The Relation Between Linguistic and Manual Asymmetries in Bilinguals and Monolinguals

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Abstract

Humans are unique in their ability for language and a strong population-wide right-hand preference for object manipulation. A number of researchers (e.g., Arbib, 2005; Crow, 2002) suggest that an association between language asymmetry and handedness was crucial for human evolution and development. However, developmental studies on language and handedness association demonstrate mixed results. Importantly, only a small number of developmental studies addressed handedness-language relations in adults. Moreover, the majority of studies on handedness and language relations rely on homogeneous samples of right-handed monolingual English speakers. To this day it is not known whether the results of such studies can be extrapolated to bilingual people, and whether results obtained from studies with children can be extrapolated to adults. The current study is the first of its kind systematically examining handedness and language in a sample of over 1,800 participants with diverse language background (over 50 different languages). The study examined handedness and language asymmetry in monolinguals, early bilinguals (acquiring a second language before age 6) and late bilinguals (acquiring a second language after age 6). Additional parameters such as motor asymmetry (a preference for right footedness) and gender were also examined for potential effects on asymmetry formation in all participants. Finally, a subsample of monolingual and bilingual participants was examined on asymmetry of a gesture and object manipulation. Study results suggest that contrary to previous claims of language asymmetry and handedness association, they are not strongly related in adults. Language asymmetry and the age of the second language acquisition predicted only a small portion of handedness score. Footedness and gender were stronger predictors of handedness. Females exhibited stronger asymmetry than males; more right-footed participants tended to be more right-handed. Contrary to studies with children, current study adult participants were more strongly lateralised for object manipulation than for gesture. In conclusion, the current study suggests that handedness and language relations are dynamic in development; that their relations are not as robust as was previously suggested; and finally, that the research field of handedness-language relations would benefit from diversifying study samples.

Keywords: language asymmetry; handedness; bilingualism; asymmetry development

For my grandparents. My long journey started from you.

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Chapter 1.

Introduction

Language and handedness are uniquely human abilities exhibiting a profound degree of asymmetry (Meguerditchian, Vauclair, & Hopkins, 2013). A number of researchers suggest that there is an association between handedness and language in humans (Arbib, 2012; Corballis, 2005). Some stronger claims of this kind suggest that handedness can be used as a proxy for language in the archeological record, and that human cognition can be partially attributed to a profound degree of asymmetry in the linguistic and manual domains (Crow, 2002; Ruck, 2014; Uomini & Ruck, 2018). Such claims, however, are based on a number of assumptions: that handedness and language asymmetry are indeed strongly (and even causally) related; that these relations are stable over the lifespan; that researchers have a clear understanding of how handedness and language are related. Despite the fact that handedness-language relations became a research field in their own right, spanning several decades and comprising thousands of studies (Sommer, 2010), a number of researchers stress that handedness-language relationship are far from being understood and require further investigation (Cochet, 2015; Cochet & Vauclair, 2012; Fagard, 2013). The present work aims to expand on previous research and fill in some of the gaps in our current understanding of handedness-language relations by examining them in a sample of adult participants with varied language background.

1.1 The Relationship Between Handedness and Language. Current Perspectives

Before proceeding with a discussion on the nature of relationship between language and handedness it is important to explicitly define what is understood by these terms in the current dissertation. By *language* I understand a human mode of communication that comprises different types of speech behavior (speaking, writing, understanding and listening) as well as cognitive aspects of language, such as vocabulary that is linked to concepts, along with other varied aspects of language (syntaxis, prosody, pragmatics, and so on). By *handedness* I understand a tendency to use one or the other hand while executing various manual tasks.

It is important to note why asymmetry of handedness and language is deemed so important for understanding their relation. Asymmetric processing of information on a functional level as well as morphological asymmetry of the brain and the nervous system are widespread in nature. Asymmetry can be (to some extend) conceptualized as specialization. In other words, when our brain specializes in processing particular information or in acquiring certain ability this processing tends to become asymmetric (Rogers, 2000). As Knudsen (2007) notes, in vertebrates cognitive efficiency depends on asymmetric processing of height and low cognitive functions. Humans are unique in their pattern of manual and linguistic asymmetries. Although other species demonstrate various levels of cognitive and behavioral functional asymmetries (Theofanopolou, 2015), only humans demonstrate a strong, population-wide right-handed bias and a profound degree of linguistic asymmetry (Meguerditchian, Vauclair, & Hopkins, 2013). That is, humans demonstrate strong left-hemisphere specialization in both linguistic and manual domains. The distribution of handedness and language asymmetry might vary and depends on the measures employed to assess both parameters. One of the most well-known accounts of such an assessment shows that while the left hemisphere dominance for language can be detected in about 95% of the right-handers, this pattern is typical for about 70% of the left-handers (Knecht et al., 2003). Moreover, when comparing language asymmetry between participants, Knecht et al. (2000 a,b), found that the degree of atypical right hemisphere dominance for language tended to be the strongest in strongly left-handed individuals (27%), followed by ambidextrous participants (15%) and finally only (4%) in strong right handers. Taken together these results suggest that handedness and language asymmetry are not completely independent from each other.

The neurological evidence suggesting an association between manual and linguistic domains comes from clinical studies, where patients with various degrees of brain damage demonstrate deficits in both communicative and manual domains. For example, research with patients suffering from brain damage demonstrates that language impairment is often associated with handedness (Provins, 2012); that aphasia (impairment in language processing) and apraxia (impairment in ability to perform movements, largely familiar ones, or to execute a movement on a verbal command) tend to cooccur in patients (e.g., Vingerhoets et al., 2013), and that deficits in both motor control and language are associated specifically with damage to the left hemisphere of the brain (Goldenberg, 2013). Additionally, incidents of apraxia tend to be more frequent among right-handers (Goldenberg, 2013), and be more severe (Kimura, 1973b) than in left-handers.

Indeed, the association between speech deficits in aphasia and handedness is pronounced to such an extent that it is possible to predict which hemisphere is likely damaged based on the handedness status of a patient. For example, Kimura (1983) has demonstrated that, in right-handers, speech deficits are more likely to be associated with the left hemisphere of the brain, while speech deficits in left-handers can be associated with either hemisphere or be bilateral. This finding is consistent with a series of studies (Gloning, 1977; Gloning, Gloning, Haub, & Quatember, 1969) investigating speech deficits and handedness in a sample of aphasic patients. While all right-handed patients had brain damage in the left hemisphere of the brain, the left-dominant and mixed-handed participants suffered from the brain damage in either right or the left hemisphere, also demonstrating a faster recovery than the right-handed group. In a more recent study, Flowers and Hudson (2013) assessed handedness via behavioural methods and questionnaires and compared these data with language asymmetry established by the Wada procedure (this method is based on injecting barbiturates into either right or left internal carotid artery to inhibit or “turn off” either right or left brain hemisphere). Behavioural measures of handedness in the study carefully predicted the pattern of language asymmetry in the brain. Taken together, results of these clinical studies suggest an association between the asymmetry of language and handedness.

Research in non-clinical populations employing direct brain-imaging methods also demonstrates an association between manual and linguistic asymmetries. One line of such evidence comes from studies demonstrating that similar brain areas are activated while participants are performing manual and communicative tasks. For example, Gentilucci and Dalla Volta (2007, 2008), Hickok and Poeppel (2007), Özyürek et al. (2007), Vingerhoets et al. (2013) and Willems and Hagoort (2007) demonstrate that neural networks controlling communicative behavior might not be entirely independent of the networks controlling manipulative activities. A number of researchers have demonstrated that Broca’s area, a canonical language structure, is activated during processing of both manual and communicative information (e.g., Binkofski et al., 2000), while speech in turn might activate canonical motor areas of the brain (Price, 2000). Fiebach and Schubotz (2006) demonstrate simultaneous activation of Broca's area and the ventral premotor cortex during perceptual, cognitive and motor processing.

A number of researchers have suggested that both handedness and language can be controlled by the left hemisphere due to its involvement in the execution of fine motor acts. Such interpretations rely on conceptualizing speech as a complex motor act (Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967). Consistent with such conceptualisations, Binkofski and Buccino (2004) and Higuchi et al. (2009) found that Broca's area is activated in complex non-linguistic tasks such as planning of an action and tool-use. The added complexity of highly skilled manual actions (in comparison to simple tasks, such as reaching) require a fine neural control that is associated with the left hemisphere of the brain (Bryden et al., 2011). Furthermore, highly skilled actions can be partially processed by Broca's area, as such processing involves hierarchical representation of sequential behaviour and syntactic operations (Ocklenburg et al., 2014). Additionally, not only are language areas activated during motor tasks, motor areas of the brain can be involved in processing linguistic information. For example, studies by Gentilucci (2003) and Tremblay and Gracco (2009) demonstrate that motor areas of the brain are activated during segmental information processing, when words are organized into sentences prior to vocalizations.

Similarly, more recent conceptualisations propose a language-handedness link through lateralized brain regions specialising in language and praxis (Hauk & Pulvermuller, 2004; Pulvermuller et al., 2005; Roy & Arbib, 2005), with praxis being defined as the neurological process by which cognition directs motor actions (Ayres, 1985). The human-unique pattern of this specialization, along with its presumed importance for human evolution, has led researchers to suggest that manual and linguistic asymmetries might co-develop and even be causally related in both ontogeny and phylogeny (e.g., Arbib, 2012; Corballis, 2003). Such approaches propose evolutionary scenarios in which modern language gradually emerged from more primitive forms of communication (such as protolanguage) co-evolving with complex motor tasks, such as tool-use. Additionally, and crucially, such scenarios stress the importance of gesture and gesture asymmetry as a potential mediating factor in handedness-language relations. Before proceeding with discussing such theories, it is important to define what is commonly understood by gesture in this line of research.

Cambridge dictionary defines gesture as “a movement of the hands, arms, or head, etc. to express an idea or feeling” (“gesture”, n.d.). While various body parts movements can be conceptualized as gesture, the theories linking handedness and language are focused on hand movements – manual gestures. Thus, throughout this dissertation I will focus on discussing manual gestures, defining a gesture as a purposeful, meaningful hand movement produced in a communicative context, often to express certain meaning (although the last criterion is not necessarily applicable to co-speech[1] gestures) (see p. 6, 87 for further discussion).

One of the dominant theoretical conceptualizations in the field (Arbib, 2005) proposes a multi-stage process in which language evolved from manual gestures, rather than vocalizations. This hypothetical scenario unites language and motor domains through gesture and praxis. Gesture is both a communicative and a motor act, and gesture usage requires both fine motor control and a communicative context. For Roy and Arbib (2005), language evolves from grasping movements that become adapted for communicative purposes by development and incorporation of abstract signs. Interestingly, Gonzalez and Goodale (2009) found a positive, albeit moderate, correlation between language lateralization measured by the dichotic listening task and hand preference for precision grasping in adults. The authors suggest that both gesture and object manipulation require visuo-motor control and attention to the target. Consequently, Gonzalez and Goodale (2009) propose that left hemisphere specialization for visuo-motor control phylogenetically preceded left hemisphere specialization for praxis and language. Other researchers (e.g., Kendon, 2009) suggest that it is the development of an intentional and representational system required for motor praxis and articulate speech control that is responsible for the association between manipulative and communicative activities.

The approaches described above tend to conceptualize gesture as simply a motor act. However, gesture is also a communicative act strongly associated with language. Patterns of gesture usage are predictive of language scores in children (Colonnesi et al., 2010; Iverson & Thelen, 1999). Research implementing direct brain-imaging techniques demonstrate activation of similar brain areas in gesture usage and language (Gentilucci & Dalla Volta, 2008; He et al., 2015). Results of clinical studies

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[1] manual gestures produced along speech production; co-speech gestures support speech and assist in conveying meaning in a message

indicate that recovery in aphasic patients can be aided by therapy that implements gestures (Rose et al., 2013). Importantly, gestures demonstrate a pronounced degree of asymmetry. The neurological substrate supporting the tight connection between the gesture asymmetry and language can be associated with the left hemisphere of the brain, and specifically Broca's area. For example, a seminal study by Xu et al. (2009) demonstrates that Broca's area is activated during processing of both words and gestures. Gesture asymmetry can also be demonstrated by behavioural studies. For example, in studies by Kimura (1973 a,b), participants tended to gesture more when they were speaking and to use their dominant hand more frequently; this right-sided asymmetry for gesture was associated with cerebral dominance for language. In a more recent study Kita, de Condappa and Moh (2007) showed that co-speech gestures tend to be performed with the right, rather than the left hand. Interestingly, in this study participants tended to increase left-hand gesturing when explaining metaphors (metaphorical processing employs right brain hemisphere). Finally, sign language users tend to use their hands unequally, and although both hands are used while signing, one of the hands tends to dominate (Corballis, 2003; Corina et al., 2003). Krifka (2008) highlights the importance of this unequal usage of both hands during gesture, suggesting that this pattern is reminiscent of manual specialization in tool-using tasks. During co-speech gesturing, the non-dominant hand "comments" on the topic supported by the dominant hand, which Krifka sees as a pre-adaptation to a universal linguistic feature – the pragmatic topic-comment organization.

To date there are several theoretical approaches concerning the relationship between language asymmetry, handedness and gesture. Vauclair and Imbault (2009) describe two such approaches that postulate an association between language and handedness while disagreeing on the underlying role of gesture. One account (Bates et al., 1986; Kinsbourne, & Hiscock, 1983) postulates that the human brain has two independent systems, a motor system and a speech processing system. This approach suggests that the asymmetry of the gesture does not correlate with language asymmetry (due to the fact that these are two independent systems), but instead should correlate with handedness. An alternative account (e.g., Bernardis & Gentilucci, 2006; Özyürek, Willems, Kita, & Hagoort 2007) proposes the existence of an integrated system that processes both linguistic and gestural information. According to this approach, the asymmetry of a gesture should be congruent with the linguistic asymmetry, but not the manual asymmetry (handedness) per se. There is, however, a third way of interpreting handedness-language relations. Iverson and Thelen (1999) view the emerging gesture-speech system as an integral part of a motor system; fine motor control is required for both vocal tract movements during speech production, and manual movements during gestural communication. From this perspective, the coordination between gesture and speech becomes a specific case of a more general movement coordination problem. As Iverson (2010) puts it: “the link between language and gesture is, of course, an instantiation of the relationship between the language and motor systems” (p. 231). Consequently, since hand preference belongs to a motor domain, and speech and gesture are not independent from the development of the motor system, handedness, gesture and language might be served by complex related networks.

To summarize this section of the chapter I would like to highlight several important points. First of all, a body of research described above suggests that it is reasonable to propose an association between handedness and language. The nature of this association is commonly associated with the profoundly asymmetric character of the linguistic and motor domains in humans. Gesture is considered to be an important and possibly mediating factor in the handedness-language relation. Finally, although a body of literature suggests an association between handedness and language, the nature and character of this association is not currently understood. Importantly, this association can be considered non-direct and incomplete (e.g., left-handers do not demonstrate “flipped”, right-hemisphere dominant linguistic profiles, although on a group level they differ from right-handers in language processing dominance). Since the left hemisphere of the brain is not an automatic default in establishing dominance for linguistic and manual demands, it is possible that both domains are affected by developmental factors. The next section of this chapter reviews studies investigating the development of handedness and language.

1.2 Development of Handedness-Language Relation Over the Lifespan

Researchers often attribute the connection between handedness and language to their common developmental roots. For example, Iverson (2010) proposed that speech and motor control share a common developmental trajectory. Such an approach does not suggest that handedness “causes” language directly, but rather that the co-development of both traits should be viewed in the context of the embodied systems of a growing organism. In such a system, developmental trajectories of different domains would likely affect each other or at least be intertwined. Specifically, new motor abilities such as an ability to walk, hold an object, and thus explore the environment set up new possibilities for communication and language development. Similarly, on a neurological level, developing linguistic abilities change the brain and thus might affect the motor domain; additionally, on a behavioural level varied communicative environments might set up different ways for the motor system to interact with the environment. In light of this view, it is plausible that language and motor domains would not be independent in development, stressing the potential importance of understanding these systems relations over the lifespan. Bishop (2013) argues that general cerebral lateralization is a plastic trait subjected to environmental factors, and thus it is crucial to understand both how lateralization profile might change in development and due to which factors. Similar claims regarding the importance of understanding developmental plasticity in motor and linguistic domains were brought up by Cochet (2015) and Michel et al. (2013).

Studies that are looking at the development of either language asymmetry or handedness demonstrate that both traits are indeed plastic in development. While some studies report that both asymmetries are pronounced already in infancy (Dehaene-Lambertz et al., 2002; Hepper, 2013), the general consensus is that asymmetry formation fluctuates in early development and does not necessarily take an adult like form until at least a preschool age (Bryden et al., 2000). Of more importance are the studies investigating the development of manual and linguistic asymmetries. Such studies, however, face significant methodological challenges that can be partly attributed to difficulties in implementing direct brain assessment measures of languages asymmetry in younger participants. Thus, studies investigating handedness and language development resort predominately to behavioural rather than neuropsychological measures. As the number of studies looking at language or handedness development separately is too great and well beyond the scope of the current work, this section of the chapter focuses on reviewing studies investigating the co-development of handedness and language.

One of the robust and consistent findings in the developmental literature is an association between patterns of manual control and vocalization in infants. For example, (Fogel & Hannan, 1985) found that 9-15 weeks old infants tended to extend their index finger during face-to-face mother infant interaction, and these extensions tended to cooccur with mouthing movements and vocalizations. A number of studies link the onset of babbling with rhythmic hand movements and shaking behaviors (Cobo-Lewis, Oller, Lynch, & Levine, 1996; Eilers et al., 1993; Ejiri, 1998). Locke, Bekken, McMinn-Larson and Wein (1995), as well as Iverson and Fagant (2004), report increased coordination between vocal communication and manual movements in 6-month-old babblers, while such coordination is much less frequent in pre-babblers of the same age.

Behavioural studies incorporating recent advancements in comparative and developmental research (e.g., Cochet, 2015; Meguerditchian, Vauclair & Hopkins, 2013; Ocklenburg et al., 2014) frequently address three, not two, important aspects: language, hand preference for gestures and hand preference for manual activities (Cochet & Vauclair, 2012). Such an approach is consistent with the potential importance of gesture and gesture asymmetry for the handedness-language relation discussed in the previous section (1.1).

Nelson et al. (2014) demonstrate that stable handedness in the first year of life can serve as a predictor of a better-developed language in the second year of life. In this study, researchers assessed handedness in infants at two time points (6-11 months and 24 months of age), additionally measuring language skills at 24 months. The results show that children who have demonstrated a stable hand preference for object manipulation in infancy and toddlerhood tended to have higher language scores. A study by Gonzalez et al. (2015) demonstrated that an early-established handedness (measured at 18-24 months) correlated with productive language scores at 36 months. A study by Vauclair and Imbault (2009) found an association between the asymmetry of the pointing gesture and hand preference in a manual task. In this study, children tended to use the same hand in order to point communicatively and to reach for an object.

In a sample of school-age participants, Hernandez, Camacho-Rosales, Nieto and Barroso (1997) assessed children’s handedness and reading abilities. Their results demonstrate that children with a convergent lateralization of manual and communicative functions (both localized in the left hemisphere) demonstrated superior reading abilities over participants with non-convergent lateralization patterns. Finally, a study by Cochet et al. (2015) with preschool children, aged 3-5, failed to report any difference in the mean handedness indexes between reaching, pointing and symbolic gestures[2]. In other words, children in this study were not more likely to use their right hand for the pointing gesture, than they did for the reaching task.

Taken together, these studies suggest that handedness and language are linked in development. However, these results are in conflict with studies investigating manual and gestural asymmetries in pre-linguistic and just-linguistic infants that fail to find an association between studied parameters. The aggregated results of these studies suggest a tight association between gestural asymmetry and language development but fail to find an association of either one of them with hand preference. For example, Cochet and colleagues (Cochet, Jover, & Vauclair, 2011; Cochet & Vauclair, 2010) demonstrated that children and pre-verbal infants exhibit a right-hand bias for gesturing (mainly pointing), but not manual reaching or object manipulation. Furthermore, children with a stronger right-hand bias for pointing tend to score higher on language measures (Esseily, Jacquet, & Fagard, 2011; Vauclair & Cochet, 2013). Vauclair and Imbault (2009) found that when children are classified based on their manual asymmetry as right-, left- or mixed- handers, all three groups exhibit a right-hand bias for pointing. In other words, in this study young children preferred to point with a right hand irrespectively of their manual preference. There is also an increase in the right-hand pointing bias during the key stages of language development, such as the vocabulary spurt, but there is no such bias in manual asymmetry (Cochet, Jover, & Vauclair, 2011).

Finally, declarative gestures tend to show greater asymmetry than imperative gestures in infants. (The distinction between imperative and declarative pointing is common in gesture development research and is based on prescribed differences in a communicative intention behind the gesture. In the imperative pointing a child points to an object requesting it from an adult, thus the child's attention is distributed between an object and "self". In the declarative pointing a child points to an object in order to attract adult's attention to it, to share information or an emotion, thus the child's attention is distributed between an object, an adult and "self"). This is particularly relevant because the acquisition of declarative gestures, and specifically declarative pointing, is

[2] Symbolic gestures are the types of gestures where the meaning expressed by the gesture is not related to the gesture shape, similar to a linguistic sign. Symbolic gestures are often conventional in a given culture. An example of such gesture can be "thumbs up" to express approval or positive evaluation of something.

considered an important step towards language development (Colonnesi et al., 2010). Jacquet, Esseily, Rider, and Fagard, (2012) examined hand preference in infants' gestural communication. In their study, infants exhibited a strong right-hand bias for the declarative, but not imperative, pointing. Similarly, a stronger right-hand bias for informative declarative pointing was found in a sample of 15-30 months old infants (Cochet & Vauclair, 2010 b). Although the degree to which declarative gestures can be interpreted as "more linguistic", or closer connected to language, is rightfully questioned (e.g., Leavens & Racine, 2009), the described above studies suggest a role for gesture asymmetry in language development in humans.

