scale spatial abilities needs to be considered. Sign language comprehension requires handshape recognition, motion discrimination, facial identification and recognition of linguistically relevant spatial contrasts, integration of mental images, and memory of spatial locations (Emmorey, 1998). So far, it is unclear whether performance on tasks assessing small-scale spatial abilities have direct implications on language production and language comprehension in signers.

Factors contributing to cognitive reserve are well known. However, isolating these factors is challenging. Even if intelligence level and educational level could have been controlled in the present study, other factors may have also contributed to the actual reserve of participants and thus influenced the results. These factors may include (but may not be limited to) engaging in cognitively stimulating activities, socioeconomic status, physical exercise, leisure activities, and social engagement. In the past, all these factors have been considered as contributors to cognitive reserve (Lyu & Burr, 2016; Marioni et al., 2012; Pool et al., 2016; Reed et al., 2011; Rodrigues et al., 2020; Scarmeas et al., 2001; Weng et al., 2018). However, they were not considered in the current study.

The sample of older HS may be considered a limitation. HS have a particular profile in terms of levels of intelligence, education, and age. Therefore, global analysis including all six groups (age [younger/older adults] X language experience [DS/HS/HNS]) would have provided results influenced by the specific characteristics of older hearing signers. Also, the pool of sign language interpreters in Quebec is limited. Based on a study by Parisot et al. in 2008, there were 263 sign language interpreters in Quebec. It can be assumed that there were even fewer interpreters before the 1980s since at that time there was no formal training program in sign language interpretation in Quebec. In the present study, recruiting 20 older HS was a challenge. Consequently, it was not possible to pair the participants in the older signer group with the participants in the older HS group on all the inclusion/exclusion criteria that were initially identified. For example, many older HS (n = 15/20) had a university degree because they taught

in a school for the deaf. On the other hand, because sign language interpreting services were not available prior to 1980s, older DS (who were between 25 and 40 years of age at that time) did not have access to post-secondary education. Although an attempt was made, it was impossible to match the older DS and the older HS on the basis of their educational background. Of the 20 older DS who took part in the study, only one of them reported that they had post-secondary education.

The tests used to confirm the eligibility of the deaf participants have their own limits. Tests were culturally and linguistically adapted in LSQ following rigorous steps (see section 4.3.1.2). However, neither the LSQ-CST, the subtests of the BECLA (Macoir et al., 2016), and the syntactic comprehension subtest of the GRÉMOTs (Bézy et al., 2016) were normalized prior to their use for experimental purpose in this thesis. The main objective underlying the use of these tests was to ensure that the deaf participants selected for the experiment did not have cognitive difficulties that would limit their reactiveness and responsiveness (LSQ-CST) and that participants used LSQ to understand LSQ discourse on a regular basis (BECLA and GRÉMOTs). Even if these tests were not used for diagnostic purposes, it is argued that their use was necessary despite the lack of standardized norms. The normalization of psychometric tests to assess cognition and language in LSQ are needed.

Finally, it is necessary to mention that, given the high prevalence of bilingualism in Quebec, few of the HNS recruited for the study were unilingual Francophones. Over the past 50 years almost all francophone students in Quebec have learned a second language (often English) while attending primary and secondary school (Lamari & Anstett, 2015). In addition, exposure to multimedia content (e.g. Netflix and YouTube) contributes to improving the level of competency of Francophones in English. In 2016, 44.5% of French Quebecers considered themselves French-English bilinguals (Statistique Canada, 2019). The proportion of bilingual people living in Quebec is even greater if one considers other forms of unimodal bilingualism (e.g. French–Italian, French–Spanish). In addition, the level of bilingualism of the deaf participants (sign-text or sign-sign) was not controlled.

5.7 Further perspectives

The present research may be considered among the pioneering studies that have investigated age-related changes in cognitive function among signers. Considering that no previous research has addressed changes in spatial cognition as a function of aging, much remains to be done. First, future research should investigate more thoroughly the relationship between speed of processing (response time) and level of ability (accuracy) with regard to spatial performance of older adults. Research data on the effect of instructions (e.g. informing vs. not informing the participant that the response times will be recorded) could provide relevant information on the real capacity of the older adults to rapidly perform small-scale psychometric spatial abilities tasks. This research would reveal the intrinsic motivation of the participants to perform the task, beyond their desire to perform the task rapidly in order to comply to the instructions given to them. As mentioned in the limits section (section 6.5), the assessment of small-scale spatial abilities may not reveal the true effect of sign language use on cognition. The use of small-scale tasks of spatial abilities has provided insights concerning the cognitive factors and processes underlying the performance on spatial tasks involving small figures only. Future research should consider large-scale abilities (e.g. navigation, spatial orientation) to investigate the effect of sign language use on spatial cognition as a function of aging. Also, as previously mentioned, age of acquisition of sign language and age of onset of deafness are two factors that may influence one's level of performance on cognitive tasks. Also, the age at which deafness is diagnosed and the type of early language intervention chosen by the family are important factors to consider. Future research could focus on investigating the effect of these factors on performance on spatial abilities throughout the lifespan. Finally, a cross-sectional study involving the measurement of cognitive and linguistic abilities could be conducted. The results of those investigations would make it possible to observe the relationship between performance on spatial ability tasks and linguistic (oral and sign language) comprehension and production.

5.8 Conclusion

This thesis provides the first set of data on age-related changes on spatial cognition among users of a sign language. More precisely, the objectives of the research program were to: i) investigate the effects of aging on performance on tasks of spatial abilities (SP, SV, MR, and PT) in DS and ii) investigate whether there are differences in performance on tasks of spatial abilities among signers (DS and HS) and HNS of different age groups (younger and older adults). The thesis is comprised of three articles consisting of one scoping review and two experimental studies. The scoping review, based on 22 sources of evidence, revealed that most studies that have addressed the relationship between sign language use and SP and PT reported no difference between signers and non-signers. It also showed that there are important discrepancies in the results of studies that investigated the relationship between sign language use and MR or SV abilities. The two experimental studies showed that, in the spatial domain, older DS exhibit similar age-related changes as those that have been observed in the hearing population. It also highlighted a specific advantage of hearing signers over hearing non-signers in terms of performance on MR and PT tasks regardless of age. A general advantage of older signers (deaf and hearing) over older non-signers on SV tasks was also observed. These findings raised interesting questions on the effects of sign language use within the specific bimodal bilingual population.