The majority of studies investigating language, gesture asymmetry and handedness have been conducted with either human infants or non-human primates, while the number of studies addressing these three aspects in the adults is quite limited. As a result, Cochet and Vauclair (2012) note that this situation makes it difficult to relate the findings of research in children and primates with the research investigating handedness and language in the adult population. Therefore, it is important to examine the relations between manual handedness, language and gesture asymmetry not only in children, but also in adults. To this day, only a limited number of studies have attempted to do that. For example, Cochet and Vauclair (2012) compared hand preference in communicative and non-communicative pointing and manual manipulation in a sample of adult participants. Their results demonstrated a moderate correlation between handedness indexes for bimanual manipulation and pointing gestures. However, while pointing in a silent condition did exhibit a right-hand bias, when pointing gestures were accompanied by speech, the mean handedness indexes for pointing and bimanual manipulation did not differ. In other words, manual and gestural asymmetries demonstrated a moderate association, and participants tended to use their right hand for the pointing (not accompanied by speech). Another study by Cochet and Vauclair (2014) investigating aspects of adult gestural communication reported a significant correlation between handedness for pointing and manipulative activities. However, there was no difference for mean handedness indices for gestures and manipulative activities, except for declarative expressive pointing. The results of this study, again, suggest an association between manual and communicative-linguistic asymmetry in adults.

In summary, studies with adults demonstrate an intricate relationship between gesture asymmetry, handedness and language asymmetry. The relationship between these asymmetries is not direct; however, they are not entirely independent from each other as well. Behavioural studies with adults suggest that there is a significant association between manipulative activities and pointing in terms of a stronger right-hand bias. This bias in the adult participants is still not as strong as the right-hand bias in pointing gesture observed in infants (Cochet, 2015).

1.3 Language and Handedness: Inconsistencies and Gaps in Research

As noted by Sommer (2010) language and handedness have been in the focus of researchers' attention for a long time and today indeed can be considered an area of research in their own right. At the same time J. Fagard stresses that the nature of relationship between handedness and language is still poorly understood and for the past 30 years the presence and even causal nature of these relationship have been often simply assumed by researchers (2013). Similar concerns have been expressed by other researchers (Vauclair & Cochet, 2012). In this section I wanted to briefly summarize major gaps in research on handedness and language and describe possible solutions aiming to advance our understanding of handedness and language.

Current research on handedness and language produces inconsistent results. This situation is notable in developmental studies as well as research employing varied methodology to examine handedness and language. Specifically, a number of studies support the proposition of handedness-language association in development, while others fail to find such an association. While the evidence coming from neurological and clinical studies suggest that there is a connection between language and handedness (Provins, 2012), the results of the studies employing behavioural methods cannot be interpreted unambiguously.

So why would we see mixed results in studies assessing handedness and language at different points of development and also employing different methodologies? I believe there are two major reasons for this. First of all, handedness and language are complex; what we call "language" or "handedness" are in fact an aggregation of varied motor and linguistic (or even cognitive-linguistic) abilities. For example, some studies report hand preference expressed in human fetuses prenatally as early as 9-15 weeks of gestation (Parma et al., 2017). I doubt this particular expression of handedness can be equated with hand preference e.g. while writing or drawing (tasks requiring developed fine motor control) in adults. Consequently, I believe it is more productive to investigate which specific aspects of handedness and which aspects of language are related to each other and how.

The second issue concerns plasticity of handedness and language. Both handedness and language are dynamic, rather than static in development. In other words, humans are not simply born right-handed and left-hemisphere dominant for language. Both abilities fluctuate in development, and consequently can be subjects to developmental factors. Additionally, following the notion regarding complexity of handedness and language discussed in the previous paragraph, not only handedness or language, but also different aspects of handedness and different aspect of language might be more or less related to each other at different developmental stages. Should this be the case, investigation of handedness and language in development becomes an important avenue for future research.

Unfortunately, it is premature to say that we have a clear developmental picture of handedness and language. In my opinion this issue steams from two major issues: developmental studies (in language-handedness research area) tend to focus on early developmental stages almost exclusively; and studies looking at handedness and language in children and adults tend to investigate different things. For example, in children researchers frequently examine pointing gesture asymmetry, while almost no study addresses this aspect in adults. I believe it is important to acknowledge that developmental studies should not be limited to early developmental stages. Development (conceptualized as systematic changes happening with time) takes place over the life span. In other words, it is important to investigate asymmetry formation not only in early development (in pre-linguistic and just-linguistic infants), but to address asymmetry in adults. Moreover, adult research can be useful for interpreting the data acquired in studies with children. That is due to the fact that in order to interpret the development of any feature (e.g., handedness or language asymmetry), it is necessary to know its final form (e.g., handedness or language asymmetry in adults). In other words, understanding the endpoint of a developmental process is important for its adequate interpretation.

On a broader scale, the investigation of asymmetry formation over the life span can provide important insights. Notably, a simple extrapolation of the results gained in studies with children to an adult population (and vice versa) is not plausible. While studies with infants suggest an independent development of asymmetries, research in adults suggests that manipulative activities and gestures are, to an extent, interrelated. When young children demonstrate a strong right-hand bias for pointing, adult participants, on the contrary, do not demonstrate a strong right-hand bias for the pointing and any asymmetry bias for symbolic gestures.

Another way to approach the problem of inconsistency is to investigate phenomena of interest in populations in which these phenomena systematically vary. In other words, in order to understand if language and handedness are related, and if they are, then how, they should be studied in populations that demonstrate variation in either one of the domains. For example, a recent set of meta-analyses of 2,740 participants investigated handedness prevalence in deaf individuals (Papadatou-Pastou & Sáfár, 2016). The authors conclude that handedness patterns in deaf participants differed from the one commonly described in hearing individuals. That is, comparing to hearing individuals, deaf participants were 2.61 times more likely to be non-right-handed, and 2.25 times more likely to be left-handed (which corresponds to an estimate of about 20% left-handers among deaf individuals and about 10% among hearing individuals). Study authors associate elevated levels of non-right handedness in deaf participants with delayed language acquisition.

Clear understanding of how language and handedness interact in development and how they systematically vary would allow researchers to make inferences regarding the nature of handedness-language relation. For example, one might contrast neurological-maturational accounts of handedness and language relation (Cochet, 2016) with embodied approaches to asymmetry formation (Casassanto, 2009). The former conceptualizations place emphasis on neurobiological factors that can affect asymmetry formation. For example, it is possible to treat human brain as a paired organ (comprised of two hemispheres), that go through a series of maturational changes. We might than expect that biological factors (such as sex) or other factors that change in development due to bio-neurological influences might be related to systematic variation in handedness, language or both. For example, previous studies (Amunts et al., 2000; Narr et al., 2001; Yuecel et al., 2001) continuously noted small but robust differences in asymmetries between sexes in various domains, including handedness and language, the current study additionally analyzed whether variables of interest significantly differed between males and females. Additionally, a number of authors (e.g., Cochet, 2016; Elias & Bryden, 1998; Previc, 1991) have long suggested that factors besides handedness should be investigated in relation to language asymmetry. Although handedness has traditionally being associated with language asymmetry, some scholars suggest that general motor asymmetry (including footedness) might be associated with language (MacNeilage, 1991). A limited number of studies have addressed this question. For example, Day and MacNeilage (1996) and Elias and Bryden (1998) compared footedness, handedness and language asymmetry (measured by the Fused Dichotic Word test) in their participants. The results of both studies suggest that footedness is a better predictor of language asymmetry than handedness. In these studies, the right-footed participants demonstrated a strong right-ear advantage (indicative of the left hemisphere processing for language), whereas the handedness status of a participant did not demonstrate such an association.

Alternative accounts (e.g. based on embodied cognition approach) would place emphasis on systematic ways of interaction with the environment resulting in a particular pattern of asymmetry in handedness and language. Such accounts would suggest that life experience, for example, knowledge of a second language, different pattern of handedness leading to a different pattern of interaction with environment would also lead to a systematic variation in another parameter, should the to be associated.

The second potential reason for inconsistent results of handedness-language research is the prevalence of homogeneous samples in this field. Quite often, adult participant samples consist of either right-handed individuals or monolingual adults. That is, if the purpose of the study is not handedness or language asymmetry per se, the sample is often homogenized for handedness, including only the right-handed individuals; additionally, such studies tend to include predominantly monolingual participants. Moreover, it is common to see samples consisting of only right-handed or monolingual participants, even in the studies aiming to investigate linguistic or manual asymmetries. While such approaches for participants' selection might not be particularly compromising for any given study, or even desirable in some cases because of experimental control, the fact that the majority of studies employ such sampling approaches may have serious implications for the field in general. It is questionable whether we can safely extrapolate the results of studies with monolingual right-handers to the general population. Importantly, it is unlikely that we can create a comprehensive model of handedness-language relationship, if the model is developed based on the data acquired from a specific portion of the population, and that is, monolingual (often English-speaking) right-handers.

To summarize this section, I wanted to briefly highlight major problems that are currently impeding our understanding of handedness relationship: lack of truly developmental data, lack of understanding how language and handedness might be related to other factors and predominantly homogeneous samples in research, resulting in a fact that we build our handedness-language models on a portion of population: monolingual, English-speaking right-handers. In my opinion to proposed solutions are especially fruitful for research on handedness and language relation: investigation of both abilities in development, as well as in populations that systematically very on one or the other parameter. One example of a population that exhibits systematic differences in a linguistic domain but has not been investigated for handedness-language relations are bilingual adults. The following section of the chapter provides a brief overview of language asymmetry in relation to bilingualism. The final section of this chapter summarizes the rationale and hypotheses for the current study.

1.4 Language Lateralization in Bilinguals and Monolinguals.

The problem of language lateralization in a brain is quite complex and is still a topic of debate (e.g., Corballis, 2014; Hickok & Poeppel, 2007; Stein, Winkler, Kaiser, & Dierks, 2014). Despite strong evidence supporting the left hemisphere specialization for language processing, certain aspects of it demonstrate bilateral brain involvement (Chernigovskaya, 1994; Chernigovskaya & Vasileva, 2015). The degree of lateralization of the right and the left hemisphere in language processing is a function of the task performed (Morillon et al., 2010). At the same time, various language processing tasks demonstrate greater activation of the left or right hemisphere and thus exhibit a pronounced functional asymmetry pattern. For example, the left hemisphere is involved in phonemic and syllabic processing, syntax analysis and some other linguistic functions (Vigneau et al., 2006). Studies in commissurotomy patients suggest that the cerebral control of speech production is more strongly lateralized than comprehension (Gazzaniga, 1970; Gazzaniga, 2005; Gazzaniga & Le Doux, 2013; Gazzaniga & Sperry, 1967). It is worth mentioning that for a majority of a population canonical language-specific areas - Broca's and Wernicke's – are localized in the left hemisphere. The use of online technology for data collection has more recently allowed researchers to investigate language lateralization in large samples and varied linguistic backgrounds. For example, Bless et al. (2015) employed a smartphone app to collect data on language lateralization via a dichotic listening task administered to over 4,000 participants from 60 language backgrounds. This task is a robust measure of language lateralization that has been validated by the sodium amytal procedure (e.g., Hugdahl et al., 1997; Strauss et al., 1987) and neuro-imaging techniques via analysis of the Broca's area activation in the fMRI (e.g., Vander Haegen, Westerhausen, Hugdahl, & Brysbaert, 2013). The study results suggest that the left hemisphere lateralization for language can be (with some caution) considered a universal phenomenon. Finally, some research (e.g., Rodd et al., 2012; Tyler et al., 2010) suggests that when language is conceptualized as a processing of real-time speech with all syntactic, semantic, prosodic, phonemic and pragmatic features, its processing relies more heavily on the left hemisphere. Consequently, it seems clear that the left hemisphere demonstrates considerable specialization for language processing. However, while the notion of left-hemisphere dominance for language is not an exaggeration in reference to monolinguals, bilingual individuals tend to have a more complex asymmetry pattern.

Two recent meta-analyses suggest bilinguals exhibit a more balanced asymmetry in language processing with the right hemisphere being more profoundly involved than in monolinguals. Hull and Vaid (2006) analyzed 23 studies with a total number of 1,234 participants to examine various aspects of language processing and associated asymmetry in monolinguals and bilinguals. The results indicated that overall monolinguals and late bilinguals (individuals acquiring a second language after the age of six) demonstrate a more left-lateralized pattern of language processing, while the early bilinguals (individuals acquiring a second language before the age of six) are less lateralized in that respect. Moreover, while other factors, such as the degree of language proficiency and the method of second language acquisition have some effect, their influence is significantly smaller than the age factor. Specifically, the age of the second language acquisition onset is the strongest predictor of the language asymmetry in the brain, with a reliably less-lateralized pattern for early bilinguals. A meta-analysis by Hull and Vaid (2007) revealed similar results. Among the 66 studies, the age of bilingualism onset was the strongest predictor of language asymmetry in the brain, with bilinguals acquiring language before the age of six showing a more interconnected pattern. Level of proficiency in the second language did not have an impact in early bilinguals but was associated with a more left-lateralized processing pattern in late bilinguals (in a lower language proficiency category).

It is not quite clear why bilinguals are exhibiting such a language asymmetry pattern and what factors are governing lateralization formation processes. Maturation might be one of such factors, and there is some neurological evidence supporting this proposition (Thatcher, Walker, & Giudice, 1987). For example, Luders et al. (2010) demonstrated that processes of myelination in the corpus callosum are not complete until a child reaches the age of six- to ten-years-old. Thus, higher brain plasticity accompanied by a specific environmental influence of language exposure seems to lead to a more balanced lateralization pattern. Another study by Kaiser et al. (2015) demonstrates that age of the second language acquisition affects the grey matter volume in language-associated areas. Contrary to the previous proposition, some researchers do not attribute a significant role of maturation to the asymmetry pattern formation. A study by Conboy and Mills (2006) with bilingual infants suggests that experience with language rather than processes of maturation are responsible for lateralization pattern in a brain. This study examining event-related potentials in 19-22 months old English-Spanish bilingual infants found that lateralized neural activity differed depending on the dominant and non-dominant language. There is evidence that early language experience leaves long-lasting effects on the brain functioning, even when the linguistic environment of an individual changes. In a recent study, Pierce, Chen, Delcenserie, Genesee, and Klein (2015) employed direct neuroimaging techniques to investigate language processing in the brain by comparing children exposed to Chinese languages in their first year of life and later being adopted to francophone Canadian families with native Chinese speakers. The results of the study demonstrate that early language experience has lasting effect on brain functioning, as adopted participants demonstrated brain activation patterns identical to native Chinese speakers, when presented with stimuli in a Chinese language. All adopted participants in this study did not master Chinese languages beyond the first year of initial exposure and were proficient French speakers.

Additionally, there are studies assessing language asymmetry and handedness in clinical populations that again highlight the importance of the age of six years for the asymmetry formation. Rasmussen and Milner (1977) assessed handedness and language asymmetry with sodium amobarbital infused in hemispheres to epileptic patients with early (before six years old) and late (after six) onset of the disease. In the group of right-handed patients, speech was localized in the left hemisphere in 96% of individuals with a late epilepsy onset, and in the 81% in the group of an early epilepsy onset. In the group of left-handed individuals, speech was localized in the left hemisphere for 70% of the late onset group and in 28% of the early onset group. This group demonstrated speech localization in the right-hemisphere in 53% of the patients and bilaterality in 19%. Similarly, Strauss, Wada and Goldwater (1992) found that early brain damage is associated with increased incidences of left-handedness and non-left hemisphere speech lateralization. Taken together these studies suggest that early onset lesions interfere with typical asymmetry formation in both linguistic and manual domains, whereas later onset lesions are less likely to cause an atypical pattern, as the asymmetry is already formed. Moreover, these studies highlight the importance of age 6-7 as critical for the formation of asymmetry.

In summary, there is evidence suggesting that early brain damage (before six years of age) affects both handedness and language lateralization. Additionally, there is good evidence that early second language acquisition (again, before six years of age) affects general linguistic asymmetry. Consequently, the timing of language acquisition might be expected to affect handedness as well as language laterality. More specifically, one might predict that early bilinguals would differ from late bilinguals and monolinguals in their handedness pattern. Importantly, bilingualism tends to affect both language processing and gesture usage. A number of studies have investigated gesture rate in bilingual and monolingual participants: French/English and English/Spanish adults (Pika et al., 2006) and French/English bilingual preschoolers and French or English monolingual preschoolers (Nicoladis et al., 2005). These studies conclude that it is bilingualism in itself rather than effects of a particular language that are more important for gesture frequency. The question remains whether gesture asymmetry differs between bilinguals and monolinguals, and whether these groups exhibit an association between gesture and handedness.

Other factors, such as the type of language or the mode of second language acquisition (formal schooling or communicative) might affect language asymmetry and potentially interact with age of second language factor. Previous research suggested that language asymmetry might differ in tonal (being more bilateral) and non-tonal (being more left-hemisphere dominant) languages (Valaki et al., 2004). Additionally, languages with non-alphabetic writing systems might have different laterality pattern. For example, Mei at al., (2015) found that long-term experience with Chinese (a logographic language) affected lateral activation of the fusiform gyros in readers of English. Although the fusiform gyros is a structure processing visual information (object and face recognition) it was activated while participants were reading in English, and in those participants that were previously exposed to Chinese language.

1.5 The Current Study

The question of asymmetry formation has both fundamental and applied scientific value. Motor laterality is used as an indicator of speech laterality in medical research and even surgeries (Flowers & Hudson, 2013). As it was noted before, patterns of asymmetry formation frequently differ in abnormal development (e.g., Escalante-Mead, Minshew, & Sweeney, 2003). Finally, many researchers hypothesized a crucial role of language asymmetry and right handedness in human evolution (Arbib, 2012; Corballis, 2003; Crow, 2002; Ruck, 2014), with strong forms of this hypothesis suggesting humans gained their advanced cognition largely due to becoming right-handed and linguistically gifted.

Research described in previous sections of the chapter highlights that despite decades of research, we still do not fully understand the relationship between handedness and language. This situation is a result of multiple factors. However, at least two initial solutions can be proposed in this regard. First of all, in order to investigate the development of handedness and language, it is important to study them not only in children, but crucially, also in adults. Only a small number of studies have previously done so (Cochet, 2016). Second, asymmetry should be studied in populations exhibiting systematic differences in one of the domains in order to see possible effects on another domain in a given population. The present study accomplished these goals by investigating handedness and language asymmetry in adults and comparing these parameters in bilinguals and monolinguals. The decision to contrast the bilingual and monolingual participants is justified by two main reasons. First, there is evidence suggesting that bilingual adults are likely to have a different language laterality pattern than the monolinguals. Second, a comparison of early and late bilinguals serves as a convenient way to address the more dynamic aspect of manual and communicative gestural asymmetry formation over the life span.

As behavioural studies investigating linguistic and manual asymmetry in adults and infants offer contradictory results, examining relations between early linguistic exposure and manual asymmetry has the potential to be a valuable avenue for future research. However, no studies aiming to assess whether language and handedness are related in bilinguals in a similar way they are assumed to be related in monolinguals have been carried out until now. Accordingly, evidence still needs to be collected in bilingual and monolingual adults to determine whether the experience and age of the second language acquisition has any association with manual handedness.

The major motivation for the current study was two-folds: to examine handedness and language in a diverse sample of adult participants, and to do so in a population that systematically varies on one of parameters of interest that is language. The present study aims first to investigate the relationship between language laterality and handedness by comparing handedness pattern in early bilinguals with late bilinguals and monolinguals. Since bilinguals utilizing both languages tend have both these languages “activated” (Grosjean, 2001), and language asymmetry in early bilinguals indeed differs as a function of the age of second language acquisition, it is expected that early bilinguals will on a group level differ in handedness strength from late bilinguals and monolinguals. In other words, if handedness and language indeed are associated in development, we might expect that a variation in one parameter – language – would also translate into similar variation in another parameter – handedness. Additionally, the study compares gestural asymmetry (laterality of the pointing gesture) and manual handedness in early bilinguals, late bilinguals and monolingual adults. Gestural research in bilinguals tends to focus almost exclusively on co-speech gestures while little attention was given to investigating other types of gestures. The current study investigates potential patterns of asymmetry of the referential (pointing) gesture in bilingual and monolingual adults.

The problem of sample homogeneity is related to the question of measures commonly employed in handedness-language research. Quite often such studies are employing categorical rather than continuous variables. In other words, rather than examining the degree of relationship between the two parameters, or small fluctuations in it, we are limited to investigation of strong effects in relationship. Should the association between the variables of interest not be strong or large in effect size, it might be missed by researchers. Categorical variables in this case lead to simplification of relationship and to a certain level or reductionism. Thus, it is possible to not find group-level differences between given parameters but capture their non-independent relation when continuous measures of asymmetry are applied. The current study purposefully employs continuous variables to capture even subtle patterns of relationship between handedness and language. Additional analyses are conducted with categorical variables of interest (gender, language experience, type of first language, etc).

In order to capture the relationship between handedness and language asymmetry more effectively while attempting to separate potential effects of confounding parameters the current study additionally examined relationships between major variables of interest and two potential confounding parameters: footedness assessed by the Waterloo Footedness Questionnaire (Elias, Bryden, & Bulman-Fleming, 1998) and gender.

The study objectives were:

1. To examine the relationship between handedness and language asymmetry. Specifically, a). to investigate language asymmetry patterns in bilinguals and monolinguals; b). to investigate handedness patterns in bilinguals and monolinguals; c). to compare handedness and language asymmetry in bilinguals and monolinguals.

2. To assess gesture asymmetry and handedness and to examine their relationship in the overall sample in order to compare these parameters between bilingual and monolingual adults.

3. To assess relationships between language asymmetry and handedness with potential confounding parameters: gender and footedness in order to examine, whether gender and/or footedness would predict variation in participants' handedness or language asymmetry scores.

Chapter 2.

Method

2.1 Design

The research has a cross-sectional design and comprised two studies. In study 1 participants (*N* = 1,833) were tested on language asymmetry (Dichotic Listening Task), Handedness (Waterloo Handedness Questionnaire), and Footedness (Waterloo Footedness Questionnaire). In study 2 a portion of the sample (*N* = 543) was additionally tested on Hand Preference in Object Manipulation (Tube Task) and Hand Preference in Pointing Gesture Usage (Hand preference in producing a pointing gesture).

2.2 Participants

The overall sample consisted of 1,833 participants drawn from two main pools: undergraduate students taking part in a study for research credits and 15 volunteer undergraduate participants. The volunteers were recruited via advertisements posted on the University`s news boards. The SFU Ethics Board has reviewed and approved the study protocols and recruitment methods.

Table 1.

Demographic Characteristics of the Overall Sample (Study 1).

Gender Composition	**Total**	**Female**	**Male**	**Other**	
N	1833	1167	664	2	
percentage	100	63.7	36.2	0.1	
Other Characteristics					
	N	***min***	***max***	***M***	***SD***

Participant Age	1829	17	59	19.55	2.55
Number of years of formal education	1833	10	24	13.82	1.66
Number of languages spoken	1828	1	5	2.36	.93
Age of the Second Language Acquisition	1530	1	24	5.11	3.75

Participant Age was defined as chronological age a participant has indicated. Gender was defined based on participant self-identification as a male, a female, or a different type of gender identity. Participants educational level was conceptualized as a *Number of Years of Formal Education*, that is, number of years participant's major occupation was being a student starting from grade one in school. *Number of Languages spoken* refers the number of languages participant indicated they learned during their lifetime (not necessarily having a full command of all these languages at the time of testing). The rationale behind this was justified by the study assumption suggesting that it is the sufficient experience with another language and not current proficiency that could affect language asymmetry.

Table 2.

Demographic Characteristics of the Study 2 Subsample

Gender Composition	**Total**	**Female**	**Male**	**Other**	
N	543	345	195	2	
percentage	100	63.5	35.9	0.6	
Other Characteristics					
	N	***min***	***max***	***M***	***SD***
Participant Age	543	17	59	19.9	3.1

Linguistic Composition of the Sample

In terms of language status, the sample consisted of 987 (53.8%) early bilinguals, 494 (27%) late bilinguals and 324 (17.7%) monolinguals. Twenty-seven (1.5%) participants could not be classified as either type due to incorrectly filled questionnaires and were excluded from analysis.

A participant was classified as a monolingual if they indicated not having a sufficient second language proficiency at any point in life. Since it is very difficult to find a person who has never been exposed to another language either through family or an educational system, I relied on language proficiency criteria, rather than exposure, to define monolinguals.

A participant was classified as an early bilingual if they indicated they started learning a second language in the interval from birth (in the data set this was operationalized as 1 year of age) to 5 years of age. Participants were classified as late bilinguals if they started learning a second language after the age of 6. I assumed that a person who started learning the first language at the age of 6 would not likely master it completely within a year, and thus most likely became fluent in a given language after the age of 6. Since the age of 6 years was defined as a benchmark for my study, such participants were classified as late bilinguals.

A number of participants classified as early bilinguals (N = 267) indicated they have started learning a second language from birth and at the same time as their first language. In this case participants were instructed to choose which of the two languages they consider the first (and native) one and fill in the rest of the questionnaire following the order of their language acquisition. In other words, the main criteria for a distinction between the first and the second language was the chronological age at which a participant started learning a second language.

Participants indicated 54 different languages as their first language (L1) and 55 different languages as their second language (L2) (see Figures 1 and 2 for language type distribution). In terms of type of the first language, the biggest number of participants indicated English (N = 1,017), followed by Chinese (N = 343), Punjabi (N = 120), Korean (N = 59), Indonesian (N = 37), Farsi (N = 34), Vietnamese (N = 28), Russian (N = 23), Urdu (N = 22), Spanish (N = 15) and Arabic (N = 14). For the type of second language biggest groups were English (N = 740), French (N = 231), Chinese (N = 160), Punjabi (N = 121), Spanish (N = 59), Hindi (N = 24), Italian (N = 22), Farsi (N = 19), Japanese (N = 16), Vietnamese (N = 12) Korean (N = 11).

Figure 1: First Language Distribution in a Sample

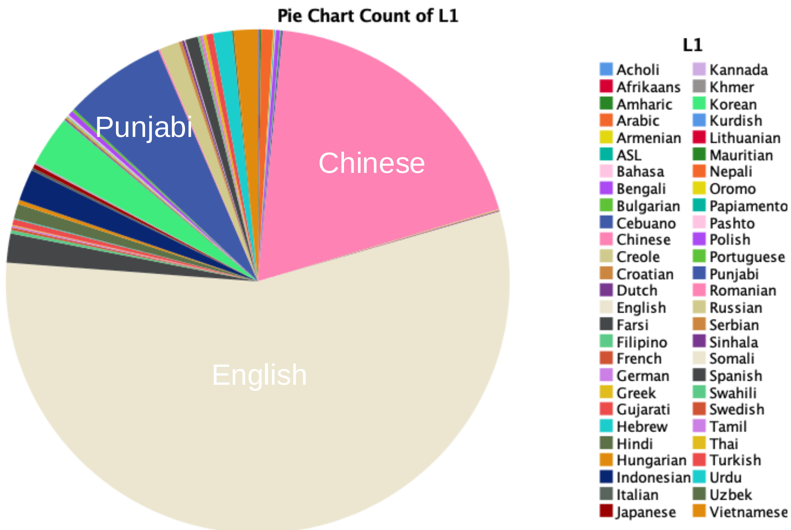
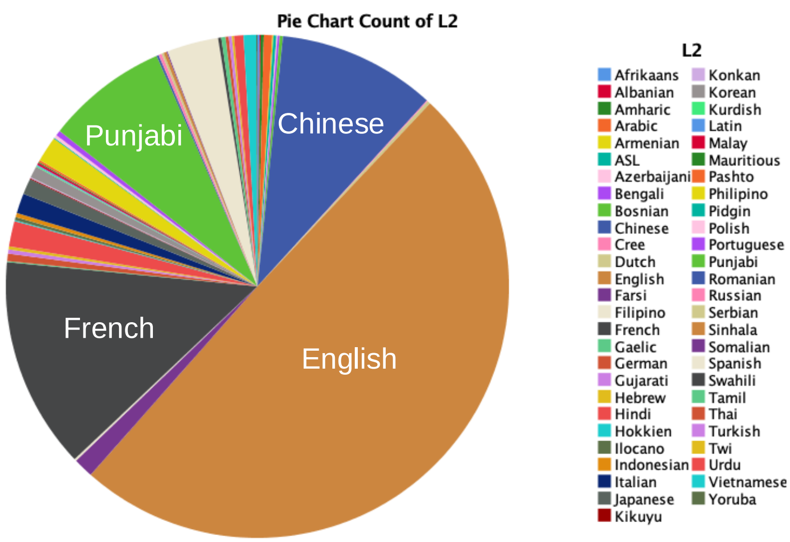


Figure 2: Second Language Distribution in a Sample



2.3 Recruitment

With the exception of the 15 volunteers, participants were recruited via the Psychology Department's online research participation system at Simon Fraser University. Participants could obtain a brief description of the study and consequently choose to sign up for an available testing slot.

Participants with no history and no formal diagnosis of severe language impairment or learning disability took part in the study. Certain data from a small number of participants were excluded during the data coding and analysis stage. The rationale for exclusion is described for each specific measure in the following sections.

2.4 Measures and Materials

Measures employed in study 1

Language Proficiency and Experience Questionnaire (LEAP) (Appendix I).

LEAP is used to classify participants into Early Bilingual (EB), Late Bilingual (LB) and Monolingual (ML) groups, and to determine the relative level of language proficiency (Marian, Blumenfeld, & Kaushanskaya, 2007). The questionnaire contains questions about the order of language acquisition, language proficiency as a self-report scale of an ability to speak, understand and read in a given language, as well as a self-report measure of how often others perceive a person to be a native speaker of a given language and how strong is an accent in a given language.

Waterloo Handedness Questionnaire (Appendix II)

The WHQ is a measure of handedness for manual manipulation (Elias, Bryden, & Bulman-Fleming, 1998). It consists of 36 questions about daily activities that can demonstrate hand preference. Participants indicate whether they perform a given activity with a given hand (left always, left usually, any hand, right usually, right always). Each response is scored from -2 to 2 (left always (-2); left usual (-1); equal (0); right usual (1); right always (2).

Waterloo Footedness Questionnaire (Appendix III)

The WFQ is used to differentiate handedness asymmetry from footedness (Elias, Bryden, & Bulman-Fleming, 1998). The questionnaire consists of 10 questions about daily activities that can demonstrate foot preference. Participants indicate whether they perform a given activity with a given foot (left always, left usually, any foot, right usually, right always). Each response is scored from -2 to 2 (left always (-2); left usual (-1); equal (0); right usual (1); right always (2).

Dichotic Listening Task

The DLT is used to determine the true language asymmetry in participants. It is a very robust measure of language laterality (Hugdahl, 2003). The standard protocol for a dichotic listening task normally includes paired stimuli (syllables, words, tones, etc., depending on the study hypothesis) presented to the participant via a headset. Each stimulus pair is presented separately in the left and in the right ear (e.g., if the stimulus is a ba-da syllable, ba would be presented to the right ear, and da to the left ear). The participants are asked to determine which stimuli they hear. The proportion of responses to the left and the right ear is assessed. A right ear advantage (REA) is indicative of left hemisphere dominance for language, and a left ear advantage (LEA) is indicative of right hemisphere dominance for language.

The Dichotic Listening Task for the study employed stimuli based on the Bergen DLT paradigm (Hugdahl, 2003). The stimuli consist of 6 CV syllables (/ba/, /pa/, /ta/, /ka/, /ga/, /da/). The total number of possible pairs is 36, with 30 non-concordant pairs and 6 concordant pairs. The general validity of the dichotic listening test as a measure of language processing asymmetry in the brain has been previously validated against the sodium amytal procedure (e.g., Strauss, 1987) and neuroimaging techniques (e.g., van den Noort et al., 2008; Westerhausen et al., 2014).

The testing was performed with iDichotic software downloaded on an iPad. The software has been previously tested in several studies on big samples (over 4,000 participants) (Bless, Westerhausen, Torkildsen, Gudmundsen, Kompus, & Hugdahl, 2015; Bless, Westerhausen, Arciuli, Kompus, Gudmundsen & Hugdahl, 2013). The app allowed participants to test the hearing in each ear before the beginning of the test to avoid possible bias in the test performance due to hearing issues. During the actual test participants listened to syllable pairs and were indicating on a touchscreen which sound they heard best (participants had to press a “button” with the syllable they have heard). The program recorded the number of answers to the left and right ear, which allowed calculating the Laterality Index (LI) = [(RE-LE)/RE + LE] x 100.

Language asymmetry was also assessed in participants based on the type of their first language (e.g. English, Chinese, etc.). Additionally, language laterality was assessed in speakers of tonal (Chinese, Punjabi, Vietnamese) and non-tonal languages (Arabic, English, Farsi, Hindi, Indonesian, Korean, Russian, Spanish, Urdu).

Measures employed in study 2

Pointing task

The pointing task was adapted from Cochet and Vauclair (2012). It consisted of visual images randomly presented to the participant, who would indicate picture preference by pointing to it.

Bimanual manipulation task

The bimanual manipulation task was adapted from Cochet and Vauclair (2012). It was used to elicit object manipulation for determining handedness.

Photographs from the International Affective Picture System (IAPS)

The IAPS was used to elicit pointing gesture in participants (based on Cochet and Vauclair, 2012). The database was developed by the National Institute of Mental Health Center for Emotion and Attention at the University of Florida. Permission to use the picture database for research purposes was obtained prior to the beginning of the study. The purpose of employing the IAPS images was twofold. First, for the purpose of maximizing participants’ engagement with the test procedure, it was beneficial to use images unfamiliar to participants. The second goal of usage of the IAPS was methodological concordance with previous literature, as Cochet and Vauclair (2012) have used the same database for their study. This approach allows for relating the new findings to other research groups’ results. The general IAPS database consists of 956 images varied in content from neutral to the ones aiming to elicit strong emotional reaction. One hundred and twenty images neutral in content (landscapes, people, food items, animals, objects) were selected for the study. The images were printed on A4 format sheets of paper with 4 images per page (30 pages total). All images displayed vertically, without a lateral bias.

2.5 Data Coding

Participants' language status was determined by LEAP responses. Early Bilinguals acquired a second language in a time interval between birth to the age of five. Late Bilinguals acquired a second language at the age of six or after. Monolinguals do not have a functional second language ability. It should be noted that it was difficult to find a person in the present sample who has several years of formal education and had never been exposed to another language. Thus, I relied on functional proficiency in a second language -- the ability to speak and understand it well (self-rated as 7 and above on a 10-point scale) -- as the criterion to classify a person as bilingual, rather than an absolute absence of a second language exposure. Additionally, only scores for "understanding a language" and "speaking a language" were taken into account, while "writing in a language" or "reading in a language" were not. The reason for this is that reading and writing skills require specific training, while speaking and understanding are acquired without formal instruction. Accordingly, participants that have indicated exposure to two languages, but have self-rated themselves as having a low proficiency in either language were coded as monolinguals (N = 53). [3]

Bilingualism can be complex and what is determined as the first and second language might depend on the context. Most often the first and the second languages are distinguished based on the chronological age at which they were learned. However, it is possible for a person to learn both languages at the same time. Additionally, bilinguals quite often do not learn both languages to the same degree (cases of extremely balanced bilingualism – a situation in which a person has an absolutely equal and very high command of both languages are very rare) and for the same function. The

[3] Some participants tested on gesture asymmetry and handedness (N = 111) were treated as monolinguals, even though they have indicated a non-English language as L1 or L2 in their questionnaires. These participants did not have a sufficient enough command in another language to be able to discuss pictures. Consequently, for the purpose of the task they were considered monolinguals and were performing a verbal and a silent condition for Pointing Task.

first language might not be the dominant language (language that a participant knows better or is using more often (in higher number of contexts)). Finally, participants might be multilinguals and have a decent proficiency in several languages. Consequently, the real-life picture of language experience might be quite complex. For the purpose of the current study, the first and the second languages were analyzed regarding variables of interest in multilingual participants. This was done for two main reasons: first, the literature discussed in the first chapter suggest existence of potential differences between monolinguals and bilinguals (and types of bilinguals), without a strong reasons to expect significant differences between bilinguals and multilinguals; second, should multilinguals differ from bilinguals and monolinguals in a population, this should likely happen because of factors varying in multilinguals (age of acquisition of each language, level of proficiency, functions for which each language is used and a mode of learning), not multilingualism itself. To summarize, I did not think LEAP questionnaire allows me to carefully distinguish between these aspects of multilingual participant experience, and thus did not employ analysis of language function or learning type. However, an additional analysis was performed investigating language asymmetry depending on number of languages a participant indicated. Since results for this test (discussed further in the section 3.4.2 were not significant, I concluded multilingualism did not introduce a systematic bias to the current study data set.

Language processing asymmetry was determined based on the dichotic listening task and operationalized as the Laterality Index. The Laterality Index was calculated with the formula: (LI) = [(RE-LE)/RE + LE] x 100, where RE refers to a number of the correct right ear responses and LE refers to a number of the correct left ear responses. The number of correct responses were provided by the iDichotic app.

Additionally, following Bless et al. (2015), right ear scores were used as an additional measure to make inferences regarding language dominance.

Handedness Indexes (HI) were calculated as a measure of asymmetry for pointing gesture and handedness (based on Cochet & Vauclair, 2012). HI were calculated with a formula (R - L)/(R + L + B), where R = right-hand responses/gestures, L = left-hand responses/gestures, and B = bimanual (no preference) responses/gestures. Possible values ranged from -1 to 1 with the absolute value indicating the strength of hand preference and positivity/negativity indicating direction (positive values for right-handed preference and negative values for left-handed). Raw scores for each task varied between 0 and 30. Participants classified as Bilinguals performed 15 number draws and 15 pointing gestures with their first language and the other 15 number draws and 15 pointing gestures with their second language. Participants classified as monolinguals performed 15 number draws and 15 pointing gestures in a *verbal condition* and the other 15 number draws and 15 pointing gestures in a *silent condition (see further details on page 32 regarding conditions procedures)*.

Handedness and Footedness was measured based on the questionnaires (Waterloo Handedness Questionnaire and Waterloo Footedness Questionnaire), where each response is scored from -2 to 2 [left always (-2); left usual (-1); equal (0); right usual (1); right always (2)]. For the Waterloo Footedness Questionnaire there were 10 questions, the scores could range from -20 to 20. For the Waterloo Handedness Questionnaire, because of a malfunction in the Qualtrics software, researchers implemented a short (25 item) and a long (36 item) version of the questionnaire. Approximately half of the sample (*N* = 865) was scored on the short version of the questionnaire; the remainder (*N* = 969) was scored on both the short and long version. Scores for the short version of the Handedness questionnaire could range from -50 to +50; scores for the long version could range from -72 to +72. Scores on the footedness questionnaire could range from -20 to +20. In all calculations mentioned above, the absolute value indicates the strength of asymmetry, while positivity/negativity indicates its direction with negative numbers suggesting left-hand/foot preference and positive numbers indicating right hand/foot preference.

Implementation of the short version of the questionnaire occurred because of a problem with the Qualtrics software that caused the last questions of the Handedness questionnaire to not be presented. This mistake was unfortunately noticed after a number of participants completed the study. As a result, handedness was assessed by a shorter version of the Waterloo Handedness Questionnaire in a portion of the sample. The remaining portion of the sample was scored separately on the shorter version of the questionnaire consisting of 25 questions, as well as the full form of the questionnaire consisting of 36 questions. This was done in order to attain a measure that was consistent for both parts of the sample.

Since initial implementation of the shorter version of the questionnaire resulted from a mistake in electronic question implementation rather than an intended choice, an additional analysis was performed to compare results of the short and long forms of the Waterloo Handedness questionnaire. This analysis was performed on the sample for which both the short and the long questionnaire scores were obtained. The goal of the analysis was to ensure predictive value of the short form of the questionnaire from the long form of the questionnaire and evaluate the strength of relationship between two types of scores.

A correlation analysis was performed to investigate an association between the scores on the short and the long version of the questionnaires. A strong positive correlation was found, $r(966) = .959$, $p < .01$. Additionally, a simple regression was calculated predicting the short version questionnaire score from the long version questionnaire score. A significant regression equation ($F(1,966) = 12368.762$, $p<0.00$) was found with R2 of .928. Short form of the questionnaire predicted about 93% of a score of a long questionnaire form.

Taken together results of these tests suggest that the short version of the questionnaire produce the scores that are not different from the scores that can be obtained from the long version of the questionnaire. Consequently, the short version of the Waterloo handedness questionnaire was considered sufficient for obtaining handedness score. Since the score was deemed sufficient and was available for the whole sample, the score obtained from the short version of the Waterloo questionnaire was used as a measure of handedness for data analysis.

Additional variables were calculated for language laterality, handedness and footedness in order to examine the strength of asymmetry regardless of its direction. Accordingly, these were calculated as simple absolute values of a given measure: LI_ABS, Hand_ABS and Foot_ABS respectively. These variables allowed examining the relation between a more lateralised or a more balanced score and other parameters.

2.6 Procedures

Prior to the beginning of the study, the participants were informed about the purpose of the study, which was an association between motor development, perception and language experience. Participants signed a consent form prior to the beginning of a study. No deception was implemented in the study.

The testing consisted of three major blocks: the dichotic listening task (3 min), questionnaires (approximately 25 min) and the behavioural task (approximately 12 min) (pointing gesture and bimanual manipulation (test site – room 4301, Robert C. Brown Building, SFU)). Testing was done by the primary investigator and trained research assistants.

Participants performed the Dichotic Listening Task first. Participants were provided with an iPad in order to complete the task and were assisted by a researcher with filling in the preliminary questionnaire installed in an app (age, native language, gender) and taking a short hearing test in order to screen for hearing impairments. The lab environment was kept quiet for the time of testing. Each participant was provided with a unique participant ID. After this, participants proceeded with filling in questionnaires (Language Experience and Proficiency Questionnaire; Waterloo Handedness Questionnaire; Waterloo Footedness Questionnaire), again, using their participant ID. The questionnaires were filled in online on the lab PC using Qualtrics software – a survey software, storing data securely on Canadian servers. After filling in the questionnaires, the participants performed the behavioral asymmetry tasks (pointing and bimanual manipulation).

Bimanual Manipulation Task:

Participants were tested individually seated at a rectangular table in front of an experimenter. In order to avoid any positioning bias, participants were asked to place their hands on two symmetrical stickers (placed about 25 cm from a table edge). A transparent tube container was used for the task. The container was filled with several pieces of paper, with numbers 1-30 written on them. A participant was asked to take a number from the container, in order to determine, which set of photographs they will be presented with. For example, if a participant picked up number 5, they were presented with picture set number 5. The task continued until 30 trials were performed. The trials of the pointing and manual tasks were alternated, allowing for randomization of the pictures sets and providing a plausible motive for the manipulation task.

Pointing Task:

Participants were tested individually seated at a rectangular table in front of an experimenter. In order to avoid any positioning bias, participants were asked to place hands on two symmetrical stickers (placed about 25 cm from a table edge). An experimenter placed a set of photographs (each set containing 4 photographs – A4 format x 30 trials) at a distance of 0.6 m away from the participant.

Participants were asked to point to a photograph they prefer and give a short explanation regarding why they preferred this particular picture over other images. Based on their language status, participants were tested in two different conditions. Bilingual participants were asked to provide justification for why they prefer this particular photo in either their first or second language. If a participant had some exposure to another language but stated that they could not speak a language well enough to discuss a picture, they were tested as monolingual participants. The monolingual participants were asked to give explanations either in a silent, or a verbal condition. In a silent condition a participant first pointed to a picture, and then explained why they preferred it, while in a verbal condition a participant simultaneously pointed to a picture and discussed it; thus, the gesture and speech production were disconnected in this task. These conditions were implemented based on Cochet and Vauclair's (2012) research design (in that study referred to as silent and co-speech condition respectively, as it has been previously suggested that gesture asymmetry might be affected by speech (Luasberg & Kita, 2003).

The two conditions for bilingual participants consisted of explanations given either in a native or a second language. The order of native vs. second language, as well as verbal vs. silent conditions was randomly alternated between participants. Each session was videotaped for further analysis.

No deception was implemented in the Bimanual manipulation and Pointing tasks. The participants were told that researchers were interested in whether "an activation of a particular language affected selection of pictures". Because knowledge of the fact that it is specifically which hand was used to point and pick up a number or point with that researchers were interested in would not meaningfully affect participants' willingness to take part in a study, there was no need to debrief participants.

2.7 Data Analysis Plan

1. **Attrition and missing data**

- To inspect the dataset on the presence of missing data. To determine if the missing data can be restored via analytical methods. Data can be restored for some variables, such as “ears of formal education”. The nature of variables of interest (language asymmetry and handedness) does not allow entering average values to substitute missing data, as such approach would affect data distribution and potentially bias the results.