Three aspects of the present research may be considered novel. To our knowledge, it is the first cross-sectional study that compares the effects of aging among three groups with different language experience (DS/HS/HNS). In addition, the thesis investigated the four small-scale spatial abilities (SP, SV, MR, and PT: Linn & Peterson, 1985; Lohman, 1988) within the same study. The experimental design used makes it possible to obtain a global portrait of how spatial information is processed by signers as well as non-signers. Finally, this research adopted an intersectoral and interdisciplinary approach, combining both cognitive and linguistic perspectives in order to present an integrative portrait of older signers.

The results reported in the present thesis will be helpful to future researchers interested in investigating cognition throughout the lifespan among signers. Future research should investigate more thoroughly the particularities of bimodal bilingualism on cognition and its effect

on aging. Further, the collection of cognitive as well as linguistic data within the same sample of participants may serve to establish links between cognitive processing and sign language production and comprehension.

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Appendix 1

This chapter presents the general methods on which Paper 2 and Paper 32 were designed. The following methodological elements are explained: a definition of the target population and the selection criteria; a description of the recruitment process; a presentation of the measuring instruments used in the selection phase and the experimental phase; and the experimental procedure.

4.1 Participants

A total of 40 prelingually deaf signers (DS: 20 older adults, 20 younger adults), 40 hearing signers (HS: 20 older adults, 20 younger adults), and 40 hearing non-signers (HNS: 20 older adults, 20 younger adults) were recruited for this study (N=120). Paper 2 presents data from the 40 prelingually DS (20 older adults, 20 younger adults). Paper 3 included the 120 participants. The groups of older adults were between 64 and 80 years of age. The groups of younger adults were aged between 18 and 35 years of age. The inclusion criteria for the DS, HS, and HNS participants are presented in Table 1.

Criteria: measure	DS	HS	HNS
Hearing status: previous audiogram or results from a portable audiogram	Bilateral sensorineural severe-to-profound hearing loss of ≥ 75 dB HL in both ears at audiometric test frequencies between 250 Hz and 3,000 Hz	Hearing detection thresholds ≤ 30 dB HL in both ears at audiometric test frequencies between 250 Hz and 3,000 Hz	Hearing detection thresholds ≤ 30 dB HL in both ears at audiometric test frequencies between 250 Hz and 3,000 Hz
Knowledge of sign language: translated and adapted version of six subtests of BECLA and one subtest of GRÉMOTs in LSQ	Self-reported use of LSQ as a mode of communication and success in all tests	Self-reported use of LSQ as a mode of communication and success in all tests	Self-reported absence of knowledge of LSQ and failure in all tests
Knowledge of French: six subtests of BECLA and one subtest of GRÉMOTs	Knowledge of oral French not sufficient to maintain an oral conversation[9] and failure in all tests	Self-reported use of French as a frequent mode of communication and success in all tests	Self-reported use of French as their primary mode of communication and success in all tests
Age of deafness: questionnaire on background information	Self-reported prelingual deafness (before age 3)	N/A	N/A
Cognitive health: DS: LSQ-CST HNS, HS: French version of ACE	≥ 83/130	≥ 83/130	≥ 71/110
Vision: Near and far Snellen Chart Confrontation test	Normal or corrected-to-normal eyesight		
Intelligence: RCPM	Within the normal range based on age and educational level (Basso et al., 1987)		
Occupation: self-reported in a questionnaire on background information	Not presently holding, nor having held, an occupation that might have trained their spatial skills (e.g. architects, pilots, taxi drivers)		

ACE = Addenbrooke's cognitive examination. BECLA = Batterie d'Évaluation Cognitive du Langage chez l'Adulte. dB HL = decibels in hearing level. DS = deaf signers. HS = hearing signers. HNS = hearing non-signers. Hz = Hertz. GRÉMOTs = *Batterie d'évaluation des troubles du langage dans les maladies neurodégénératives*. LSQ = *Langue des signes québécoise*. LSQ-CST = *Langue des signes québécoise*-Cognitive Screening Test. N/A = not applicable. RCPM = Raven Coloured Progressive Matrices.

Table 3. – Inclusion criteria for the DS, HS, and HNS participants and the instrument measure used to assess each criterion

[9] DS are generally bilingual (also referred to as sign-print or sign text bilinguals: Piñar et al., 2011) because they acquire a sign language and have a certain level of knowledge of the surrounding spoken language or its written form (Lillo-Martin et al., 2016). However, spoken language comprehension through lip-reading is difficult and few deaf signers are comfortable using this means of communication.

To ensure that the spatial processing differences were not due to differences in demographic factors, participants in the HS and HNS groups were matched to the participants in the DS group on the basis of their educational level and intelligence performance at Raven's Coloured Progressive Matrices Test (Raven, 1984). Groups were also matched for gender due to reports of a potential gender effect on spatial abilities (Linn & Petersen, 1985; Voyer et al., 1995). Table 2 presents the characteristics of participants in terms of age, education level, score on intelligence test, score on cognitive screening test, sex, and handedness.