- To exclude certain data points based on the previous literature (LI scores equal to 100, LI scores where the error rate exceeds 24 out of 30 responses).

2. **Data analytic approach**

- To inspect the data distribution regarding normality via visual inspection and measures of skewedness and kurtosis. Variables that do not deviate from normality will be analyzed via parametric methods (MANOVA and Pearson Correlation Coefficient). Variables that notably deviate from normality will be analyzed via non-parametric methods (Chi-square test, Wilcoxon Signed Rank test, Mann-Whitney test and Pearson’s rho).

3. **To examine variable of interest in the current dataset**

- To examine language asymmetry by calculation Language Laterality index and examining the Right Ear score distribution (following Bless et al., 2015).

- To examine sample composition on the proportion of participants demonstrating the right ear advantage, the left ear advantage and equal scores on language asymmetry. The purpose of these analyses is to determine whether resulting distribution is concordant with the one in Bless et al. (2015) study as well as to determine if participants in the current sample exhibit overall right ear advantage for the dichotic listening task.

- To examine the strength of asymmetry by calculating absolute values of language asymmetry (the variable is examined following Cochet and Vauclair (2012) approach to assess not only the direction but the strength of asymmetry.

- To examine handedness distribution by calculation Handedness Laterality Score

- To examine sample composition on the proportion of participants categorized as the right-handers, the left-hander and ambidexters. The purpose of these analyses is to determine whether handedness distribution in the sample exhibits strong right-hand bias and proportion of hand preference groups defined categorically is similar to the one predicted by the literature (about 90% right handers).

4. To examine the relationship between language asymmetry and handedness

- In order to determine whether there is an association between language asymmetry and handedness a correlational analysis is performed between language laterality index and handedness scores. In order to determine whether there is an association between the strength of a symmetry in both domains a correlational analysis is performed between the absolute value of language laterality index and the absolute values of handedness scores. It is predicted that measures should correlate with each other respectively.

- In order to determine whether in the current dataset the variation in language asymmetry has an effect on the variation in handedness score a regression analysis is performed with handedness score as an outcome variable. It is predicted that handedness score should systematically vary depending on language laterality score and/or the right ear score. While implementation of regression analysis does not allow to directly infer causal relations between the variables, it allows propose such relationship with more certainty than a correlational analysis. The latter determines a simple association between two variables, while a significant regression shows that variation in one variable (language asymmetry) is systematically related to variation in another variable (handedness score) in a given dataset. Results cannot be directly extrapolated to the general population and cannot be interpreted as a proof of causality.

- to examine the relationship between the strength of laterality index the strength of handedness a correlation analysis and a regression analysis (absolute value of handedness score as an outcome variable) were performed. It is predicted that participants more strongly lateralized for language are also more strongly lateralized in handedness

- it is further predicted that participants classified based on their hand preference would have different language asymmetry scores (one-way MANOVA, between-subject design, group level differences). The right handers are expected to have higher language asymmetry scores.

- correlation and regression analyses are performed in each hand-preference group (within-subject design). It is predicted that scores and handed the scores will correlate in each group and variation in language asymmetry would predict variation in handedness.

5. To examine the relationship between language status and age of L2

- the effect of language status (early bilingual, late bilingual, monolingual) on language laterality index, the right ear score and strength of language asymmetry (absolute value of laterality index score) is examined by a one-way MANOVA. It is predicted that early bilinguals as a group will have lower language asymmetry scores than late bilinguals and monolinguals.

- it is further predicted that early bilinguals will have lower language asymmetry scores in comparison with late bilinguals and monolinguals (Mann-Whitney test).

- should the age of second language acquisition have an effect on language a theory formation, it is expected that language asymmetry scores should correlate with the age of the second language acquisition (the older a person was when started learning a second language the more lateralized language processing became). Analysis is performed in the bilingual subsample. Additionally, it is expected that variation in the age of the second language acquisition will be predictive of language laterality scores.

6. To examine the relationship between asymmetry and language type

- In order to determine whether speaking a particular language, rather than language in general, has an effect on language asymmetry scores on language asymmetry are compared between major language types (one-way MANOVA, between-subject design).

- Whether language scores vary between speakers of tonal and non-tonal languages a one-way MANOVA test is performed comparing language laterality indexes and the right ear scores. Speakers of tonal languages are expected to have lower language laterality scores.

- In order to determine if language types groups systematically vary on handedness asymmetry a Kruskall-Wallis test is performed (between-subject design).

7. Examine the relationship between language asymmetry, handedness and gesture

- to examine whether object manipulation or pointing gesture is more lateralised. Following Cochet and Vauclair (2012) categorical classification of participants based on hand preference in both tasks is performed, as well as a Wilcoxon signed-rank comparing handedness indices for object manipulation and gesture.

- To examine the relationship between manual and gesture asymmetry by means of correlation and regression analyses. It is expected that handed the scores for object manipulation and gestures would correlate with each other, and that variation in the handedness score for object manipulation would predict variation in the handedness score for gesture.

- To examine the relationship between gesture asymmetry and language. Should language be strongly associated with gesture, the scores on both variables are expected to correlate with each other

- Hand preference for object manipulation and gesture are analysed separately in linguistic sub-samples. It is expected that in bilinguals gesture asymmetry will be weaker in the second language condition; following Cochet and Vauclair (2012) gesture asymmetry is expected to be weaker in monolinguals in a verbal condition.

- Handedness in object manipulation and gesture are expected to correlate in participants and between different conditions (between-subject and within-subject designs). Strength of correlations are compared by additional tests (Pearson-Fillon test).

8. Analysis of potential confounding parameters

- in order to examine whether variables of interest very depending on gender a one-way MANOVA (laterality index and right ear score as dependent variables) and Mann-Whitney tests (the strength of laterality index, handedness and the strength of handedness) are performed.

- prevalence of hand preference groups among males and females is analyzed by a chi-square test of independence

- whether handedness for object manipulation and gesture differ between males and females is analyzed by a Mann-Whitney test.

- In order to analyze weather handedness is associated with footedness correlation coefficients are calculated (within-subject design) and regression analysis predicting variation in the hand of the score based on the variation in the foot in the score is conducted. A Kruskall-Wallis test further compares footedness scores between participants classified based on their hand preference in order to determine whether participants with a certain pattern of hand preference tend to have similar pattern of foot asymmetry (for example, whether right handers tend to be more right footed) (between-subjects design).

Chapter 3.

Results

3.1. Attrition and Missing Data

Regarding general study sample attrition, no participant refused to take part in a study or chose to discontinue their participation. However, the total data set contains some missing data. These missing data were treated differently depending on the nature of the variable these data referred to. Specifically, a number of participants did not indicate a number of years of formal education they had (total number of such cases = 17). The variable Years of Formal Education (YFE) represented a number of years participants have spent in formal schooling starting from grade one. Missing values for this variable were added to the dataset manually. This was done for two reasons. First of all, the homogeneous nature of the sample could be used to give good estimates of how many years of formal education a participant of a given age likely to have. The second important reason concerned the very nature of the variable. Since participants were undergraduate students, they clearly had several years of formal education. Consequently, the number of years of formal education were added for missing values based on estimated relationship between an average age of the participant and number of years of education this participant has indicated. Missing values for this variable were estimated for these participants as follows: 12 YFE for an 18-year-old, 13 YFE for a 19-year-old, 14 YFE for a 20-year-old, 15 YFE for a 21-year-old, and 16 YFE for a participant 22 years of age or older. Using the same method, five additional values were recoded because these values were impossible (e.g., participants indicated 5 or 6 years of formal education). These recoded values suggested participants did not understand the question and entered an incorrect value.

The sample contained missing data for other reasons. Data obtained from questionnaires were typically missing either due to incorrect responses (for example, an incorrect indication of the first and second language, the type of language or level of language proficiency), or if a participant had skipped a part of the questionnaire. The main reason for missing video or dichotic listening data was equipment failure.

Missing data on variables of primary interest were not added or recoded. Specifically, missing dichotic listening scores, number of languages spoken, type of language, language proficiency, handedness and footedness scores were not substituted. Although it is common to use mean score calculations on a given measure to impute missing values for quantitative numerical variables, such an approach was not suitable because scores on language asymmetry, handedness and footedness reflect the strength of asymmetry in a given variable. Consequently, the missing values on these variables were not entered and thus the number of cases for different variables in the final sample varies. These numbers are indicated in further sections of the chapter and sample descriptive statistics.

Some data for the dichotic listening task were excluded from the final analysis. These included participants that scored perfectly 100% on the test (based on recommendations by Bless et al., 2015), as such a perfect score is highly improbable even in a lab setting and is more likely indicative of an incorrect testing procedure. Additionally, as per Bless et al. (2015), participants with a high error rate were also excluded from the analysis. Error rate was calculated by a formula Err = 30 - (R + L); Bless at al. (2015) recommend excluding participants with an error rate of 24 and above because a high error rate likely indicates hearing issues, equipment failure, or participant reluctance to take the test when they simply pressed buttons randomly.

3.2 Data Analytic Approach

All descriptive and statistical analyses were completed in SPSS Version 25. Relationships between variables were examined by means of parametric and non-parametric tests. The choice of a test depended largely on distributional values of skewness and kurtosis, the Kolmogorov-Smirnov test, visual inspection of histograms and Q-Q plots, and conventions employed in previous studies examining the measure in question. Recent recommendations regarding assessing normality distribution based on skewness and kurtosis values suggest acceptable limits of these parameters to be +/-2, when a normal distribution can be inferred (Field, 2000, 2009; Gravetter & Wallnau, 2014; Trochim & Donnelly, 2007).

Language Asymmetry Measures. Inspection of Language laterality Index and the Right Ear Score skewness and kurtosis values revealed that the distribution of right ear scores does not drastically deviate from the normal distribution (see Table 3).

Table 3.

Language Measures Skewness and Kurtosis Values

	Skewness	**Skewness *SE***	**Kurtosis**	**Kurtosis *SE***
Language Laterality Index	-.099	.058	.695	.115
Right Ear Score	.411	.058	.094	.115

Further inspection of the Language Laterality Index and the Right Ear Score variables with Histograms and Q-Q plots (see Figures 3 and 4) revealed that these variables do not deviate from normality, and thus were analyzed by parametric tests (MANOVA and Pearson Correlation Coefficient).

Figure 3: Right Ear Scores Distribution

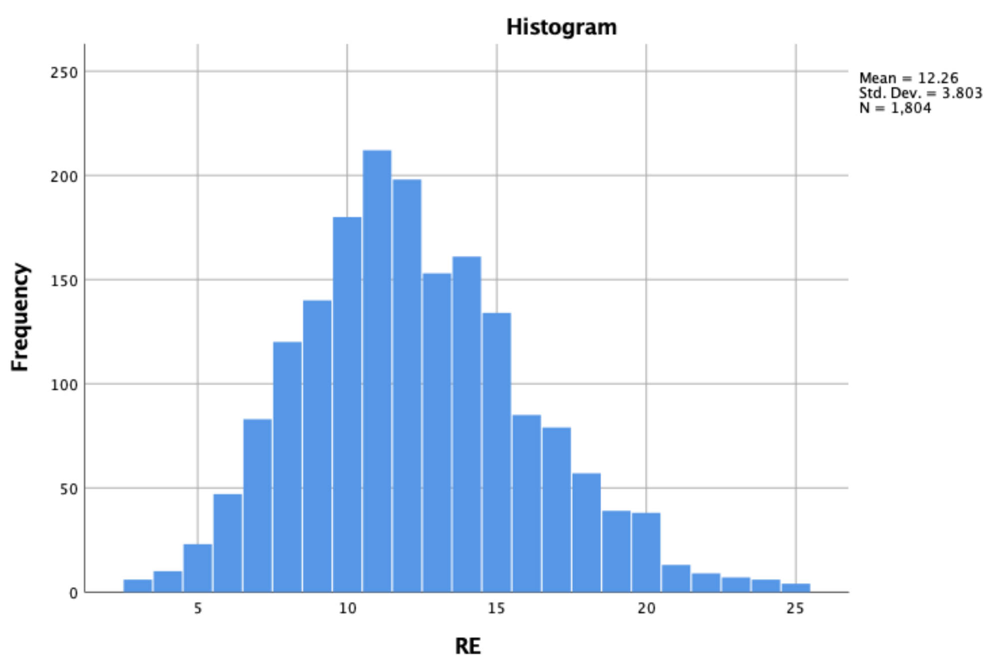
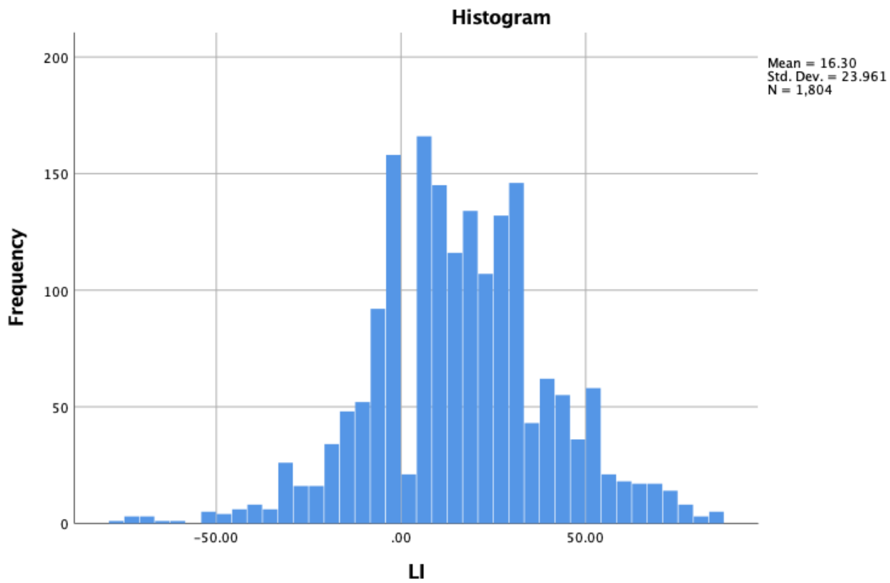


Figure 4: Language Laterality Index Scores Distribution



Handedness and Footedness Measures. Handedness and footedness scores, as well as absolute values of these scores (Hand_ABS; Foot_ABS) and the language laterality index (LI_ABS), significantly deviated from the normal distribution.

Table 4.

Handedness and Footedness Measures Skewness and Kurtosis Values

	Skewness	Skewness *SE*	Kurtosis	Kurtosis *SE*
Handedness Score	-2.249	.058	5.724	.116
Footedness Score	-.795	.057	1.239	.115
Absolute Handedness Score	-.676	.058	.491	.116
Absolute Footedness Score	.129	.057	-.970	.115
Absolute Language Laterality Index	.953	.058	.515	.115

Visual inspection of histograms and Q-Q plots further indicated deviation from normality in these measures, thus these parameters were analyzed by non-parametric tests (Chi-square test, Wilcoxon Signed Rank test, Mann-Whitney test and Pearson's rho).

Figure 5: Handedness Scores Distribution

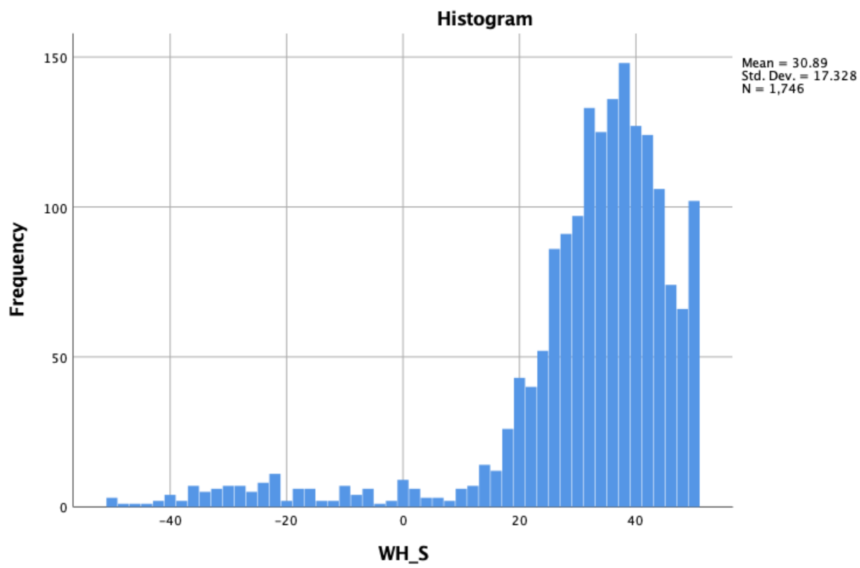


Figure 6: Absolute Handedness Scores Distribution

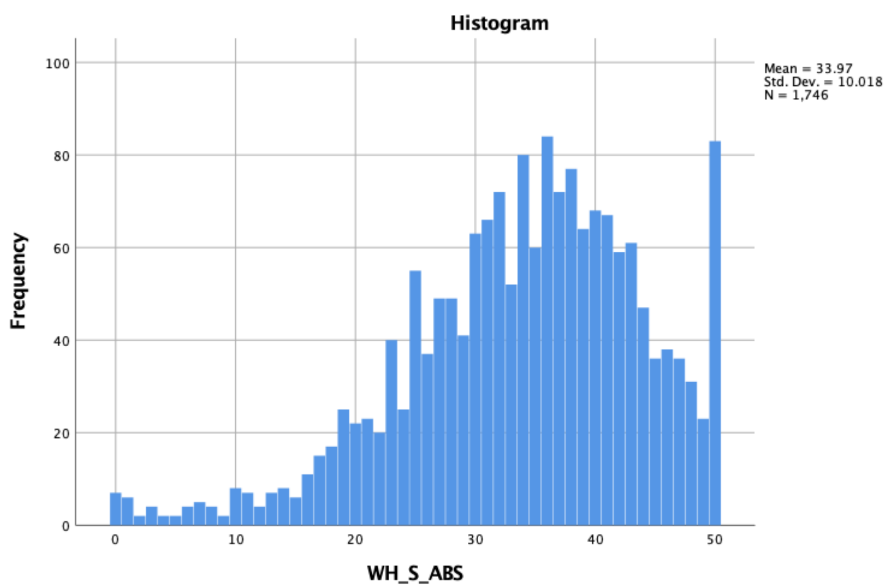


Figure 7: Footedness Scores Distribution

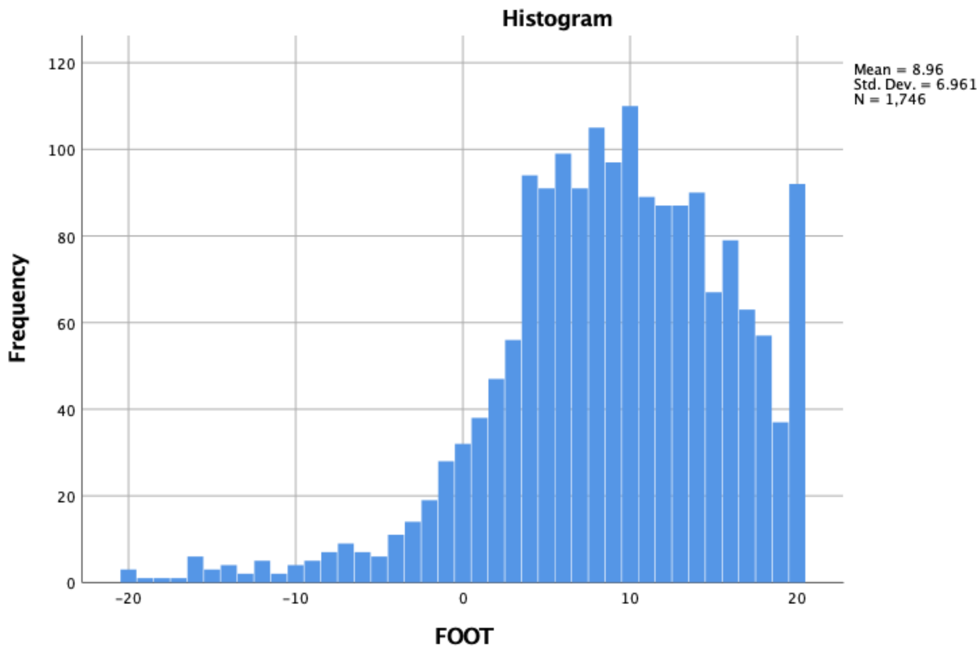


Figure 8: Absolute Footedness Scores Distribution

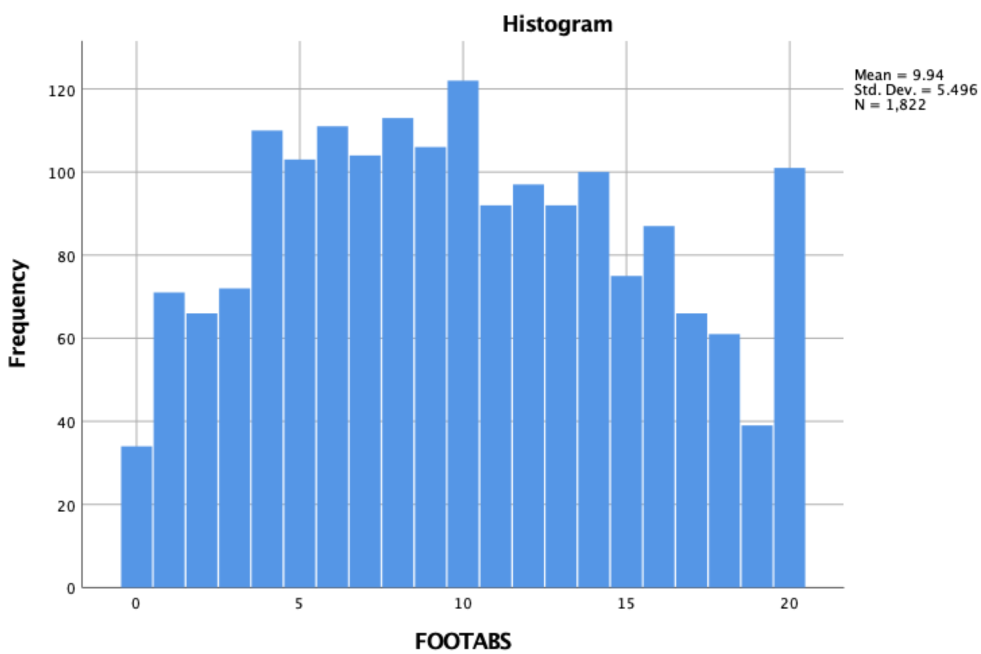
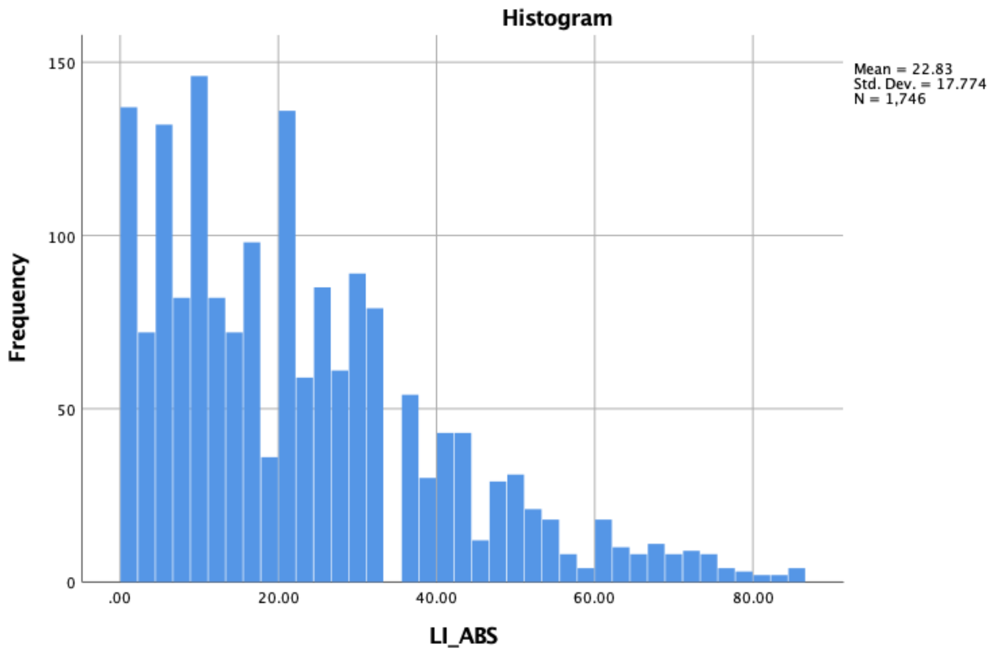


Figure 9: Absolute Language Laterality Index Scores Distribution



3.3 Demographics and Descriptive Analysis

Investigation of Variables of Interest

Language Asymmetry

Language Laterality index scores (*N* = 1,806) ranged from – 76.92 to 85.19 (*M* = 16.23, *SD* = 24.05).

The Right Ear Score (*N* = 1,817) ranged from 1 to 27 (*M* = 12.26, *SD* = 3.81).

Regarding the Right Ear Advantage (REA) distribution, out of 1,811 participants 1,328 (73.3%) demonstrated the REA (determined as positive values of LI), 343 (18.9%) demonstrated the LEA (determined as positive values of LI) and 140 (7.7%) scored equally for the right and the left ear (language laterality index equal to 0). Accordingly, a left hemisphere dominance for language can be inferred in 73.3% participants, a right hemisphere dominance for language can be inferred in 18.9% participants and an equal hemisphere processing of language could be inferred in 7.7% participants.

The strength of language asymmetry regardless of its direction was assessed by an additional parameter – the absolute value of the laterality index (*N* = 1,806, *min* = 0, *max* = 85.19, *M* = 22.92, *SD* = 17.88).

Handedness

Handedness scores are derived from the Waterloo Handedness Questionnaire (*N* = 1,774, *M* = 30.87, *SD* = 17.33). The strength of handedness asymmetry regardless its direction was assessed by an additional parameter - an absolute value of handedness score (*N* = 1,774, *M* = 33.96 *SD* = 10.02). Participants were also classified as right handers, left-handers or ambidexters, based on their handedness score. Specifically, participant scoring from 10 to 50 were classified as right handers, participant scoring from -50 to -10 were classified as less left-handers, and participants scoring from -9 to 9 were classified as ambidexters. As a result, the sample consisted of 1639 (92.4%) right-handers, 97 (5.46%) left-handers and 38 (2.14%) ambidexters.

Footedness

The footedness score (*N* = 1,822) had a *M* = 8.94 (*SD* = 7.01). The strength of footedness asymmetry regardless its direction was assessed by an additional parameter - an absolute value of footedness score, regardless its direction (*N* = 1,882, *M* = 9.94 *SD* = 5.5).

3.4 Primary Analysis

3.4.1 Examining the relationship between language asymmetry and handedness

It is predicted that language asymmetry scores would correlate with handedness scores, and that participants more strongly lateralized for language will be more strongly lateralized for hand preference. It is further predicted that in the current dataset the variation in language asymmetry has an effect on the variation in handedness score.

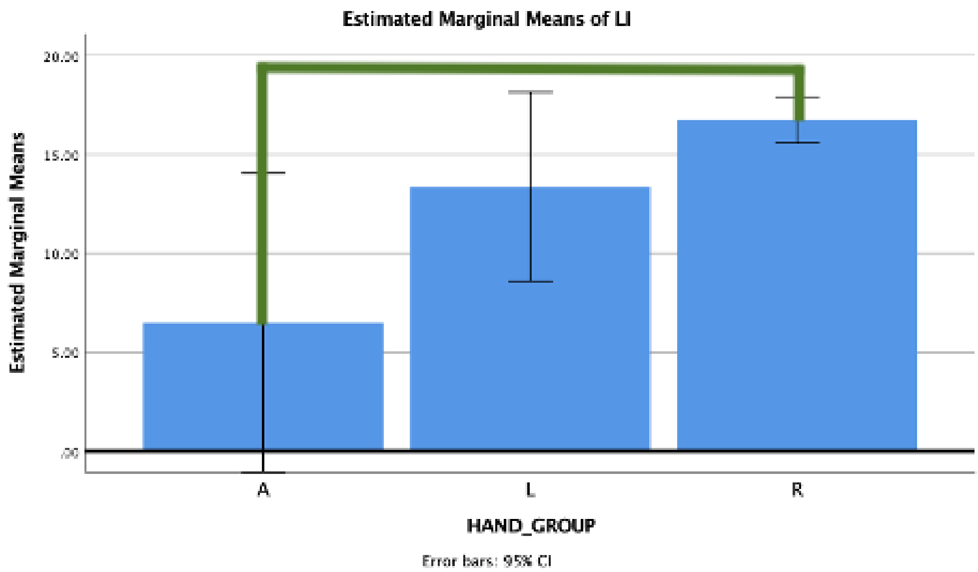
A correlation analysis was performed in order to investigate whether there is an association between language asymmetry score (language laterality index) and handedness. An extremely weak positive correlation, $r(1748) = 0.047$, $p < .05$, was found between language laterality index and handedness score. Additionally, a Spearman's rho correlation coefficient was calculated to examine the relationship between the strength of laterality index (LI_ABS) and the strength of handedness (Hand_ABS). No significant relationship was found, $r(1748) = 0.013$, $p = .590$.

Variables that demonstrated significant correlations were further inspected by a regression analysis. Specifically, multiple linear regression was calculated to predict participants' handedness based on their language asymmetry (language laterality index) and the right ear score. Results indicated a significant effect, $F(2,1747) = 3.892$, $p < .05$, was found with an $R^2 = .004$. Among the individual predictors the language laterality index was a significant predictor, $t = 2.505$, $p < .05$, while the right ear score was not, $t = -1.185$, $p = .236$. In other words, laterality index explains less than 1% of variation in handedness score.

An additional regression analysis was performed in order to examine the strength rather than direction of asymmetries. Specifically, handedness absolute scores were treated as an outcome variable and laterality index absolute scores along with the right ear scores as predictors. This model was not significant, $F(2,1747) = .084$, p = .919. Participants more strongly lateralised in language were not more likely to be strongly lateralized in hand preference.

A one-way MANOVA was calculated examining the effect of handedness group (right handers, left handers, ambidexters) on laterality index (LI) and the right ear score (RE). The analysis produced significant results, $F(4,3492) = 2.633$, $p < .05$, partial $\eta_2 = .003$, with LI significantly varying between groups $F(2,1747) = 4.245$, $p< .05$, partial $\eta_2 = .005$. Post hoc comparisons using the Tukey HSD test indicated that right handers tended to have higher language laterality index score (*M* = 16.79, *SD* = 23.78) than ambidexters (*M* = 6.49, *SD* = 23.3). There was no significant difference in scores between ambidexters and left-handers ($p = .935$), as well as right-handers and left-handers ($p = .482$).

Figure 10: Language Laterality Index Scores between Handedness Groups



Note: R – right handers, L – left-handers, A - ambidexters

Finally, participants were grouped into right handers, left-handers and ambidexters based on handedness questionnaire scores (10 to 50; -50 to -10 and -9 to 9 respectively). The relationship between handedness and language asymmetry were analyzed separately in these groups.

In the right-handers language laterality indexes and handedness scores did not correlate significantly $r(1598) = .024$, $p > .05$. A regression analysis was not significant either $F(1,1597) = .512$, $p > .05$. Similarly, analysis of handedness and language laterality indexes in ambidexters did not produce significant results $r(64) = -.015$, $p > .05$; $F(1,63) = .02$, $p > .05$. In the left-handers, however, handedness scores and language laterality indexes significantly correlated $r(86) = .221$, $p < .05$. A regression analysis produced significant results $F(1,85) = 7.05$, $p < .01$, with an $R^2 = .077$. The language laterality index could explain about 8% of handedness score in left-handers.

3.4.2 Examining the relationship between language status and age of L2

Overall early bilinguals are expected to be less lateralized in both linguistic and manual domains, this as a group having lower language asymmetry and handedness scores. Late bilinguals and monolinguals are expected to have higher language asymmetry and handedness scores.

A one-way MANOVA was calculated examining the effect of language status (early bilingual, late bilingual, monolingual) on language laterality index, the right ear score and strength of language asymmetry (absolute value of laterality index score). No significant effect was found, $F(9,1315) = 1.659$, $p = .093$. Laterality index scores, the right ear score and the strength of language asymmetry were not influenced by language status. Since Hull and Vaid (2006) suggest that the laterality pattern in language might be more similar between late bilinguals and monolinguals than early bilinguals, an additional analysis was performed where late bilinguals and monolinguals were grouped together and compared to early bilinguals. A One-Way MANOVA test was performed with language status (early bilingual vs. late bilingual + monolingual) as a factor and laterality index, the right ear score and strength or language asymmetry as dependent variables. No significant effect was found, $F(3,1774) = 2.359$, $p = .07$.

Effects of language status on handedness and an absolute handedness score were examined by a Kruskall-Wallis test. Specifically, they were compared between language status groups (early bilinguals, late bilinguals, monolinguals). A significant result, $H(3) = 8.28$, $p < .05$, was found for the absolute handedness score.

A post-hoc analysis employing Dunn's test applying Bonferonni corrections revealed previous differences to be non-significant (the smallest adjusted p value = .13). Consequently, none of the variables (regular or absolute handedness and footedness scores were significantly different between three language status groups). However, when the same analysis was performed with a Mann-Whitney test in the bilingual sub-sample, a significant difference in the absolute strength of handedness was found between early and late bilinguals, $U = 214.529$, $p < .05$, with early bilinguals demonstrating stronger laterality for handedness (*Mdn* = 35) then late bilinguals (*Mdn* = 34). These results should be taken with caution, as the follow up chi-square test of independence comparing the frequency of males and females among early and late bilinguals suggested a significant interaction, $\chi^2(3, 1480) = 3.863$, $p < .05$. Early bilinguals as a group tended to have more females than expected (crosstabulation values of 650 count with 632 expected), and fewer males than expected (crosstabulation values of 336 count with 353 expected), which in turn could potentially have resulted in this group scoring higher on the absolute laterality handedness measure. (Effects of gender are discussed in section 3.5.1).

Similar to the analysis discussed above, distributions of handedness and footedness scores were inspected comparing these variables in early bilinguals vs. late bilinguals and monolinguals as a single group. A Mann-Whitney U test was not significant, $U = .810$, $p > .05$.

The bilingual sample was additionally examined for potential effects of the age of the second language acquisition on variables of interest. It was predicted that older age of the second language acquisition would correlate with higher language asymmetry score. A Pearson correlation coefficient was calculated for the relationship between age of the second language acquisition, laterality index, absolute value of laterality index, right ear score and number of languages spoken. A small negative correlation was found between the age of the second language acquisition and the absolute value of the language laterality index, $r(1463) = -.066$, $p = .011$, meaning that the strength of laterality index tended to decrease in participants that started learning their second language at an older age. A small negative correlation between the age of the second language acquisition and the number of languages spoken was also found, $r(1477) = -.130$, $p < .000$, suggesting that the older was a person when they started learning a second language, the smaller number of languages they would learn on average.

A multiple linear regression was calculated to predict participants' absolute laterality index score based on their age of the second language acquisition and the number of languages spoken as predictors. Significant results were found $F(1,1749) = 6.268$, $p < 0.05$, with an $R^2 = .004$. Among the individual predictors, the age of the second language acquisition was a significant predictor, $t = -2.563$, $p < .05$, while the number of languages the participant learned was not, $t = -.220$, p > 0.05.

3.4.3 Examining the relationship between asymmetry and language type

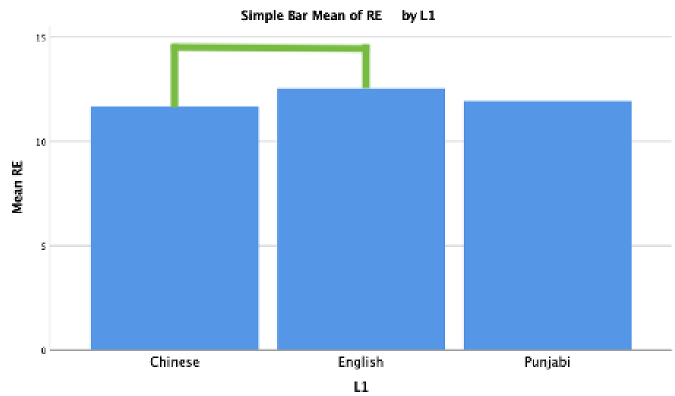
Due to the heterogenous linguistic composition of the sample, relations between language type and variables of interest were analyzed separately in subsamples of participants.

First, an analysis was performed separately in two subsamples, based on a number of participants indicating a given language as their first language. This was done as the number of participants in different language groups varied, with some groups having many more participants than others. Since I was interested in whether speakers of different languages differ on variables of interest, comparing language groups drastically varying in participant number would not be meaningful. In other words, comparing speakers of English (679 participants) and Arabic (14 participants) on language asymmetry would not be statistically valid. Consequently, analyses were performed in two subsamples based on more or less similar number of participants in each language group. The first subsample consisted of participants who indicated Chinese (N = 337), English (N = 679) or Punjabi (N = 120) as their first language. The second sample consisted of participants who indicated Arabic (N = 14), Farsi (N = 33), Hindi (N = 17), Indonesian (N = 37), Korean (N = 59), Russian (N = 23), Spanish (N = 15), Urdu (N = 22) and Vietnamese (N = 28) as their first language. Participants that indicated any other language as their first language were not included in this analysis, as a small number (less than 10) of participants in each language group would not make such an analysis meaningful. In other words, participants in the first subsample (those who indicated their L1 as either English, Chinese or Punjabi) were compared on language asymmetry and handedness scores.

Test results will first be reported for the first subsample (Chinese, English and Punjabi groups). A one-way MANOVA test was computed comparing language laterality indexes and the right ear scores. A significant difference in the right ear score was found depending on the first language, $F(4,2240) = 5.162$, $p < .000$. Follow up univariate ANOVAs indicated that the RE score was significantly different between English (M = 12.56) and Chinese speakers (M = 11.69), $F(2,1124) = 5.829$, $p < .05$.

The absolute values of the language laterality index, handedness score and absolute value of handedness score were compared by means of a Kruskall-Wallis test. None of the parameters differed between three language groups: absolute value of language laterality index, $H(2) = 2.979$, $p > 0.05$, handedness score, $H(2) = 2.629$, $p > 0.05$, and absolute value of handedness score, $H(2) = 3.684$, $p > 0.05$.

Figure 11: Language Laterality Index Scores in Different Language Groups



The second subsample results did not provide any evidence of between-group differences. A one-way MANOVA test was computed comparing language laterality indexes and the right ear scores. The test was not significant, $F(16,472) = 1.410$, $p = .132$.

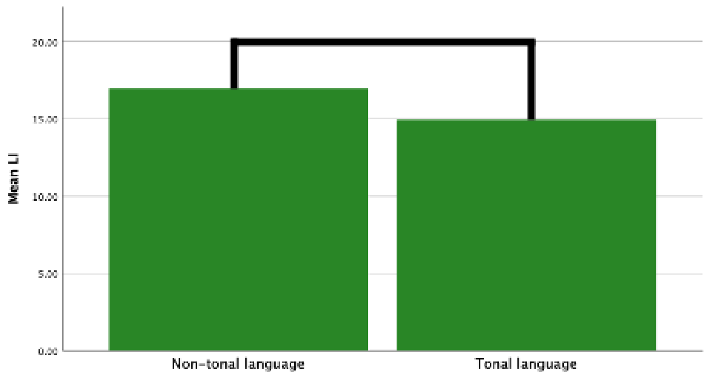
The absolute values of the language laterality index, handedness score and absolute value of handedness score were compared by means of a Kruskall-Wallis test. None of the parameters significantly differed between language groups: absolute value of language laterality index, $H(8) = .534$, $p > 0.05$, handedness score, $H(8) = .136$, $p > 0.05$, absolute value of handedness score, $H(8) = .278$, $p > 0.05$.

In the second set of analyses concerning language type, participants were grouped based on whether their first language was a tonal or a non-tonal one, as literature suggested this factor might affect language asymmetry (Valaki et al., 2004). As a result, speakers of a tonal first language (Chinese, Punjabi, Vietnamese) were compared to speakers of a non-tonal first language (Arabic, English, Farsi, Hindi, Indonesian, Korean, Russian, Spanish, Urdu) on variables of interest.

A one-way MANOVA test was computed comparing language laterality indexes and the right ear scores. The test was significant, $F(2,1362) = 7.438$, $p < .05$. Follow up univariate ANOVAs indicated that the laterality indexes were significantly different between the tonal ($M = 11.76$) and non-tonal ($M = 12.48$) groupings, $F(1,1363) = 2.095$, $p < .05$. The absolute values of the language laterality index, handedness score and absolute value of handedness score were compared by means of a Mann-Whitney test.

None of the parameters differed between two groups: absolute value of language laterality index, $U = 211{,}054$, $p > 0.05$, handedness score, $U = 206{,}476$, $p > 0.05$, or absolute value of handedness score, $U = 208{,}247$, $p > 0.05$.

Figure 12: Language Laterality Index Scores in Tonal and Non-tonal Languages



3.4.4 Examining the relationship between language asymmetry, handedness and gesture.

In study 2, variables of interest were first analyzed in the whole sample (N = 543), and later were additionally examined in bilingual (N = 338) (62.4%) and monolingual (N = 204) (37.6%) subsamples separately.

Descriptive Statistics of Variables of Interest

Table 5.

Gesture Laterality and Handedness Indexes (range from -1 to 1)

Gesture LI	**Mean**	**SD**
Total sample	.60	.65
Bilingual subsample	.58	.66
Monolingual subsample	.63	.64

Handedness LI		
Total sample	.65	.70
Bilingual subsample	.64	.71
Monolingual subsample	.64	.69

Note. LI refers to Laterality Index.

Right hand preference for pointing and right-hand preference for object manipulation varied between 0 and 30. The mean value for right-hand pointing preference was 24 (*SD* = 9.76); the mean value for the right-hand object manipulation preference was 24.76 (*SD* = 10.51). The figures indicate that participants on average, as expected, were right-handed for both object manipulation and pointing gesture.

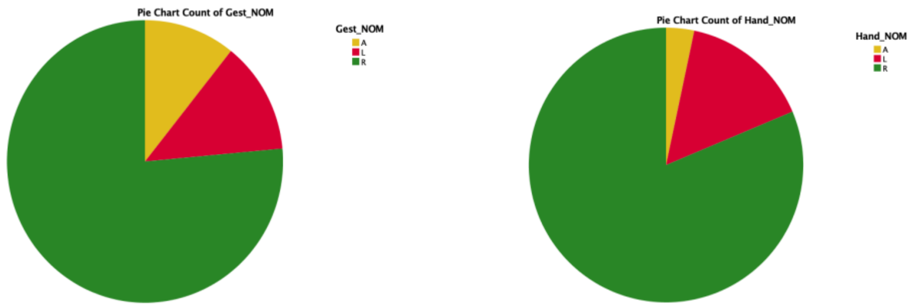
Categorical analysis of the number of right handers and left handers in pointing and object manipulation in the total sample was performed. Participants were classified as right handers or left hander if they performed at least 20 out of 30 actions with the right or left hand respectively.

Table 6.

Categorical Analysis of Handedness Groups

	Right handers	**Left handers**	**Ambidexters**
Pointing Gesture number (percentage)	401 (73.8)	66 (12.2)	55 (10.1)
Object manipulation number (percentage)	425 (78.3)	81 (14.9)	17 (3.1)

Figure 13. Gesture and Hand Preference Groups



Pointing Handedness Object Manipulation Handedness

Note: green – right handers, red – left-handers, yellow - ambidexters

The figures indicate that the number of participants classified as right handers was about the same in object manipulation and a pointing gesture condition. Slightly more participants were classified as left handers in the object manipulation condition, rather than in pointing gesture condition. Most notably, more participants were classified as ambidextrous in the pointing gesture condition rather than in object manipulation condition (10.1% and 3.1% respectively).

Language mean laterality index in the sample was M = 15.57 (SD = 24.8); the mean right ear score was M = 12.17 (SD = 3.88).

Relationship between Manual Handedness and Gesture Asymmetry

In order to examine the relationship between handedness for object manipulation and handedness for pointing, several analyses were performed. Spearman correlation coefficients were calculated for handedness for object manipulation, handedness for pointing, as well as an absolute value of handedness for object manipulation and handedness for pointing. Significant positive correlation coefficients were found between handedness for object manipulation and pointing, $r(522) = .480$, $p < .000$, as well as an absolute value of handedness for object manipulation and pointing, $r(543) = .337$, $p < .000$. These results indicate a moderate association between handedness for object manipulation and pointing gesture, while the association between the strength of two parameters was weaker.