	DS			**HS**			**HNS**			
Variable	M	(SD)	rg	M	(SD)	rg	M	(SD)	rg	***p***
Older adults										
Age	71.5	(4.6)	66-80	68.1	(3.5)	64-78	71.5	(5.2)	65-80	.051
Years of education	11.4	(2.7)	6-15	17.1	(2.3)	10-21	12.2	(3.5)	4-18	.000*
RCPM	26.0	(4.9)	17-33	30.8	(4.1)	21-36	24.6	(4.2)	19-31	.000*
CST	102.1	(4.8)	93-108	96.3	(3.5)	87-100	90.4	(4.7)	83-98	
Gender (Ma;F)		10;10			4;16			10;10		
Handedness (R;L;A)		14;5;1			16;3;3			16;1;3		
Younger adults										
Age	30.8	(3.5)	25-35	28.0	(4.1)	20-34	29.7	(3.7)	19-34	.073
Years of education	15.0	(3.0)	11-23	16.3	(2.7)	11-22	15.0	(2.1)	10-18	.236
RCPM	33.9	(2.3)	28-36	33.4	(1.8)	30-36	34.0	(1.9)	30-36	.568
CST	108.7	(2.0)	104-110	96.4	(3.19)	89-100	95.7	(4.6)	83-100	
Gender (Ma;F)		10;10			10;10			10;10		
Handedness (R;L;A)		16;4;0			19;0;1			18;1;1		

A = ambidextrous. CST = Cognitive Screening Test. DS = deaf signers. F = Female. HS = hearing signers. HNS = hearing non-signers. L = left dominance. *M* = mean. Ma = male. RCPM = Raven's Coloured Progressive Matrices. R = right dominance. rg = range. *SD* = standard deviation.

Table 4. – Participant characteristics including age, education level, score on intelligence test, score on cognitive screening test, gender, and handedness

As a group, 30 DS self-reported being congenitally deaf while 10 indicated becoming deaf before 2.5 years of age. 5/40 reported that both parents are deaf, 13/40 had a close deaf family member other than their parents, and 22/40 reported no deaf family members. Etiology of deafness was unknown for 14/40 participants, while 11/40 participants were deaf due to genetic

factors, and 15/40 became deaf due to illness in utero or at an early age (e.g. meningitis, measles, otitis, rubella). Younger DS reported acquiring sign language at an average age of 3.8 (*SD* = 4.4, rg = 0–15), while older DS acquired sign language at an average age of age 7.9 (*SD* = 2.3, rg = 4–15). The late acquisition of the older DS is attributable to the fact that they acquired sign language when they entered the institutionalized school for the deaf.

All HS self-reported being bilingual (LSQ-French); 11 were native-bilingual children of deaf parents, three were bilingual and had a close deaf family member, and 26 acquired LSQ in adulthood (*M* age = 23.7, *SD* = 3.6, rg = 18–33). Most of the younger and older HS group (37 out of 40) were, or had been, LSQ-French interpreters or LSQ teachers. The other three worked in a deaf environment and used LSQ regularly. On average the older HS had used LSQ for 47 years (*SD* = 10.5; rg = 30–71) while younger HS had used LSQ for an average of 15 years (*SD* = 9.0; rg = 5–29). At the time the data were collected, older HS self-reported a less frequent use of LSQ than their younger counterparts. This is attributable to the fact that they were retired or partly retired. For this group, the mean self-reported use of LSQ in their daily life was 14.70% (*SD* = 16.0; rg = 0.5–60). All the younger HS reported a use of LSQ in daily life of 45.75% (*SD* = 21.5; rg = 10–90). The group of older HS is an exception due to the characteristics of the recruitment pool available in the province of Quebec. Specifically, the educational level of this group of participants exceeded by 5–5.5 years the education of the two other groups of older adults, and 4 men (out of 20 participants) were recruited in this group.

4.2 Recruitment process

Considering that DS and HS are considered as hard-to-reach communities with a limited number of potential participants (e.g. 263 sign language interpreters in the province of Quebec based on the last recruitment: Parisot et al., 2008), we planned on recruiting 120 participants (20 per group: [older adults; younger adults] X [DS; HS; HNS]). On the basis of previous research conducted with deaf people (Rudner et al., 2010), the proposed group sizes are estimated to be sufficient for planned statistical analyses (analyses of variance [ANOVAs]) and to ensure adequate statistical power.

The initial stage of the recruitment was to contact relevant key organizations in relation with the targeted population. For the DS population, social centres within the Deaf community (i.e. *Centre de loisirs des Sourds de Montréal*, *Maison des Sourds*, *Association des personnes avec problèmes auditifs des Laurentides*, *Association des Sourds de l'Estrie*) and a deaf occupational therapist from Raymond-Dewar physical and sensory rehabilitation centre provided lists of interested participants. For the HS population, regional interpretation services (i.e. *Services régionaux d'interprétations*, *Service d'interprétation visuelle et tactile*, *Services adaptés* [SAIDE]) and individual members in the sign language interpreters' community contributed by providing names and contact information of potential participants corresponding to the selection criteria. For HNS, a senior centre and a community organization (respectively, *Réseau Sélection Québec* and *Les Accordailles*) allowed an access to their members for the recruitment. The initial contact with potential participants was made by telephone, email, or using a videoconference platform (e.g. Skype) in order to assess their interest to participate in the study and confirm their eligibility. The recruitment was based on a snowball sampling technique, consisting in asking currently involved participants to identify other potential participants. This technique has proven to be efficient when recruiting hard-to-reach participants, as it was the case with DS and HS (Valerio et al., 2016). Data collection was completed between October 2018 and August 2019.

4.3 Material

4.3.1 Measuring instruments used to assess the eligibility of the participants

4.3.1.1 Source of background information

Participants responded to a questionnaire on background information that was administered in a directed-interview format. Information collected included: birthdate, handedness, level of education, occupation (at the moment of the test or, when applicable, before they retired), eye health, and family background (hearing status of parents, siblings, and relatives). Additional questions in DS' and HS' questionnaire covered the age of acquisition of LSQ and their current use of sign language (context, frequency). Exclusively for the DS' questionnaire,

hearing status, age of onset of deafness, age at which they began their formal education (only for older adults) were added as supplementary questions.