A linear regression was calculated to predict participants' laterality index for pointing based on the laterality index for object manipulation. The analysis produced a significant result, $F(1,1770) = 156.933$, $p < 0.000$, with an $R^2 = .231$. Thus, variation in the object manipulation laterality index could explain about 23% of variation in pointing laterality index.

An additional linear regression was calculated to predict participants' gesture laterality index based on the raw score on handedness questionnaire. The analysis produced a significant result, $F(1,465) = 61.979$, $p < 0.000$, with an $R^2 = .118$. Thus, variation in the handedness questionnaire score could explain about 12% of variation in pointing laterality index.

Finally, a related sample Wilcoxon signed-rank test was conducted to compare the difference between laterality indexes in pointing and object manipulation. The test produced significant results, $Z = -3.265$, $p = 0.001$, indicating that laterality indexes in object manipulation task were higher ($M = .66$, $Mdn = 1$) than laterality indexes for pointing gestures ($M = .60$, $Mdn = 1$).

Language Status

A Kruskal-Wallis test was conducted comparing early bilinguals, late bilinguals and monolinguals on the variables of interest. No significant results were obtained for any of the four parameters: laterality indexes for pointing, $H(3) = 2.500$, $p = .475$, object manipulation, $H(3) = .578$, $p = .901$, absolute values of laterality indexes for pointing, $H(3) = 8.793$, $p = .066$, or object manipulation $H(3) = 6.420$, $p = .170$, did not differ between early bilinguals, late bilinguals and monolinguals.

Relationship Between Gesture Asymmetry and Language

Participants classified as right handers, left-handers or ambidexters based on their hand preference for pointing were compared on variables of interest. No significant results were obtained regarding the difference in the language laterality index and the right ear score, $F(4,1020) = .447$, $p = .774$, as well as the absolute value of the language laterality index, $H(2) = .541$, $p = .763$. No significant results were obtained. An additional analysis was conducted comparing the differences in the same parameters for participants classified as right handers, left-handers or ambidexters based on their hand preference for object manipulation. A significant result, $F(2,1022) = 2.637$, $p < 0.05$, was found for the distribution of language laterality index between handedness groups. A post-hoc analysis employing Tukey HSD test, however, did not reach significance (lowest obtained = .079). Participants classified based on their hand preference for the object manipulation task did not differ in their language laterality index.

Table 7.

Correlation Between Language Asymmetry and Gesture Asymmetry Measures

Measure	1	2	3	4	5
1. Language LI	__				
2. Right Ear Score	.772**	__			
3. Gesture LI	.047	.018	__		
4. Gesture LI_ABS	.029	.001	.760**	__	
5. Gesture right hand score	.053	.018	.988**	.754**	__

Note. LI refers to Laterality Index. ** $p < .01$

Analysis of Pointing Gesture and Hand Preference for Object Manipulation in Linguistic Subsamples

As has been previously mentioned, monolingual and bilingual subsamples were additionally analyzed in order to examine potential effects of task condition on pointing and object manipulation performance. In the monolingual group, participants performed pointing and object manipulation in a verbal and silent conditions. The total number of actions for either pointing or object manipulation was 30; thus, the total number of possible actions per condition was 15.

Table 8.

Descriptive Statistics for Handedness in Gesture and Object Manipulation (Monolinguals)

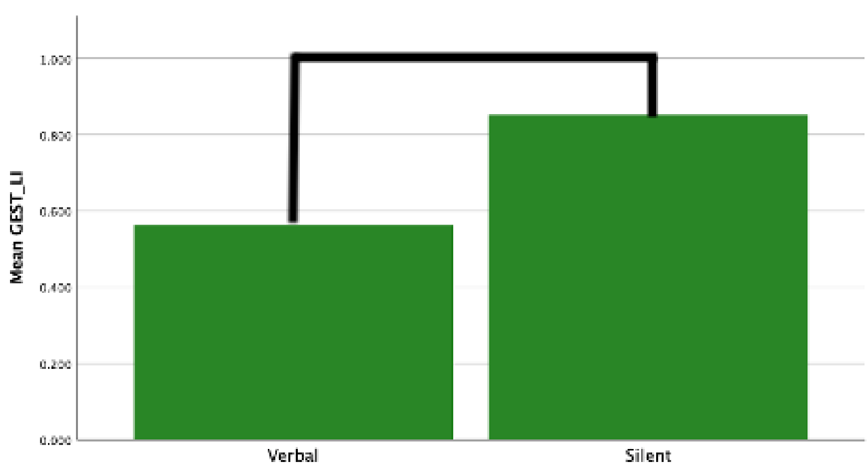
	Silent condition *M (SD)*	**Verbal condition** *M (SD)*	**Both conditions** *M (SD)*
Right hand preference in pointing	12.47 (4.97)	12.19 (4.95)	24.64 (4.45)
Right hand preference in object manipulation	12.75 (5.12)	12.45 (5.29)	25.08 (10.33)
Laterality Index for pointing gesture	.67 (.66)	.62 (0.67)	.60 (.65)
Laterality Index for object manipulation	.71 (.68)	.61 (1.02)	.65 (.70)

In order to investigate the relationship between hand preference in the pointing condition and the object manipulation condition, a correlational analysis was performed. Laterality indexes for pointing gestures performed in the verbal and silent conditions were significantly correlated, $r(193) = .764$, $p < .000$. Laterality indexes for object manipulation performed in the verbal and silent conditions were significantly correlated, $r(193) = .760$, $p < .000$. The laterality index for pointing gestures and object manipulation in the verbal condition was significantly correlated, $r(193) = .442$, $p < 0.000$. Laterality index for pointing gesture and object manipulation in silent condition was also significantly correlated, $r(193) = .338$, $p < .000$.

Steiger's (1980) test for comparison of dependent samples correlations strength was employed to determine whether there is a difference in the strength of correlation between the laterality index for object manipulation and laterality index for pointing in either verbal (r = .442) or silent (r = .338) conditions. A Pearson-Fillon test comparing two correlations did not provide significant results, Z = 1.80, p = .07. These results suggest that hand preference for pointing and object manipulation was not more strongly associated in either verbal or silent conditions.

The strength of asymmetry in object manipulation and pointing in both conditions was examined by means of a Wilcoxon test comparing the absolute values of the pointing gesture laterality index and bimanual manipulation laterality index. Results of the test revealed a significant difference between the strength of asymmetry of a pointing gesture, Z = 2.13, p = .03, with pointing gestures produced in a silent condition (mean rank = 0.91) being more strongly lateralized then pointing gestures produced in a verbal condition (mean rank = 0.88). The strength of asymmetry in object manipulation did not differ between two conditions, Z = -1.22, p > .05.

Figure 14. Gesture Asymmetry in the Verbal and Silent Conditions



In order to examine potential associations in the strength of asymmetry between pointing and handedness, an analysis of the difference of correlations was conducted comparing the absolute values of the laterality indexes for the gesture and object manipulation conditions. Absolute values of hand preference laterality indexes significantly correlated between gestures produced in verbal and silent conditions, $r(193)$ = .532, p < .000, and hand preference in object manipulation produced in same conditions, $r(193)$ = .211, p < .000. Absolute values of hand preference between pointing and object manipulation also correlated in verbal, $r(199) = .210$, $p < .05$, and silent, $r(193) = .226$, $p < .05$, conditions.

Steiger's (1980) test for comparison of dependent samples correlations strength was employed to compare whether there is a difference in the strength of correlation between the absolute value of laterality index for pointing or an absolute value of laterality index for object manipulation in both conditions. The test produced significant results, $Z = 3.80$, $p = .000$, suggesting that absolute values of laterality indexes for pointing were more stronger correlated to each other in both conditions, $r(193) = .532$, $p < .01$, than the absolute values of laterality indexes for object manipulation that were less stronger correlated with each other in both conditions, $r(194) = .211$, $p < .01$.

In the bilingual group, participants performed pointing and object manipulation in two conditions: speaking their first or second language. The total number of actions for either pointing or object manipulation was 30, thus the total number of actions per condition was 15.

Table 9.

Descriptive Statistics for Handedness in Gesture and Object Manipulation (Bilinguals)

	L1 condition **M (SD)**	**L2 condition** **M (SD)**	**Both conditions** **M (SD)**
Right hand preference in pointing	11.92 (5.11)	11.87 (5.10)	23.59 (9.95)
Right hand preference in object manipulation	12.41 (5.38)	12.28 (5.41)	24.55 (10.64)
Laterality Index for pointing gesture	.60 (.67)	.59 (0.67)	.60 (.65)
Laterality Index for object manipulation	.66 (.71)	.61 (.71)	.65 (.70)

Note. L1 refers to first language, L2 refers to second language

In order to investigate the relationship between hand preference in the pointing and object manipulation conditions, an analysis of the difference of correlations was performed. Laterality indexes for pointing gestures performed in the first and second language conditions were significantly correlated, $r(324) = .785$, $p < .000$. Laterality indexes for object manipulation performed in the first and second language condition were significantly correlated, $r(324) = .781$, $p < .000$. The correlation between the laterality index for pointing gestures and object manipulation in the first language condition was significant, $r(324) = .467$, $p < .000$. The correlation between the laterality index for pointing gesture and object manipulation in the second language condition was also significant, $r(324) = .494$, $p < .000$. The correlations between laterality indexes for object manipulation and laterality indexes for pointing did not differ significantly between the first and the second language conditions based on Steiger's (1980) test for comparison of dependent samples correlations strength, $Z = -0.66$, $p = .50$.

The strength of asymmetry in object manipulation and pointing was examined by means of a Wilcoxon signed-rank test. Pointing was generally less right-handed than object manipulation, $Z = -7.402$, $p < .000$, pointing laterality index ($M = .83$, $SD = .28$) and object manipulation laterality index ($M = .94$, $SD = .18$). However, there was no difference in laterality indexes of pointing in either the first or the second language condition, $Z = -0.21$, $p > .05$, as well as laterality indexes of object manipulation in either the first or the second language condition, $Z = -.393$, $p > .05$. Since the difference between correlations for pointing and object manipulation in the first language, $r(324) = .467$, $p < .000$, and the second language, $r(324) = .494$, $p < .000$, conditions was small, no additional tests comparing these correlations were performed.

In order to examine potential associations in the strength of asymmetry between communicative pointing and handedness, an analysis of the difference of correlations was conducted comparing the absolute values of the laterality indexes for gesture and object manipulation conditions. Absolute values of hand preference laterality indexes significantly correlated between gestures produced in first language and the second language conditions, $r(323) = .578$, $p < .000$, and hand preference in object manipulation produced in same conditions, $r(322) = .345$, $p < .000$. Absolute values of hand preference between pointing and object manipulation also correlated in the first language, *r*(326) = .280, *p* < .01, and the second language conditions , *r*(324) = .236, *p* < .01.

Steiger's (1980) test for comparison of dependent samples correlations strength was employed to determine whether there is a difference in the strength of correlation between an absolute value of laterality index for pointing and an absolute value of laterality index for object manipulation in both conditions. The difference was significant, *Z* = 3.91, p < .00, suggesting that absolute values of laterality indexes for pointing were more strongly correlated to each other in both conditions, *r*(323) = .578, *p* < .000, than were the absolute values of laterality indexes for object manipulation, *r*(322) = .345 *p* < .000.

Finally, independent sample correlation comparisons (Cohen & Cohen, 1983) were carried out to compare the strength of correlations between the two subsamples (see Table 10). All tests were not significant, suggesting that participants in monolingual and bilingual subsamples did not differ on the strength of association between these parameters.

Table 10.

Strength of Correlations Between the Two Subsamples

Measure	Monolinguals r values	Bilinguals r values	Test Statistics *Z*
Object Manipulation LI (between conditions)	.760	.781	-0.566
Pointing LI (between conditions)	.764	.785	-0.575
Object Manipulation LI absolute value (between conditions)	.211	.345	-1.594
Pointing LI absolute value (between conditions)	.532	.578	-0.728
Gesture LI * Hand LI	.449	.500	-0.721
Gesture LI absolute * Hand LI	.314	.289	-0.301

absolute			
Right hand preference for pointing and object manipulation	.452	.481	-0.406

Note. *p*-values for all tests are above .05. LI refers to Laterality Index.

3.5 Analysis of Potential Confounding Parameters

3.5.1 Examining the relationship between asymmetry and gender

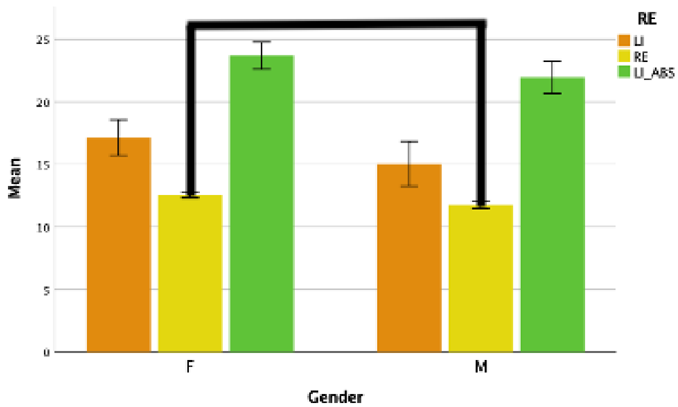
In order to investigate effects of gender on variables of interest, additional analyses were performed.

A one-way MANOVA was calculated examining the effect of gender on the laterality index and right ear score. A significant effect was found, $F(2,1811) = 10.875$, $p = 000$. Follow up univariate ANOVAs indicated that groups were significantly different on the right ear score, $F(1,1813) = 15.819$, $p = 0.000$, $\eta_2 = .009$, while the values of the laterality index were not significantly affected by gender, $F(1,1813) = 3.463$, $p = .119$. Males on average tended to have lower RE score ($M = 11.78$) than females ($M = 12.78$).

Effects of the strength of language asymmetry in relation to gender were assessed by a Mann-Whitney U test. No significant difference in the strength of laterality index was found between males and females, $U = 365{,}032.5$, $p > 0.05$. Additionally, a chi-square test of independence was calculated comparing the frequency of highly lateralized (absolute value of laterality index above 40) and lower lateralized (absolute value of laterality index from 0 to 39) in males and females. No significant relationship was found, $\chi^2(1,1813) = 2.221$, $p > 0.05$. Females were not more likely to be strongly lateralized on language than males.

The effects of gender on handedness were examined by a Mann-Whitney U test. Gender had a significant effect on both raw handedness scores as well as absolute handedness scores. Men scored significantly lower on the handedness questionnaire ($Mdn = 33$ versus $Mdn = 36$ in females), $U = 321{,}880.5$, $p = .000$, and the absolute value of handedness ($Mdn = 33$ in males and $Mdn = 36$ in females), $U = 313{,}249.5$, $p = .000$.

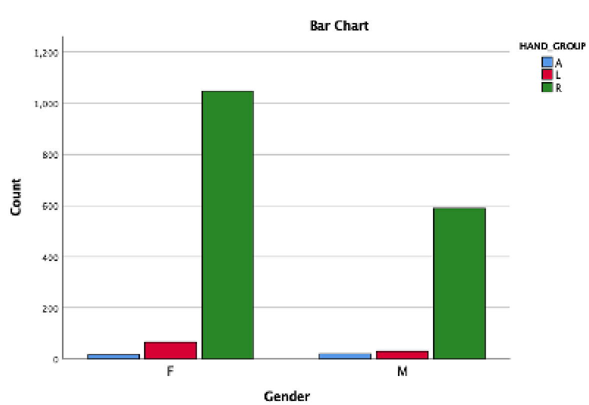
Figure 15. Language Asymmetry Scores in Based on Gender



Note: orange – language laterality index, yellow – the right ear score, green – absolute value of language laterality index

Additionally, a chi-square test of independence was calculated comparing the frequency of right-handers, left-handers, and ambidexters in males and females. A significant relation was found, $\chi^2(1,1772) = 6.749$, $p < .05$. Males were more likely to be ambidextrous than females. Additionally, among males there were more ambidextrous participants than expected (21 count with 13.8 expected) and fewer left-handed participants than expected (31 count with 35.1 expected); among females there were less ambidextrous (17 count with 24.2 expected) and more left-handed (66 count with 61.9 expected) participants than expected. Taken together these results suggest that in my sample males on average are slightly less lateralized on handedness than females. However, Cramer's V value was only .062, indicating a very weak relationship between gender and handedness.

Figure 16. Distribution of Handedness Groups Based on Gender



Note: blue – ambidexters, red – left-handers, green – right-handers

The relationship between gesture, object manipulation and gender

Table 11.

Categorical analysis of right and left handers in males and females

Pointing Gesture N (%)	**Right Handers**	**Left handers**	**Ambidexters**
Males	149 (76.4)	18 (9.2)	20 (10.3)
Females	249 (72.2)	48 (13.9)	35 (10.1)
Object manipulation N (%)	**Right Handers**	**Left handers**	**Ambidexters**
Males	157 (80.5)	22 (11.3)	8 (4.1)
Females	267 (77.4)	57 (16.5)	9 (2.6)

A chi-square test of independence was calculated comparing the proportion or right handers, left handers and ambidexters in males and females. No significant relationship was found for either pointing, $\chi^2(2) = 2.541$, $p > .05$, or hand preference for object manipulation, $\chi^2(2) = 3.377$, $p > .05$. In other words, gender was not a factor in a probability of a participant to be classified to any of the hand preference groups. Additionally, a Mann-Whitney U test was used to examine the difference in laterality indexes for pointing and object manipulation, as well as absolute values of laterality indexes for communicative pointing and object manipulation for males and females. No significant results were obtained: there were no significant differences between males and females on laterality indexes for pointing, U = 32,090, p = .392, object manipulation, *U* = *32,376*, *p* = .248, absolute values of laterality indexes for pointing, *U* = 33,013, *p* = .956, or object manipulation, *U* = 32,337, *p* = .631.

3.5.2 Examining the relationship between handedness and footedness

In order to examine the relationship between handedness and footedness several analyses were performed. Spearman correlation coefficients were calculated for handedness scores, footedness scores, as well as an absolute value of handedness and footedness.

Table 12.

Correlation Coefficients for Handedness and Footedness Measures

	1	2	3	4
1. Handedness	__			
2. Absolute Handedness	$.947^{**}$	__		
3. Footedness	$.560^{**}$	$.508^{**}$	__	
5. Absolute Footedness	$.479^{**}$	$.509^{**}$	$.918^{**}$	__

Note. ** coefficients significant at *p* < .000

These results indicate a moderate association between handedness and footedness, as well as between the strength of asymmetry in handedness and footedness parameters.

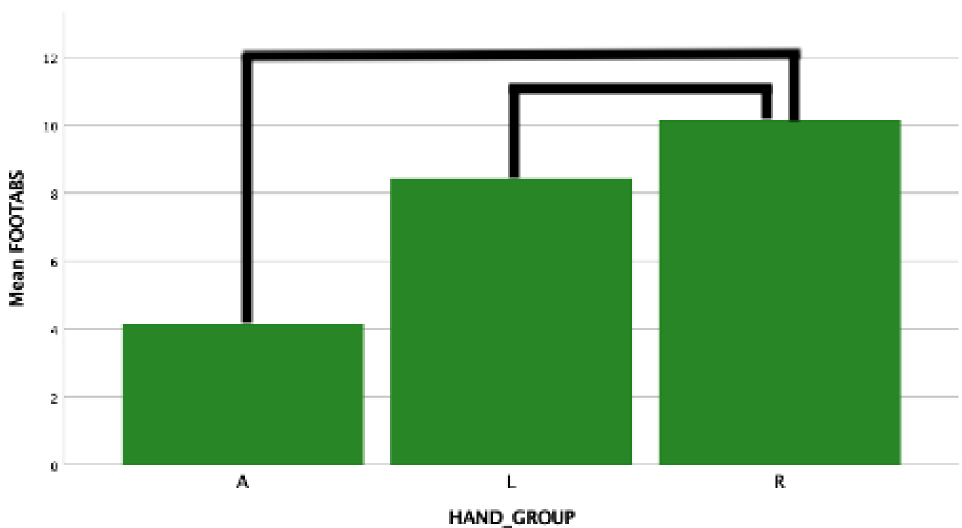
A linear regression was calculated to predict participant handedness based on their footedness scores. Results were significant, $F(1,1770) = 1003.628$, $p < 0.01$, $R^2 = .362$. Thus, variation in the footedness score could explain about 36% of variation in handedness score.

An additional regression analysis was performed with handedness absolute score as an outcome variable and footedness absolute score as a predictor. Results were significant, $F(1,1769) = 582.608$, $p < .00$, $R^2 = 248$. Thus, variation in the strength of asymmetry of foot preference could explain about 25% of variation in handedness score. Participants that were strongly lateralized in their foot preference were more likely to be stronger lateralized in their hand preference.

Finally, in order to examine whether right handers, left-handers and ambidexters differed in foot asymmetry, a Kruskall-Wallis test was performed. Raw footedness score, along with an absolute footedness scores were compared between hand preference groups. A significant result, $H(2) = 195.945$, $p < .00$, was found for a raw footedness score as well as an absolute footedness score, $H(2) = 52.881$, $p < .00$.

A post-hoc analysis employing Dunn's test with Bonferonni corrections revealed that right-handers significantly differed from both ambidexters, $U = -618.967$, $p < .000$, and left-handers, $U = -648.925$, $p < .000$, on footedness score, and tended to be significantly more right-footed then other two groups. The strength of foot preference asymmetry significantly differed between all three groups: right handers and ambidexters, $U = -562.598$, $p < .000$, left-handers and ambidexters, $U = -400.222$, $p < .000$, and right-handers from left-handers, $U = -162.376$, $p < .05$.

Figure 17. Foot Preference in Right-handers, Left-handers and Ambidexters



Note: A – ambidexters, L – left-handers, R – right-handers

Table 13.

Footedness and Absolute Footedness Scores in Participants Classified by Handedness

	Median footedness	*Median* absolute footedness
Right handers	10	10
Left handers	-4	8
Ambidexters	0	3

Chapter 4.

Discussion

4.1 Main Findings and Implications

4.1.1 Language Asymmetry and Bilingualism

Before proceeding with considering the study's main hypothesis and results regarding the relationship between handedness and language asymmetry, it is necessary to discuss the findings of the language asymmetry task and whether language asymmetry varied in bilinguals and monolinguals. Based on the current study hypothesis, it was predicted that early bilinguals would have more bilateral language processing (lower absolute values of the language laterality index), whereas late bilinguals and monolinguals would have a more lateralized language processing (higher absolute values of the language laterality index). Additionally, it was predicted that in bilinguals older age of the second language acquisition would be associated with higher language laterality index scores.

The notion that bilingualism can affect the anatomy of the brain (Li et al., 2014; Stein et al., 2014) was one of the key assumptions of the current study. Among parameters that were previously shown to affect language processing in the brain are the age of the second language acquisition, language dominance in bilingualism, and the nature of second language learning (instructional rather than natural conversational type of second language acquisition). For example, Mechelli, Crinion, Noppeney, O'Doherty, Ashburner, Frackowiak, et al., (2004) applied direct brain imaging methods and found structural differences associated with bilingual and monolingual experience as well as early or late age of second language acquisition. Experience of speaking multiple languages affects brain structure; however, these effects are not homogeneous. It is obviously necessary to stress that the current study did not employ direct brain imaging techniques, and it is impossible to make a direct connection between brain processes and behavioral patterns. It is known though from previous literature that the brain is affected by language experience, and it is appropriate, albeit with caution, to compare results of a behavioral measure with known facts about brain processing described in neurological literature.

The study did not find significant differences in language asymmetry that could be associated with language status (early bilingual, late bilingual or monolingual). Among bilinguals, however, a small negative correlation was found between the age of the second language acquisition and the strength of asymmetry in the linguistic domain (absolute language laterality score), with late bilinguals demonstrating slightly more bilateral language processing. Such results are opposite to the prediction based on the meta-analysis by Hull and Vaid (2007), where late bilinguals (as well as monolinguals) demonstrated a more asymmetric processing profile. One possible explanation for this pattern is that late bilinguals are engaging their right hemisphere for language to a greater degree than early bilinguals. Intense experience with languages might be a factor that, perhaps counterintuitively, leads to decreased grey matter volume in language related areas and decreased laterality. Elmer et al. (2014), compared grey matter density in language areas in multilinguals and highly trained professional multilingual interpreters, showing that the latter had decreased gray matter volume in areas associated with language control and executive functions. The authors hypothesize that intensive usage of both languages might lead to pruning of some synaptic connections resulting in a more effective language processing. In this case a “more effective” language processing is associated with decreased in grey matter volume in given areas and increased bilateral activation. It is possible that late bilinguals in the current study overall had a less (even slightly so) efficient language network, then early bilinguals, forcing them to engage the right hemisphere for language processing.

Another way to explain early bilinguals demonstrating more asymmetric language processing is that they, unlike late bilinguals, already have built an effective language network and did not need to engage the right hemisphere to the same extent. Previous accounts (Kaiser et al., 2015) suggest that multilinguals have additional pressure of managing several articulatory systems, which puts an additional load on the left hemisphere of the brain and corresponds with enlarged grey matter density of various language-related areas in the left hemisphere of the brain in multilinguals. Kaiser et al. (2015) showed that gray matter in the extended language network in the brain varies in simultaneous and successive bilinguals (people acquiring both languages from birth and people acquiring second language after they have mastered their first language respectively). In this study, successive bilinguals (which correspond to late bilinguals in Hull and Vaid's (2007) terminology) had increased grey matter volume in language-associated cortexes in the right hemisphere in comparison with simultaneous bilinguals. Such results demonstrate two important things: early bilingual experience has lifelong effects on adult brain, and it is the early exposure rather than bilingualism itself that has this profound effect on brain processing. Early exposure to another language apparently has a profound effect on brain structure even when this language is not used. Pierce et al. (2015) compared brain activation of participants performing a logical working memory task. In this study participants exposed to a second language (Chinese) activated errors associated with cognitive control. This was true not only for Chinese speaking children learning French as a second language, but for Chinese children who were adopted before the age of three and did not use Chinese language after that.

Contrary to my initial prediction regarding language laterality processing, there was more similarity between monolinguals and early bilinguals than late bilinguals. Such results are generally more consistent with the two hypotheses taking into account the age of the second language acquisition. The age of second language acquisition hypothesis (Genesee, Hamers, Lambert, Mononen, Seitz, & Starck, 1978; Vaid & Genesee, 1980) postulates that languages acquired closer to each other in time will be more alike in their lateral representation in a brain. The stage of second language acquisition hypothesis (Albert & Obler, 1978; Galloway & Krashen, 1980; Obler, 1981; Schneiderman, 1986) suggests that in earlier stages of L2 acquisition the right hemisphere is more involved due to its orientation of processing contextual cues. With increased mastery of the second language processing becomes more automatic and "shifts" to the left hemisphere. Thus, people who started learning a second language later in life are less proficient in it than those who acquire their second language from birth leading early and late bilinguals to rely on different language processing mechanisms. Ullman (2001, 2004) further suggests that this difference is due to a difference in left-lateralized procedural/grammatical system employed by the left hemisphere in L1 and somewhat right-lateralized declarative-lexical memory employed in L2. As a result, both of these hypotheses predict late bilinguals to have more bilateral language processing than early bilinguals or monolinguals.

An important factor in this conceptualization, of course, is the level of proficiency in bilingualism and how the language was learned. In my study I evaluated participants' language proficiency by self-report measures and compared only ability to comprehend and speak a language rather than write or read in it. This was done because I wanted to get a basic understanding of language experience in its relation to other factors. Future studies should address language laterality in bilinguals by more precisely matching them not only on language type but on language proficiency. It is impossible to rule out other factors such as language learning intensity, or language learning method, that could impact the distribution of language asymmetry in study participants. However, my sample was quite large and relatively homogeneous, as it consisted of university students that have a significant level of education and language proficiency. In particular, those students whose first language was not English had a high-enough level of proficiency to allow them to enroll in a content-based course taught in English. Additionally, not only is there a difference between a first and second language, but either one can be the dominant language. In many participants in the current study, the first language was not the dominant language, a typical case for those who immigrated to Canada in early childhood. Interestingly though, the dominant language is not necessarily the language in which participants are the most proficient either. It is possible to be more proficient in your first language, when your dominant language is your second (and less proficient one). Such a situation is not uncommon for late bilingual learners. As Birdsong (2014) notes, factors such as the age of second language acquisition language dominance and language proficiency are not interchangeable and should be treated as separate factors. The field of language asymmetry and hand preference research still needs to make this distinction while investigating relationships between the asymmetries.

I did not find significant group-level differences in language asymmetry between monolingual and bilingual participants. Both groups demonstrated overall right ear advantage, previously reported by other studies (e.g., Bless et al., 2015). In fact, a comparison of my study results regarding distribution of the ear advantage scores among participants was concordant with previous studies employing the Dichotic Listening Task (and the iDichotic app specifically). When I classified participants as having right hemisphere dominance, left hemisphere dominance, or a bilateral profile for language processing, my sample composition was very similar to a review provided by Westerhausen and Kompus (2018). The number of participants with the RE advantage in my sample was 73.3% versus 70.6% in that review; the LE advantage was present in

18.7% in my study versus 22.4%, and finally, participants with bilateral processing composed 7.7% in my study versus 6.9% respectively. Therefore, there seems to be no reason to suggest that the dichotic listening test employed in my study was not working correctly or was not sensitive enough to detect language asymmetry. The dichotic listening test is also a commonly used measure of language asymmetry in the brain. For example, Harkvoot et al. (2016) examined laterality of language processing in children with familial risk of dyslexia as well as healthy controls by testing subjects via DL test in the 3rd, and then the 5/6th grades. As expected, children from the familial dyslexia risk group performed worse on correctly reporting sounds from the left ear than healthy controls, and this pattern was associated with impairments in reading fluency. Presence of the overall right ear advantage in both bilinguals and monolingual in the current study is consistent with a proposition made by Bless et al. (2015) that a right ear advantage is apparently a robust effect found across varied populations, cultures, and different languages spoken by people. Based on the results of the current study, it is possible to add that a group level right ear advantage (and thus a corresponding left hemisphere dominance for language) is also a robust effect in both bilinguals and monolinguals.

It can be noted as well that the right ear advantage was not present in all participants, which might be expected based on claims regarding proportion of humans with a left hemisphere dominance for language (Kimura, 1973ab). Such results can be explained by the nature of the Dichotic Listening Test, which in this study measured syllable perception in participants. Previous research suggests that speech production is overall more left hemisphere oriented, while speech perception tends to be more bilaterally processed (Holowka & Pettito, 2002; Price, 1998; Vaid & Hull, 2002; Hickock, 2001). As the current study employed sound perception to measure language laterality, an overall high (above 5-10%) percentage of bilateral and right hemisphere-oriented participants is perhaps not surprising. Should a study have employed speech production task to measure language asymmetry, the results might have resembled the 90-95% left hemisphere dominance. Additionally, as previous studies were based largely on monolinguals, little is known to which extent these results can be extrapolated to bilinguals. One way to examine this difference is to examine language asymmetry in bilingual participants matched on their languages and compare asymmetry profile during language perception and language production in L1 and L2. In the current study the closest thing to the first and second language production was a condition in which bilingual participants were asked to point to a picture and discuss it in either first or second language. However, it was asymmetry of a gesture rather than language asymmetry that was compared in this task, with no significant differences being found between participants speaking in their first or second language.

Finally, the proportion of participants with right and left ear advantage might vary should the dichotic listening task employ not syllables but words for stimuli. Previous studies demonstrated varied involvement of brain hemispheres in language processing depending on whether the target stimuli were neutral or emotionally charged. For example, Bryden and McRae (1988) demonstrated the REA when identifying a neutral target word, and a LEA when identifying a word prosody. Similarly, Godfrey and Grimshaw (2016) found a LEA when participants heard emotionally-charged words. Such studies suggest that the right hemisphere of the brain specializes in processing speech that carries an emotional component or varied prosodic features. As the stimuli in my study consisted of neutrally pronounced syllables, it is might not be surprising that participants demonstrated an overall right ear advantage; perhaps the right hemisphere was to some extent “less involved” in language processing because of emotional neutrality of the stimuli, leading to a smaller overall left ear advantage.

The current study differentiated between late and early bilinguals following the work of Hull and Vaid (2006, 2007), taking the age of 6 as a demarcation line. Future studies could employ other conceptualizations of early and late bilinguals. For example, the onset of puberty is known to be the time period which sets significant constraints on learning an accent-free pronunciation. Decrease in flexibility of phonological processing was previously attributed to maturation of brain areas responsible for phonological processing. The onset of puberty, and specifically the 10-12 age period, was previously linked with maturation of the corpus callosum. Pujol et al. (1993) demonstrate that the corpus callosum continues development up to the early twenties; however, a more rapid growth takes place in childhood. Future studies could investigate whether bilinguals learning their second language shortly after, or at the time of puberty onset differ from bilinguals acquiring their second language before this age. Since previous studies found a general effect of bilingualism on the corpus callosum (Stein, Winkler, Kaiser, & Dierks, 2014), future research employing a matched sample could investigate effects of the age of the second language acquisition on white matter connectivity. The bilingual subsample in the current study had only a small portion of participants that acquired their second language after the age of 10. Consequently, an analysis of group differences between bilinguals that acquired their second language before the age 10 and after was not deemed meaningful. Additionally, those who acquire the second language after the age of 10 are also more likely to learn this language via formal instruction in a school setting rather than in natural communication. Thus, future research could compare early and late bilinguals using other ages as benchmarks and matching participants on language proficiency and the type of instruction. Such research could assist in elucidating environmental factors and precise brain mechanisms that determine language asymmetry formation.

Finally, language asymmetry varied based on the age of the second language acquisition but not participants' overall age. Previous research found a tendency for asymmetry reduction associated with age in overall cognitive processing (Dolcos, Rice, & Cabeza, 2002; Cabeza, 2002) and auditory processing specifically (Chen et al., 2013) with some effects of age-associated changes being also sex-contingent (Hausmann, Gunturkun, & Corballis, 2003). However, these studies report reduction of asymmetry in later years (usually about 60). Given the homogeneity of participants' age in my sample it is possible that there was not enough variation to detect any differences between older and younger participants.

Regarding the analysis of potential relations between the type of language and language laterality the following results were obtained. Participants whose first language was Chinese demonstrated a lower overall right ear score in comparison with native English and Punjabi speakers. Additionally, when participants' first languages were classified as tonal (Chinese, Punjabi, Vietnamese) versus non-tonal (Arabic, English, Farsi, Hindi, Indonesian, Korean, Russian, Spanish, Urdu) and compared to each other, participants belonging to the former group had lower language laterality indexes (M = 14.94), than the latter group (M = 16.95). The Chinese language is a tonal one, in which lexical items are identified based on prosodic characteristics of a word. Previous research suggests that native Chinese speakers indeed tend to engage the right hemisphere to a larger degree then speakers of nontonal languages such as English (Ge et al., 2015). Interestingly though Punjabi is considered a tonal language (the only one among Indo-Aryan language group), Punjabi speakers did not show significant differences in their ear advantage from English speakers. A possible explanation to this pattern is that native Chinese and Punjabi speakers in my sample could have differed from each other demographically in a systemic way, which led to Chinese but not native Punjabi speakers showing decreased right ear advantage in the dichotic listening task. Future studies could decipher the relationship between the type of language and the age of second language acquisition by matching early and late bilinguals in language proficiency and the type of language. Such matching could provide a better understanding of which factors are more determining for language laterality: the type of language or the developmental pattern of language acquisition. A small number of brain imaging studies tentatively suggest that the age of second language acquisition is a stronger predictor of language asymmetry in participants with similar language experience (Savio, Spinks, Liu, Chen, & Tan, 2004, with Chinese-English bilinguals and Abutalebi, Cappa, & Perani, 2001, with Italian-English bilinguals), but further research is necessary to confirm that. Additionally, previous studies suggesting that structurally distant languages such as English and Chinese might be more differentially represented in the brain (and thus lateralized) than more closely related languages, such as English and German (Obler, Zattore, Galloway, & Vaid, 2000; Klein et al., 2001) with dichotic listening results varying between participants with varied L1 and L2 (D'Anselmo et al., 2013). Future research could address the questions of how the age of the second language acquisition and the type of languages spoken relate to language asymmetry patterns.

4.1.2 Language and Handedness Relations

The study examined relationships between language asymmetry and handedness in a sample of participants with varied linguistic backgrounds. The primary hypothesis suggested that early bilinguals, late bilinguals and monolinguals would differ between each other in the degree of language asymmetry and handedness, and that in each group language asymmetry and handedness would be associated. Study results did not fully support this hypothesis. The analysis revealed an extremely weak correlation between language laterality indices and handedness scores in the overall sample, $r(1748) = 0.047$, $p < .05$. The R^2 value of 0.004, although statistically significant, should be interpreted as an absence of a meaningful relationship between language laterality index and handedness in participants. A more detailed analysis also revealed no differences in handedness or language laterality scores between early bilinguals, late bilinguals and monolinguals. Such a result was present whether early bilinguals, late bilinguals or monolinguals were analysed separately, or whether late bilinguals and monolinguals were compared against early bilinguals. How can such results be interpreted?

One potential explanation is an actual absence of relations between language laterality and handedness. Participants in the current study were tested on robust standardized measures of language asymmetry and handedness. With a sample size of approximately 1,800 participants, one would expect to find a strong relationship between handedness and language should the two be indeed associated. However, Fagard (2013) questions the presence of a relationship between handedness and language and suggests that researchers frequently simply assume this association and take it for granted. Moreover, researchers sometimes establish groups of language to generalize participants solely on the basis of their handedness. Fagard (2013) further stresses that for the past 30 years not only has the presence of a relationship between handedness and language been assumed, but the causal nature of this relationship specifically (e.g., Annett, 2002). It is possible then that language asymmetry and right-handedness appear to be related simply because they are so prevalent in humans. But humans reliably demonstrate asymmetric processing in other domains, yet they are not necessarily causally equated with either language or handedness. For example, spatial cognition and face recognition relies largely (up to 90%) on the right hemisphere for processing (Willems, Peelen, & Hagoort, 2010). Despite such a strong asymmetry in these domains they are not frequently examined in relationship to language or handedness. As an exception, Badzakova-Trajkov, Haberling, Roberts, and Corballis (2010) compared language asymmetry, face processing, spatial processing and handedness in a group of 155 participants. Results of the study suggest that right hemisphere processing for spatial cognition is associated with the left hemisphere processing in language, with no relationship to handedness. The authors of the study interpret these results as an absence of a causal relationship between the described asymmetries.

If there is no strong causal relationship between handedness and language, it might make sense to revise theoretical accounts built on the assumption of the existence of such a relationship. Handedness and language were long to be considered a hallmark of humans and an important aspect of our evolution. For example, a strong role is assigned for handedness and speech asymmetry in human cognitive evolution (e.g., Chance & Crow, 2007; Crow, 2002). Similarly, gestural theories of language evolution propose a causal relation between handedness and language and parallel origins for laterality in both manual and linguistic domains (Corballis, 2003). The results of my study also suggest that an assumption of the causal relationship between handedness and language should be taken with caution. In addition, contrary to previous suggestions (Crow, 2002; Ruck, 2014), it might be problematic to assume that right-handedness can be used as a direct proxy for language abilities in paleo archeological records or used to make direct inferences to human cognitive evolution. Based on a lack of a strong causal relationship between language and handedness in modern day humans, we cannot assume, for example, that ancestral Hominins necessarily had developed linguistic abilities just because they had a pronounced degree of handedness.

If there is no causal relationship between handedness and language, does this necessarily mean they are completely independent? I would speculate that this is not necessarily the case. The relationship between handedness and language might be simultaneously *non-causal* yet *non-independent*. Suggestively in the present study, when the overall sample was analyzed separately based on hand preference (right handers, left handers and ambidexters), significant differences were found. Specifically, right handers tended to have significantly higher language laterality indexes then ambidexters and left handers. Language asymmetry and handedness correlated in left-handers, with language laterality index explaining about 8% of handedness scores variation in this group. Additionally, early bilinguals were significantly different from late bilinguals in both absolute strength of language asymmetry and handedness, demonstrating a higher level of lateralization in both domains (although the difference between groups on handedness can be partially explained by gender differences (as discussed in the following section). Taken together these results might provide partial support for the existence of a handedness and language association.

How could such an association be explained? As Fagard, Sirri, and Rama (2014) put it, language and handedness might not be causally related, yet they could co-evolve in development. This might mean that handedness and language asymmetry formation reflect: a) patterns of brain development (Michel, 2002), b) patterns of systemic variation in organism-environment interaction (Casasanto, 2009), and c) that both are affected by similar reinforcing factors (Fagard, 2013). This in turn would lead to the fact that patterns of handedness and language development can be predictive of each other and of other aspects of cognitive development. For example, Ramsey (1980) found that an ability for dissimilar syllable production in infants coincided with the onset of bimanual handedness.

Michel (2002) notes that the way one asymmetry (handedness) develops can be treated as a model of other forms of cerebral asymmetries development (especially control of speech). Furthermore, handedness can represent patterns of hemispheric specialization in other cognitive and emotional domains (Michel, Nelson, Babik, Campbell, & Marcinowski, 2013). In such conceptualizations, right and left-handedness represents patterns of neurobehavioral organization (Jones & Martin, 2010). Neural systems, for example, for motivation, affect and other cognitive processes might become differently lateralized in left and right handers (Michel, Nelson, Babik, Campbell, & Marcinowski, 2013). This has been argued to partially explain why design-copying skills in preschoolers become good predictors of scores on reading and mathematics in middle school (Cameron et al., 2012; Grissmer, Grimm, Aiyer, Murrah, & Steele, 2010). As Michel et al. (2013) explain, individuals with early developed hand-use preference likely exhibit better skills for copying designs than the individuals without an early developed hand preference. As such, hand preference becomes an indicator of general neuro-behavioural development and thus becomes relevant for patterns of, for example, language asymmetry, reading and math. In my study, left-handers demonstrated weaker asymmetry in both linguistic and manual domains. Such results are consistent with previous research finding that right-handers show more profound right-hemisphere dominance for face-processing than left-handers (Bourne, 2008); and that the planum temporale (a brain structure frequently associated with language processing) was more leftward oriented in right-handers and less asymmetric in left-handers (Steinmetz, Herzog, Schlaug, Huang, & Jancke, 1995).

Embodied theories of development highlight the potential importance of multiple environmental factors in development of even basic motor asymmetries (Bruun & Langlais, 2003; Casasanto, 2009; Glenberg, 1999; Porac, 1993; Provins, 1992), conceptualizing hand preference as a result of an organism-environment interaction. Such approaches suggest that even complex cognitive processes are not independent from the way our body systematically interacts with the environment, especially during development. On a conceptual level such an approach parallels developmental theories suggested by Piaget (1952) and Bruner (1973), who argue that complex cognition (such as symbolic thinking) is partly based on sensorimotor abilities formed in early development. Should left and right-handers experience their environments in systematically different ways, we might expect them to differ systematically in other cognitive domains. Such conceptualizations would be consistent with systemic differences in language asymmetry found in right handers and left handers in the current study. As Casasanto (2009) suggests, right and left handers might engage in different neurocognitive processing even at the level of abstract thinking. Previous research suggests that right and left handers show opposite patterns of lateralization for manual action verbs and non-manual action verbs as well as imagining manual actions (Willems et al., 2010). Additionally, abstract concepts such as “good” or “bad” in right and left handers are frequently associated with the opposite sides of the body (Casasanto, 2009; Casasanto & Chrysikou, 2011). It would be interesting to know if these effects of handedness are more uniform between speakers of different languages. Specifically, between speakers of languages where such abstract concepts are linguistically marked differently. As the current study did not have data to address this question, this is a matter for future research.