4.3.1.2 Cognitive assessment tests

To ensure that all participants were cognitively healthy, a general cognitive screening test was administered to the six groups. The French version of Addenbrooke's Cognitive Examination (ACE; Bier et al., 2004) was administered to all hearing participants (HS and HNS). This test is a widely used screening tool validated for measuring global cognitive functioning. The ACE is administered in 10 to 20 minutes. It is divided in seven domains of cognition including visual-spatial abilities, delayed recall (memory—anterograde and retrograde), attention/concentration, language, orientation, verbal fluency, and perceptual abilities. The French version of the ACE, designed to detect mild cognitive impairment, has a sensitivity of 86.6% and a specificity of 70.5% (Bier et al., 2004). The threshold score to distinguish cognitive abnormalities from normal-cognitive functioning is 83/130 points (Bier et al., 2004). This cognitive screening test was selected because many of the test items are similar to the test items included in the cognitive assessment protocol administered to the DS.

To assess the cognitive abilities of the older DS participants, a cognitive screening tool had to be adapted in sign language. Lack of "cultural fairness" in testing minorities' cognitive abilities has been a preoccupation since the 1960s (Marschark, 2003). Using standardized tests based on norms obtained from a population of hearing individuals to assess the cognitive abilities of deaf signers has been shown to lack validity (Baker & Baker, 2011). Also, previous research reported the unreliability of using an interpreter to evaluate cognition due to language and cultural differences between deaf signers and hearing oral speakers (Dean et al., 2009; Hill-Briggs et al., 2007). Traditional neuropsychological screening tests, such as the Montreal Cognitive Assessment (Nasreddine et al., 2005), the Mini-Mental State Examination (Folstein et al., 1975), and the ACE (Bier et al., 2004), include items linguistically and culturally non-reliable when translated into sign language and administered to the deaf population (Atkinson et al., 2015). Recently, the British Sign Language Cognitive Screening Test (BSL-CST) was developed by Atkinson and her colleagues (2015). This test was shown to be culturally and linguistically suitable for assessing users of BSL in the deaf population (Atkinson et al., 2015). For the proposed research project, an adapted version

of the BSL-CST was developed in LSQ, which will be referred to as the LSQ-CST. The LSQ-CST is administered in 30 to 40 minutes. It is divided in seven domains of cognition including orientation, attention, delayed recall, verbal fluency, language, visual-spatial abilities, and executive function. The steps taken to adapt the cognitive screening test into LSQ are outlined in Figure 4. Based on a population of 226 deaf signers, Atkinson et al. (2015) reported that using a cut-off score of 71/110 points eliminated participants with dementia with a sensitivity index of 100%. Given the minor cultural adaptation that was made to produce the LSQ-CST, the same cut-off score was used to screen deaf participants who took part in the investigation.

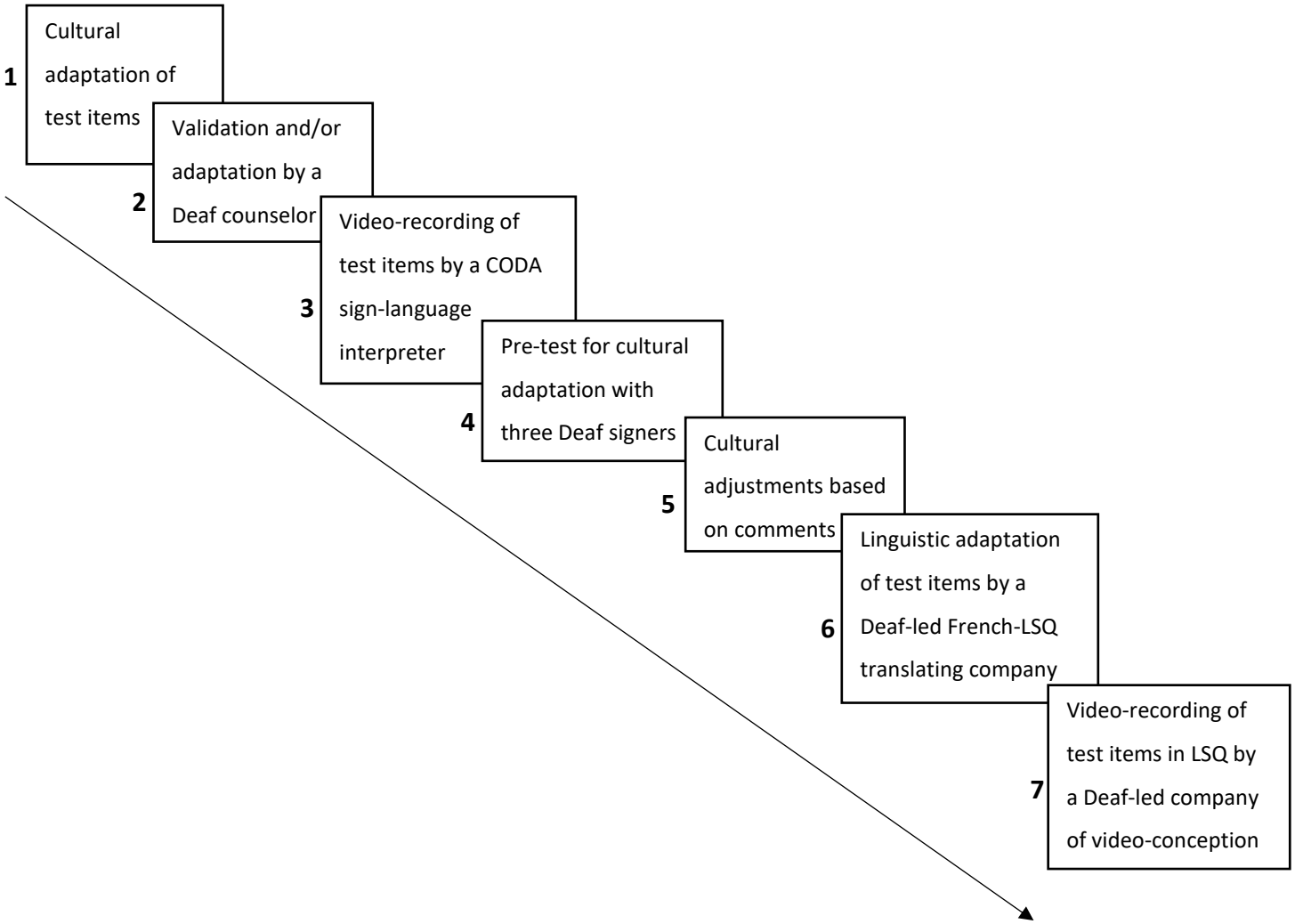

Figure 6. – Steps of cultural and linguistic adaptations of psychometric measures

4.3.1.3 Intelligence Assessment

To assess general intellectual abilities, the Raven's Coloured Progressive Matrices (RCPM: Raven, 1984) was administered to all participants. The RCPM is a non-verbal test with little verbal instructions. It is divided in three sections (A, Ab, and B) containing 12 items each, for a total of 36 points. For each item, an incomplete nonrepresentational coloured design is presented with six alternatives to complete the design. The participants must choose the best alternative to complete the pattern. A correct answer results in one point. Test items increase in difficulty within the sections and from one section to another. The completion time is between 15 and 30 minutes. The RCPM has been shown to be highly valid for the assessment of older adults (Panek & Stoner,

1980; Villardita, 1985) as well as groups with cultural differences (Carlson & Jensen, 1981). The original version of the Raven's Progressive Matrices (Raven, 1938) was shown to be reliable in assessing deaf population using sign language (Blennerhassett et al., 1994). Normative values stratified by age and educational level are available for individuals between 15 and 80 years of age (Basso et al., 1987; Smits et al., 1997).

4.3.1.4 Auditory assessment

Hearing screening tests were conducted using TDH-39 headphones and a Maico MA-41 audiometer. For the hearing participants, the inclusion criteria stated that the hearing detection had to be ≤ 30 dB HL in both ears at the following test frequencies: 250, 500, 1000, 2000, and 3000 Hz. Hearing detection thresholds were obtained from deaf participants who were not able to provide (or give access to) a previous audiogram. The inclusion criteria for the deaf participants stated that the hearing detection thresholds had to be ≥ 75 dB HL at the following test frequencies: 250, 500, 1000, 2000, and 3000 Hz.

4.3.1.5 Vision acuity assessment

Because deaf individuals have been reported to have more visual impairments than hearing individuals (Guy et al., 2003), a vision acuity assessment was conducted. A farsighted visual acuity test with a Snellen chart (GF #1240) was conducted to ensure that all participants have normal or corrected-to-normal visual acuity. Self-reported information on previous eye pathologies was obtained from the background interview. The Snellen chart test consists of viewing a standard set of multiple letters viewed from a distance of 20 feet. A score of 20/20 is considered as a normal visual acuity. This score means that the person is able to read the letters at a distance of 20 feet (represented by the first number) that most people would be able to read at 20 feet (represented by the second number). First, visual acuity was checked separately in each eye (the untested eye is covered by the participant's hand). Then the same test was administered while the participant used both eyes. For the purpose of this study, the inclusion criteria stated that the visual acuity in each eye had to be ≤ 20/40. An equivalent chart was used to assess nearsighted visual acuity. The chart is placed at a distance where the participant feels comfortable reading. Again, visual acuity was tested for each eye separately and then for both eyes

simultaneously. The inclusion criteria stated that the nearsighted visual acuity in each eye had to be ≤ 20/50. In addition, a confrontation test was administered to assess peripheral vision. For this test the experimenter's finger is moved from the outside of the visual field (four quadrants are tested: upper, lower, left, and right) to a more central position until the participant confirms that the target is detected. The participant is seated in front of the experimenter and is instructed to fix the experimenter's nose. When the experimenter is able to detect the target in his/her peripheral field, the participant is expected to also be able to detect the finger. Left and right eyes were tested separately. These tests were conducted to ensure that the participants did not have any peripheral vision impairment and that they were able to see the stimuli presented in the experimental tasks. Specifically, the visual test battery was used to exclude any deaf participants with Usher's syndrome.

4.3.1.6 Language assessment

Subtests of the *Batterie d'Évaluation Cognitive du Langage chez l'Adulte* (BECLA: Macoir et al., 2016) was administered to the six groups. The subtests selected from the battery are the following: i) pairing of images based on their semantic class (20 pts), ii) object and verb naming (20 pts), iii) repetition of words (15 pts), iv) repetition of non-words (10 pts) and v) pairing of word/signs with an image (20 pts). In addition, a syntactic comprehension subtest from the *Batterie d'évaluation des troubles du langage dans les maladies neurodégénératives* (GRÉMOTs: Bézy et al., 2016) was used to assess language comprehension (24 pts). Language tests were administered to all the participants in both languages (LSQ and French). The LSQ version of the subtests of BECLA and GRÉMOTs was adapted and translated following the same procedures as those summarized in Figure 4. A series of 10 consecutive errors ended the test, indicating the participant's lack of knowledge in the language being tested (i.e. French or LSQ).

4.3.2 Test stimuli used to measure spatial abilities

4.3.2.1 SP tests

The Water-Level Test (WLT: Piaget & Inhelder, 1956) was used to assess the constancy of horizontality related to gravity. Schematic water bottles were presented to participants at different angles of inclination. The participants were asked to draw the line showing where the

water would be if the bottle were half-full. The test consists of eight stimuli that are presented in a predetermined order, with a bottle angle of inclination being 210°, 60°, 330°, 240°, 300°, 120°, 150°, and 30° (see Figure 5). Errors were calculated on the basis of the horizontality of the line. A response is scored as correct if the line drawn on the screen is within ±10° of inclination.

Figure 7. – Example of a test item adapted from the WLT: a bottle of water with an angle of inclination of 300°.

The Computerized Rod-and-Frame Test (CRFT, version 3.2: Docherty & Bagust, 2010) was used to assess SP ability by evaluating the verticality of lines. In this test, the participant had to adjust a tilted linear marker, a rod, under two conditions: in isolation on a dark background or embedded within a square frame. The participant was instructed to move the rod until it was vertical, independently of the surrounding information (i.e. tilted frame). The disposition of the frame and the rod varied in their degree of orientation (frame: 0°, 18°, -18°, absence of frame; rod: 20°, -20°). Participants adjusted the rod using the right and left button of a computer mouse. The computer was placed 70 centimeters directly in front of the participant. To constrain their dependence on the visual field, participants wore a pair of goggles from Low Vision Simulators (model R104), reducing their visual field to a tunnel of 20° vision (see Figure 6B). For this test, lighting in the room was reduced to its minimum. This test contained 18 trials. Errors are scored based on the degree deviation of the rod relative a 0° inclination (i.e., ±2° inclination is accepted).

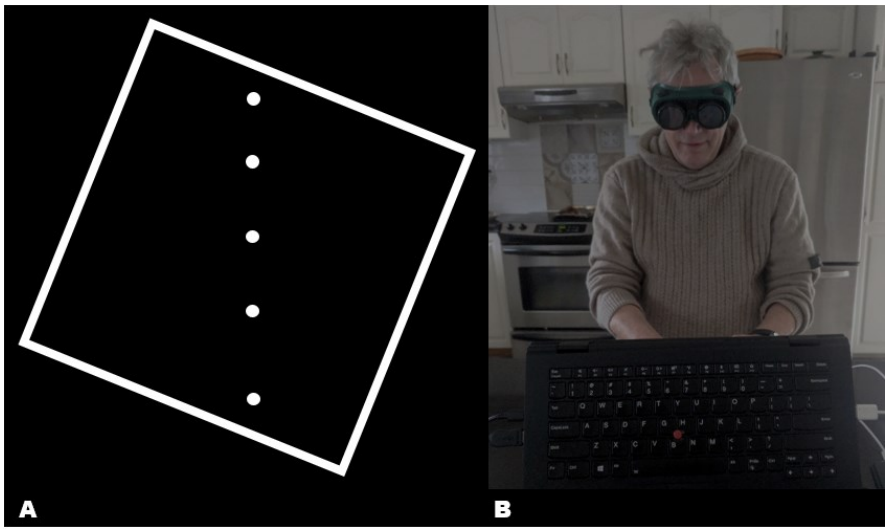

Figure 8. – A. Example of a test item adapted from the CRFT: rod positioned at 0° (expected response) and a frame exhibiting a +22° tilt. B. The participant is wearing goggles used to simulate low vision (model R104). Testing is conducted in a room with minimum lighting.

4.3.2.2 SV tests

The Hooper Visual Organization Test (HVOT: Hooper, 1983) was used to assess visual analytic and synthetic abilities. It consisted of two-dimensional line drawings cut into two to four pieces. Each drawing represented a common object or animal such as an apple or a cup (see Figure 7). The participant was instructed to name (in French or LSQ) the picture after reorganizing the pieces mentally. The test contained 28 items. Each correct answer is awarded one point.

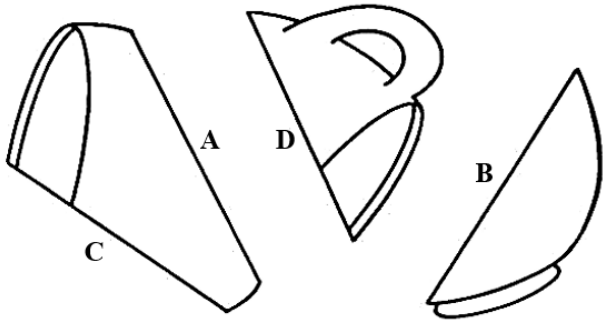

Figure 9. – Example of a test item adapted from the HVOT where the *A* face connects with the *B* face, and the *C* face with the *D* face, resulting in an image of a cup.

The Revised Minnesota Paper Form Board Test (RMPFBT: Likert & Quasha, 1941) was used to assess SV ability. In this multiple-choice test, the participant was required to manipulate two-dimensional geometrical shapes cut into two to five segments. For each item, the participant had to look at the target figure cut in fragments (upper left corner of the screen) and touch on the tactile screen the correct option (from A to E) in order to show what the figure would look like if all the pieces were put together (see Figure 8). The level of difficulty increased from one item to another. This test comprised 64 test items. Each correct answer is awarded one point.

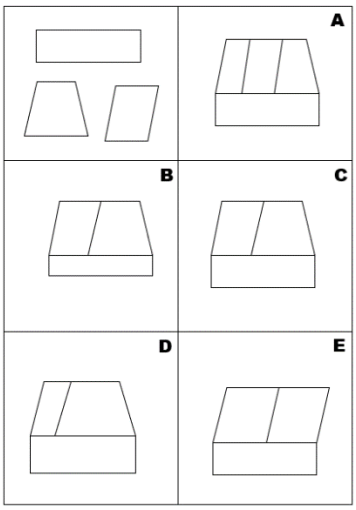

Figure 10. – Example of a test item adapted from RMPFBT. The target separated segments appear in the upper left corner, and the five response foils are displayed in segments A to E. In this example the expected response is C.

4.3.2.3 MR tests

The Mental Rotation Test (MRT: Vandenberg & Kuse, 1978, redrawn by Peters et al., 1995) consisted of a test where a three-dimensional target figure was shown next to four similar three-dimensional figures. Each figure consisted in an abstract structure made of assembled cubes. The participant was instructed to identify, by touching the tactile screen, which of the four test figures were rotations of the target figure (see Figure 9). For each test item, two of the four figures were correct matches (same structure as the target but rotated) and two were distractors (rotated mirror image of the target or rotated target from another item). The test was comprised of 24 items. Both correct matches need to be identified to be awarded a point.

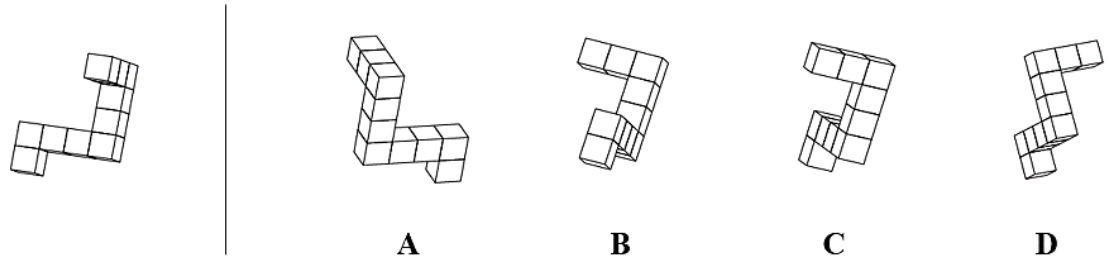

Figure 11. – Example of an item adapted from the MRT representing the target figure on the left and the four response foils on the right. For this test item, the expected responses were alternatives A and C.

The Card Rotation Test (CRT: Ekstrom et al., 1976) was used to assess MR ability. In this task, a two-dimensional target figure was displayed on the left of the screen, followed by eight similar figures (see Figure 10). The participant was instructed to identify, by touching the tactile screen, all figures that represented a rotation of the target figure, avoiding those involving a mirror effect with or without a rotation. Therefore, a good match would be a representation of the target figure as is or rotated, while an incorrect match would correspond to a representation of a mirror version or a mirror-rotated version of the target figure. For each trial, correct answers could vary between two and seven figures. The participant was informed that a good match would award one point, while a bad match would retrieve one point. The test was comprised of 20 items. Each correct identification is awarded one point and each incorrect answer retract one point.

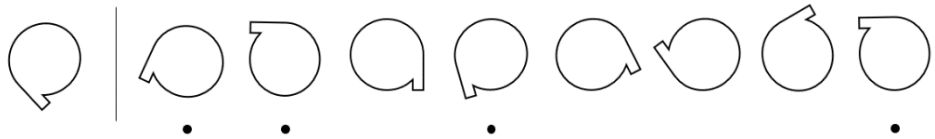

Figure 12. – Example of an item adapted from the CRT representing the target figure on the left and the eight similar figures on the right. For this test item, the correct responses are indicated by a dot placed below the figure.

4.3.2.4 PT test

The Perspective Taking/Spatial Orientation Test (PTSOT: Hegarty & Waller, 2004) was used to assess perspective-taking ability. For this test, participants viewed drawings of seven common

objects (car, stop sign, house, cat, flower, tree, and traffic light) that were displayed in a specific layout that appeared in the upper-left quadrant of the screen (see Figure 11). In the upper-right quadrant, participants viewed a circle that contained two of the seven objects from the left quadrant. One of the objects was positioned in the centre of the circle while the second object was positioned at the top of the circle. The two objects were connected by an arrow. Finally, at the bottom of the screen, there was a box with a LSQ signer (for DS) or a French sentence (for HNS and HS) giving instructions for the current set of stimuli. For each test item, participants were instructed to imagine themselves in the upper-left layout: (1) in the same position as the object that appeared at the centre of the circle and (2) facing a second object that appeared at the top of the circle. While imagining this spatial configuration, they had to draw a line with their index finger showing the relative direction of a third object. The third object was indicated by the LSQ signer in the video instruction or the written sentence. In the example illustrated in Figure 11, instructions were to imagine that you were standing at the position of the cat, facing the tree. From that perspective, you were asked to draw a line in the direction of the car (i.e. the third object). By placing a finger on the monitor, the participant had to trace a line from the centre of the circle to its circumference, by pointing at the relative position of the third object. DS viewed the video instructions twice: At first, the instructions appeared as a full-screen presentation of the signed instructions. Then, the size of the video was reduced, and the test items also appeared on the screen (as seen in Figure 11). The task consisted of drawing a line for 12 stimuli presented consecutively. Each participant completed one practice trial. Of the 12 items, six required a perspective change of more than 90° and six required a change of 90° or less. Scoring is based on the angle disparity measures between the answer produced and the expected response.

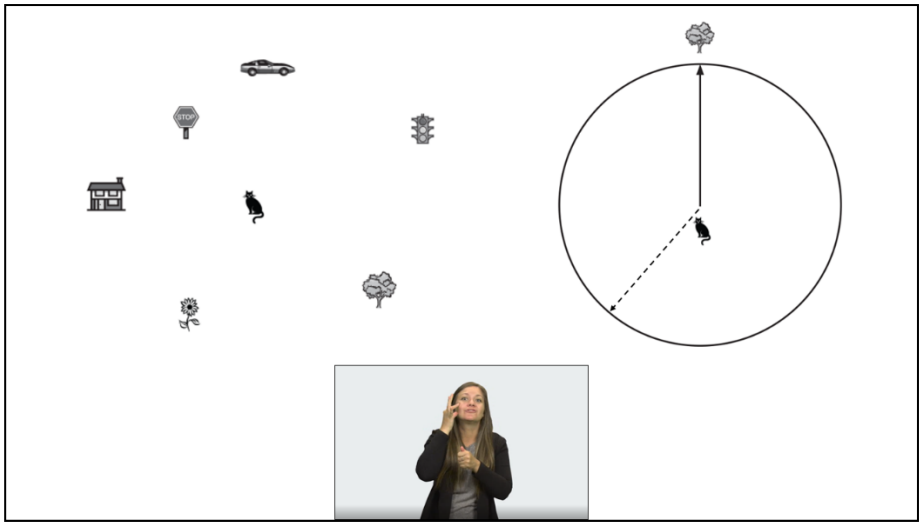

Figure 13. – Example of instructions for a test item adapted from the PTSOT: “Imagine that you are standing at the position of the cat facing the tree. Draw a line to the car.” LSQ video-instructions for DS appeared in the lower-centre part of the monitor. A French sentence replaced the video instructions for HS and HNS. The dotted line in the circle represents the expected response.

The stimuli for the CRFT were programmed with Python 2.7 software. E-Prime 3.0 software (Psychology Software Tools, Inc. [E-Prime 3.0], 2016) was used to program the stimuli for the other six tests. The computer used for data collection consisted of a Lenovo ThinkPad Yoga X1 with a 14” tactile screen, enabling data collection through touchscreen and mouse device (for CRFT only). Techentin et al. (2014) have shown that for spatial tasks the test administration format (e.g. computerized, paper-pencil, cards, or slides) does not influence performance. Therefore, the test administration and scoring (accuracy and response times) of all tests were computerized. There was no time restriction on any of the tasks. The automatic scoring generated by E-Prime or Python was manually checked by two independent people.

4.4 Procedure

The performance of older adults on tasks of spatial abilities has been shown to be influenced by the environment in which the tests are administered (Kirasic, 1989). In the present study, the experimental test sessions were conducted at a location that was convenient for the participants (e.g. their home), a private room in a public place (e.g. a private room in a library, a

private room designed for social activities in a residential home for older adults, or a private room at their current workplace), or at the *Centre de recherche de l'Institut universitaire de gériatrie de Montréal* (CRIUGM).

Two test sessions were scheduled for each participant. The total time required to administer the complete protocol ranged from 2.5 h to 4.5 h. Session 1 served to verify that the participant met all the recruitment criteria. All the experimental tests were administered during session 2 (see Figure 12 for the complete procedure). The tests of spatial abilities were administered in a random order across all the participants. Each task included one to eight practice trials, depending on the complexity of the task. The participants were tested individually by a bilingual (LSQ-French) experimenter. Standardized video-recorded instructions were provided in LSQ for DS and in spoken French based on written instructions for HS and HNS. For each task, participants were informed that their response time would be recorded. Accuracy scores and response time were automatically recorded by the computer, with the exception of HVOT. For this task, the response provided by the participant was manually coded by the experimenter and response time was encoded when the participant pressed the spacebar to skip to the next item.

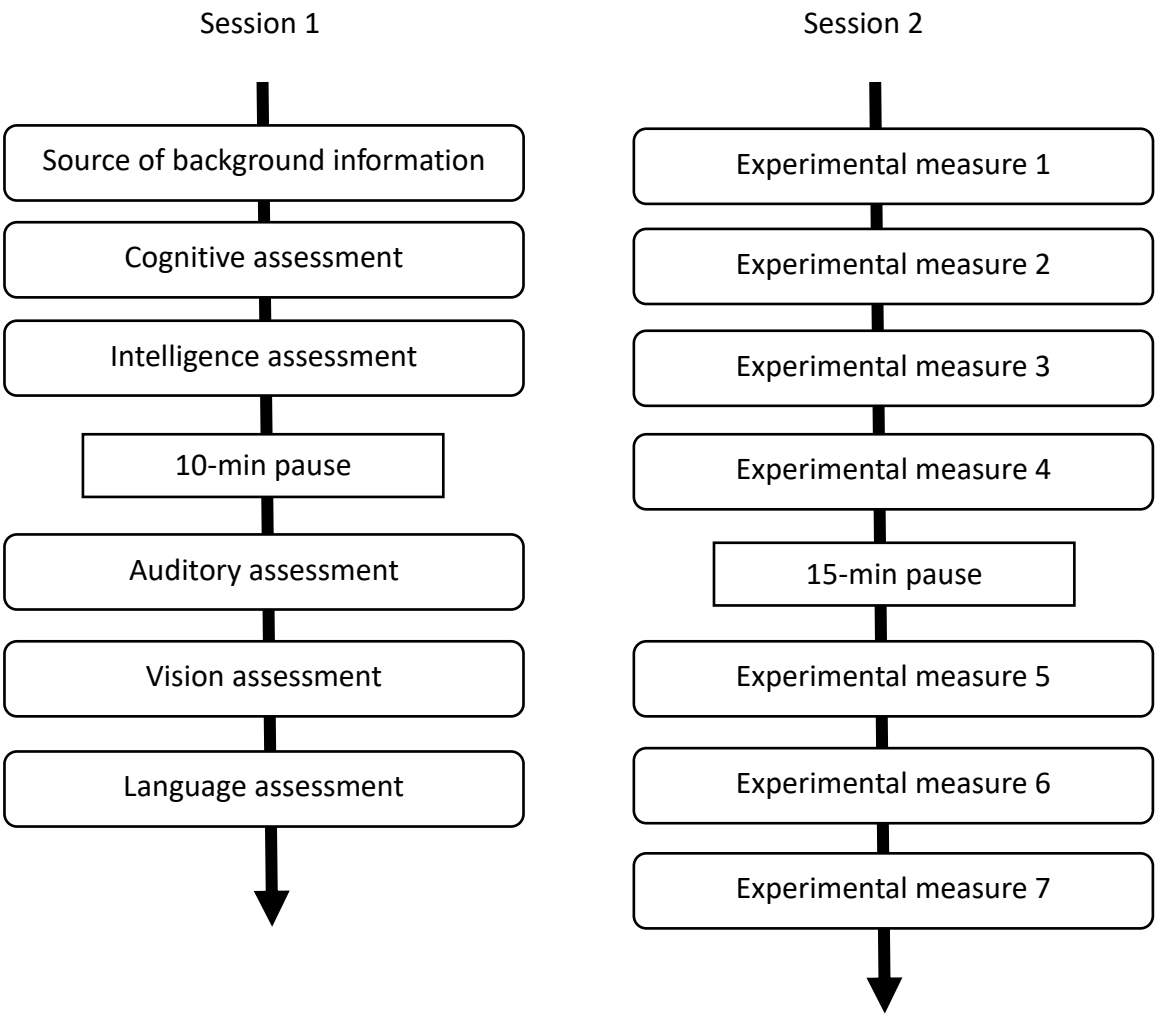

Figure 14. – Procedure of test administration for session 1 and session 2

4.5 Ethical considerations

This study satisfied the ethical principles of the Helsinki Declaration and met the requirements of the Ethics Committee for Aging-Neuroimaging Research of the CRIUGM. All participants signed the consent form that was presented in a paper format as well as in a video format in which the same information was presented in LSQ for DS. All participants were paid Can$40 for their participation.