Differences in asymmetries found between early and late bilinguals in the current study suggest though that environmental factors can have some effect on both handedness and language. It is currently not well understood which of these asymmetries are more robust and which ones are more plastic in development. Studies investigating the heritability of handedness and language asymmetry suggest the importance of environment in asymmetry formation (Sommer, Ramsey, Mandl, & Kahn, 2002; Steinmetz, Herzog, Schlaug, Huang, & Jancke, 1995). Some researchers suggest that handedness asymmetry is more subjected to environmental effects than asymmetry of language (Badzakova-Trajkov, Haberling, & Corballis, 2010), for example, through different parenting practises and patterns of interaction with objects. As a result, some researchers (e.g., Laland, 2008) attribute handedness largely to environmental rather than strictly genetic factors. Ocklenburg et al., (2016) investigated the heritability of language laterality measured by the dichotic listening task. Results of this study suggest that while the right ear score was not similar between relatives, cognitive control of speech had a certain degree of heritability. Similarly, studies on the heritability of handedness suggest that different aspects of handedness have varied levels of heritability (Lien, Chen, Hsiao, & Tsuang, 2015). Taken together such studies again demonstrate the potentially complex nature of language asymmetry and hand preference, and that no single factor can explain their distribution in a population. Additionally, as Fagard (2013) notes, handedness and language asymmetry might share common reinforcing factors or may indirectly influence each other in a shared developmental context resulting in systemic group-level differences. One of the productive avenues for future research is a combination of more nuanced developmental studies with research investigating group-level systemic variation in varied asymmetries formation. For example, Sivagnanasunderam et al. (2015) examined asymmetry development over the life span in a large sample of participants and concluded that asymmetries in various domains are dynamic; some aspects of cognitive processing become less bilateral with age, while others increase in bilateral processing. Similarly, Michel, Babik, Nelson, Campbell, and Marcinowski (2018) suggest an evo-devo approach in researching asymmetries formation. In this approach, systemic patterns of development, rather than simple associations between parameters of interest (such as handedness and language) are investigated.

As Bishop, Holt, Whitehouse, and Groen (2014) suggest, the field of language and hand laterality studies seems to be presented with an apparent paradox: altered asymmetry in either language or manual domains on an individual level does not appear to be associated with particular cognitive or developmental outcomes. At the same time, on a group level, altered, reduced and overall non-typical asymmetry is associated with developmental disabilities and different levels of language impairments. One possible explanation for this paradox is that the formation of language and manual asymmetries is a part of general developmental processes. If so, group level altered asymmetries might be indicative of altered developmental pathways. Additionally, both asymmetries might be affected by similar factors in development. This would mean that studying manual and linguistic asymmetries might be "too general" of a level to understand specifics of these asymmetries and why they are altered in special populations. A solution to this problem would be to apply a systemic approach to asymmetry study and diversify samples in a systemic, theory driven way. In other words, this means we will need to study participants that are systematically different from each other on parameters of interest (for example bilinguals and monolinguals, left and right handers, adults and children) to compare how asymmetries are formed in these populations, which aspects of asymmetries systematically differ between compared individuals, and which factors likely contribute to formation of asymmetries in given groups in a systemic way.

As noted, to this day, the majority of studies on language laterality and handedness are conducted with monolingual right handers. Given the fact that the majority of the world’s population speaks more than one language, it seems essential to include bilinguals in such studies and test whether hypotheses derived from research with monolinguals can be extrapolated to a bilingual population (Hull & Vaid, 2006). Additionally, as Willems, Van der Hoegen, Fisher, and Francks (2014) note, left handers are frequently excluded from studies on asymmetry in order to homogenise data, which highlights the point that bilinguals and left handers should be included in research on asymmetry more consistently. Based on the results of my study, bilinguals do not strongly deviate from monolinguals in language asymmetry, which suggests that establishment of language dominance in the left hemisphere of the brain is quite resilient to perturbations and environmental factors. Asymmetry in handedness, apparently, has stronger connections to establishment of asymmetries in other domains, where right handers and left handers differ from each other on group-level. Systemic exclusion of left handers from research leads to a loss of valuable information on existing variation and thus limiting our ability to understand mechanistic factors behind asymmetry formation.

4.1.3 Language, Gesture and Handedness Relations

Another of the study objectives was to analyze the relationship between gesture, handedness and language asymmetry. Specifically, whether gesture asymmetry is associated with handedness in object manipulation, handedness assessed by the questionnaire and language asymmetry, and if these parameters differ between monolinguals and bilinguals.

In the current study handedness for object manipulation and pointing was significantly correlated in the general sample as well as monolingual and bilingual sub-samples. Additionally, object manipulation tended to be significantly more lateralised than pointing. Categorical analysis showed more participants to be classified as ambidextrous based on their hand preference for pointing, rather than their hand preference for object manipulation. These results are consistent with the ones reported by Cochet and Vauclair (2012), and opposite to a pattern observed in children, who tend to demonstrate a pronounced right-hand bias for pointing gestures. Previous studies conducted with children (e.g., Cochet & Vauclair, 2010) suggest that hand preference for pointing and object manipulation is relatively independent in early development (although some studies report an association, e.g., Vauclair & Imbault, 2009). Children aged 1 to 3 years tend to exhibit stronger right-hand preference for pointing than object manipulation (e.g., Bates, O'Connell, Vaid, Sledge, & Oakes, 1986; Vauclair & Cochet, 2013). In adults, however, the pattern is different. Hand preference for manipulative activities and gestures tends to correlate (although moderately), with no strong right-hand preference for pointing in adults (Cochet & Vauclair, 2012). This suggests that pointing and object manipulation might serve different functions in adults and children. Gesture development plays a crucial role in the language acquisition process (Butterworth, 2003; Colonnesi, Stams, Koster, & Noom, 2010; Rowe & Goldin-Meadow, 2009). Some researchers suggest that this process is a result of developing referential abilities and cooperative communication (Liszkowski, Carpenter, Henning, Striano, & Tomasello, 2004; Liszkowski, Carpenter, Striano, & Tomasello, 2006; Liszkowski & Tomasello, 2011). However, the rate of gesture usage in children tends to decline once they master language to a certain level (Bates & Dick, 2002; Bretherton et al., 1981; Butterworth, 2003; Iverson, Capirci, & Caselli, 1994; Namy et al., 2004). By contrast, adults have a fully developed language ability, and gestures in adults typically accompany, rather than substitute for, communication.

A number of studies (Cochet & Vauclair, 2010b; Esseily, Jacquet, & Fagard, 2011; Jacquet et al., 2012) find that children demonstrate a more pronounced right hand bias for pointing than adults. Cochet (2016) attributes this difference to hand preference in gesture being a part of a developing communicative system that is more closely associated with the left hemisphere of the brain in early development. Handedness for object manipulation continues developing through childhood. Adults demonstrate a more pronounced asymmetry in object manipulation in comparison with children, perhaps, as they have more experience (and thus proficiency) with object manipulation. As Cochet (2016) suggests, hand preference for pointing in children might be initially associated with language lateralization and later become associated with hand preference for manipulative activities, resulting in the complex intertwined network presumably observed in adults. One of the ways to address this issue is to compare not only adults and children, but children living in different environments (such as for example an industrial and a small scale society to determine whether different developmental contexts would be reflected in different patterns of hand preference for object manipulation and gesture in these children). It is important to stress though that behaviourally assessed asymmetry of gestures or manipulative activities can provide only indirect measures of brain processing. I would argue, however, that this is a good indirect evidence, as recent studies employing direct brain imaging methods provide a link between "surface-level" behavioral and cognitive parameters with actual brain processes. For example, Mills, Coffey-Corina, and Neville (1993) investigated language development and hemisphere processing in 20 months old by means of an event related potentials (ERPs). Their findings demonstrate an association between increasing left hemisphere specialization for language processing in the temporal and parietal regions with increasing language abilities. Similarly, Benga (2005) argues that the anterior cingulate cortex is a substrate for intentional gestural communication and vocalization, becoming a starting point for linguistic communication in development.

A somewhat different account of gesture-handedness relations conceptualizes gesture as a part of a developing fine motor system (Iverson & Thelen, 1999; Iverson & Fagan, 2004) and associates language development with sensorimotor experience (Iverson, Capirci, & Caselli, 1994). It is plausible that communicative and motor domains are associated through a developmental context. Iverson and Fagan (2004) found an association between rhythmic hand movements and vocalizations in infants. As noted, an earlier study by Fogel and Hannan (1985) showed an association between index finger extensions and mouthing movements in 9- and 15-weeks old infants occurring during face-to-face mother-infant interactions. Holowka and Pettito (2002) similarly suggest left hemisphere preferential implication in mouth movements associated with babbling but not with other types of mouth movements such as crying or smiling. In adults, brain imaging studies (e.g., Astafiev et al., 2003) suggest an association between attention, pointing and the motor domain. In this study, specific left lateralized areas of the brain responsible for motor processing were activated during preparation of a pointing gestural movement. The authors suggest a strong role for motor planning in pointing. Hand preference in a motor domain, however, does not explain pointing asymmetry entirely. Moreover, as it has been previously discussed, in the current study object manipulation was more strongly lateralized then pointing. In adults, pointing gestures are likely associated with the motor domain; however, this association might be weaker than the one found in children. The current study could not address potential differences between the two approaches. Research on the link between gesture and handedness suggest the presence of a more nuanced developmental process that comparison of adult and child data might shed light on. Future research, employing longitudinal or microgenetic approaches, could address the role of gesture in developing communicative-linguistic and motor systems.

It is interesting to note that the handedness questionnaire score predicted only 12% of asymmetry in a pointing gesture, while object manipulation asymmetry accounted for 30% of it. This difference implies that the handedness questionnaire and directly observed behavioral measures of hand preference might address different aspects of handedness. Cavill and Bryden (2003) suggest that this questionnaire measures a sort of a “cognitive component” of hand preference more tightly associated with memory, while behavioral measures are more concerned with the motor aspect of it. This distinction might have relevance for understanding predictions regarding degrees of relationship between hand preference and language. For example, it might be important to differentiate between aspect of handedness that imply a pure motor component and more elaborate aspects of hand preference associated with toolmaking for testing an evolutionarily relevant hypothesis regarding language and hand preference. For example, Cavanagh, Berbesque, Wood, and Marlowe (2016) examined hand preference in communicative gesture and object manipulation in modern hunter gatherers (the Hadza). Researchers concluded that it was toolmaking, and not gestural communication that drove the evolution of right-handedness in humans. This conclusion, however, was made based on the data obtained from the adult male participants only. Incorporating data that addresses the dynamic relationship between gesture and handedness in development, again, could help elucidating mechanisms and factors involved in asymmetries formation.

Importantly, previous studies on gesture asymmetry in adults focused predominantly on co-speech, rather than referential pointing gestures (Dalby, Gibson, Grossi, & Schneider, 1980; Kimura, 1973a; Saucier & Elias, 2001). This is an important notion, as co-speech gestures seem functionally (and likely mechanistically) different from pointing gestures. McNeill (2005) argues that co-speech gestures provide support for verbal narrative, accentuating rhythm and stress of speech, thus in a way providing “less” communicative intent than referential or symbolic gestures. Interestingly, in a study on gesture asymmetry in adults, Cochet and Vauclair (2014) do not find referential or symbolic gestures to be more right-handed than manipulative activities. One way to explain this result is that in adults gestures do not, as noted, become a substitute for communication, but rather support a fully developed speech, while in children gestures might be an integral part of a developing communicative competence. In line with such reasoning Sheehan, Namy, and Mills (2007) found that in the second year of life, gestures and words are processed by common cerebral areas, while this processing becomes more divergent with further language development, when gestures are used less as referential labels. Following this assumption, it is possible that when hand preference in gesture and manipulative activities are compared in adults, we should not observe stronger righthandedness in gesture usage, probably because in adults deictic[4] gestures are less associated with language per se, than in children. Consistent with such a conceptualisation is the fact that gesture asymmetry in the current study did not correlate with language asymmetry or the right ear score. Additionally, when monolingual participants were compared on the verbal and silent conditions, their gestures tended to be more right-handed in the silent condition. These findings are congruent with the ones by Cochet and Vauclair (2012), where monolingual French-speaking adults had a stronger right-hand bias in the silent condition, rather than in a co-speech one (same as verbal condition in my study). Cochet and Vauclair initially have hypothesised the trend to be the opposite, expecting co-speech gestures to be more right-handed, as gesture were presumed to be “co-activated” by speech production. However, it might be that their results and the results of the current study are more consistent with the proposition that gestures become more right-handed when they take over the full burden of communication (in other words, when gestures are used in the absence of language), and thus become more right-handed in the silent condition. Further indirect evidence supporting a differential role of gesture in the silent and verbal conditions comes from comparison of the bilingual and monolingual subsamples. Hand preference for object manipulation and pointing gesture correlated in both conditions and in both these groups. However, in bilinguals, the correlation between pointing and object manipulation was .467 in the first and .494 in the second language conditions, while in monolinguals they were .442 and .338 for a verbal and silent condition respectively.

[4] Deictic gestures direct a recipient’s attention towards a specific referent in the environment (proximal or distal). Pointing is a type of deictic gesture.

Additionally, there was a statistically significant difference in pointing and object manipulation between bilinguals in the second language condition and monolinguals in the silent condition (.494 and .338). These figures could suggest that in bilinguals there may be a closer association between hand preference for object manipulation and gesture regardless of the type of language, as speaking either first or the second language while gesturing is more similar to monolinguals in the verbal condition. In monolinguals, an association between gesture and object manipulation would be least pronounced in a silent condition. However, in the current study the difference between correlations in object manipulation and pointing in a monolingual subsample was not significantly different between conditions (.442 and .338), and thus the interpretation discussed above the discussed above interpretation should be taken with caution. Future research could further address the question of whether bilinguals and monolinguals differ on gesture and object manipulation asymmetry in varied contexts.

In the present study, there was no relationship between pointing asymmetry and language asymmetry. Results did not find an association between language asymmetry (i.e., the right ear score, or an absolute language asymmetry score) and pointing gestures. It is possible that the dichotic listening task employing syllables as a stimulus was not sensitive enough to detect any relations with gesture asymmetry. An alternative explanation would suggest that similar to handedness, in adults, language asymmetry is not strongly associated with referential gestures such as pointing, at least to the extent that it is associated in children. In the current study, pointing gestures produced in the silent condition were more right-handed than pointing gesture produced along with speech, and there was no difference between participants performing a pointing gesture along with speech in either their first or second language. Such results further support the proposition that in adults a referential gesture is associated with language when it takes on majority of a communicative load. When adult participants are using actual language, pointing gestures might become less asymmetric and (albeit speculatively) less associated with language asymmetry. It is might be that in adults a pointing gesture is “too simple” to engage language network to the same degree.

One of significant limitations of the study is investigation of a single type of gesture in adults - referential pointing gestures. Future studies should address asymmetry of not only referential, but iconic and symbolic gestures in bilingual adults. The only study investigating different types of gestures is the one by Cochet and

Vauclair (2014). However, the study specifically looked at monolingual participants of a similar age, all living in the same French culture. Linguistic diversity of the current sample did not allow for the examination of hand preference in iconic and symbolic gestures based on study methodology developed by Cochet and Vauclair (2014), as this methodology would have required me to provide instructions to participants in their respective languages. Since the linguistic variation of the sample comprised over 50 different languages, this was not feasible. Future studies should investigate other types of gestures in bilinguals and specifically hand preference of these gestures. Additionally, it is important to address a question of association between the type gesture, its asymmetry and speech content. For example, Kita et al. (2007) found that degree of right-hand usage of co-speech gestures tended to decrease when participants were speaking about metaphorical linguistic expression, but not concrete or abstract ones. It remains an open question whether speech content can affect gestures other than co-speech ones to the same extent. For example, Ozyurek, Willems, Kita, and Hagoort (2007) investigated integration of speech and iconic gestures on a neurological level and concluded that speech and gesture indeed activate similar areas of the brain associated with semantic information. It is also possible that more conventional, culturally learned or symbolic gestures have a stronger association with language in adults. Pettito et al. (2000) found that brain areas that are associated with speech are activated in congenitally deaf individuals during sign language production. Given varied effects of bilingualism on brain processing it would be interesting to see whether bilinguals demonstrate patterns of speech-gesture integration similar to the ones observed in monolingual participants.

Only a small number of studies generally investigate gesture usage in bilinguals with the majority of these studies focusing on co-speech gestures (Nicoladis, 2007). Additionally, a limited number of studies address the developmental aspects of gesture usage in bilinguals (Nicoladis et al., 1999; Nicoldais, 2002; Nicoladis, Pika, Yin, et al., 2007; Pika et al., 2006; Sherman & Nicoladis, 2004). Taken together results of these studies highlight the fact that bilinguals seem to differ from monolinguals in their gesture usage (quite often depending on which language they are speaking at the time), that different gestures (deictic, iconic, symbolic) have different levels of association with speech and language, and effects of cross-linguistic transfer can be observed on a gestural level. Future studies could further investigate whether different types of gestures vary in hand preference in bilingual children at various ages, tackling the dynamics of language-gesture relations over the lifespan.

In summary, siding with Cochet and Byrne (2013), I would propose that research on gesture asymmetry over the life span demonstrates the importance of incorporating adult data, as restricting studies to children (and non-human primates for a comparative perspective) limits our ability to understand a variety of factors that might contribute to manual and communicative development. Although to this day a small number of studies have focused on gesture asymmetry and handedness in adults, they tentatively suggest that the relationship between gestures, language and handedness might be dynamic in development and are not necessarily equivalent in adults and children. Incorporation of adult data in such research allows first of all that we can better understand the final point of developmental processes and second better understand contextual factors contributing to asymmetries formation.

4.2 Potential Confounding Parameters

4.2.1 Gender

Previous studies on brain structure demonstrate a small, but robust, effect of sex differences, where the brains of males tend to be more asymmetric than those of females (Amunts et al., 2000; Narr et al., 2001; Yuecel et al., 2001). Consequently, it could be expected for males to be more right-handed than females. In the present study, however, females tended to be more lateralized on hand preference than males. There were more males classified as ambidexters in comparison with females (in terms of proportion to a general sample). These results are consistent with previous studies reporting higher proportion of less lateralized individuals among males. For example, Nalçaci, Kalaycıoglu, Çiçek, and Genç (2001) comparing handedness in 300 participants found that right-handed females were more strongly lateralized than right-handed males. Categorical analysis of participants in my sample demonstrated that males were slightly less likely to be categorized as right handers; however, they were also less likely to be categorized as left handers than females. Such results seem to contradict previous accounts of increased left-handedness in males (for example, a meta-analysis by Papadatou-Pastou, Martin, Munafo, & Jones, 2008). However, it is important to acknowledge that left handers are not simply “mirrored” right handers, meaning that left handers are not necessarily as strongly lateralized as right handers are, but in the opposite direction. Darvik (2004) suggests that left handers tend to be overall less lateralized than right-handers. Right-handers tend to perform worse with their non-preferred hand then left handers do. The number of participants categorized as ambidexters in my sample was higher in males than females which would be in line with such an explanation. Consistent with this is the fact that females tend to have higher absolute handedness value scores than males, again, suggesting they are on average stronger lateralized than males, regardless of the direction of laterality.

Regarding language laterality, females as a group showed higher right ear scores. Such results can be explained by previous studies finding female advantage in auditory subcortical functions (Krizman, Skoe, & Kraus, 2012), suggesting that females tend to have better bottom-up auditory processing and speech detection than males, which could explain higher overall right ear scores in that group. Krizman et al. (2012) suggest that differences in basic speech discrimination between sexes can contribute to higher proportion of males diagnosed with language impairments (e.g., SLI-specific language impairment), dyslexia and reading difficulties. Wadnekar, Whiteside, and Cowell (2008) further demonstrate that not only sex per se, but the hormonal profile specifically might contribute to scores on dichotic listening tasks. In this study, right ear scores were different not only between males and females, but also between females at different stages of the menstrual cycle, with women in the higher estrogen phases showing a greater right ear advantage.

Finally, an important factor in sex-contingent language asymmetry profiles is the method utilized to determine asymmetry. In a comprehensive review by Voyer (1996), the biggest gender-related differences in laterality were found in verbal and visual tasks such as a word naming task, with males demonstrating greater left hemisphere dominance. Similar to results of the current study, Magistre (1989) found males demonstrated stronger right hemisphere involvement than females; however, this study analyzed rapid-eye movement during sentence processing. Inconsistent results of previous studies on gender and language laterality could stem from methodological differences in assessing laterality. Caution should be taken comparing results of studies investigating similar parameters such as gender that employ different measures to assess language asymmetry. Additionally, as Hirnstein, Hugdahl, and Hausman (2019) conclude in their review of forty years of research of cognitive sex differences and hemispheric asymmetry, cognitive (or behavioural) sex differences can be observed in the absence of actual hemispheric differences and vice versa. Further research is necessary to determine factors affecting sex differences in asymmetries on both functional and structural levels.

4.2.2 Footedness

Results of handedness and footedness analysis revealed a moderate association between handedness and footedness (correlation coefficient of .560), as well as between the strength of asymmetry in handedness and footedness parameters (correlation coefficient of .509). Variation in footedness could explain 36% of variation in the handedness score and the strength of footedness (absolute footedness score) about 25% of variation in the absolute handedness score. Participants that were strongly lateralized in their foot preference were more likely to be stronger lateralized in their hand preference. Further analysis revealed that this pattern was driven by right-handers, who were more strongly lateralized for footedness than left-handers and ambidextrous participants.

These results are in line with studies examining the relationship between handedness and footedness. For example, a review of 14 studies (Gabbard & Iteya, 1996) suggests that footedness is not independent from other asymmetries in development, that it establishes sometime around late childhood and that the pattern of asymmetry establishment in the upper and lower limbs is similar across the lifespan. In the current study, footedness scores predicted handedness scores better than language asymmetry predicted handedness.

Although previous research found footedness to be a better predictor of language asymmetry than handedness (Day & McNeilage, 1996; Elias & Bryden, 1998), and of emotional lateralization (Elias, Bryden & Fleming, 1997), the current study did not find an association between footedness and language asymmetry. A lack of association might be attributed to a smaller sample size than previous studies (for example, Day & McNeilage, 1996, had over 2,000 participants) and employment of syllables, rather than words as stimuli for a dichotic listening task (Elias & Bryden, 1998). The latter study recruited only 32 participants; however, these participants were completely crossed for handedness, footedness and gender. It is possible that a similar crossing for participants in my study could lead to significant results, where language laterality could be predicted by footedness. It is feasible that a potential relationship between these parameters was masked by variation in my sample, especially regarding varied linguistic profiles of my participants.

Should conclusions put forward by Gabbard and Iteya (1996) regarding importance of footedness for understanding other asymmetries (including handedness and linguistic) be correct, future research should not overlook footedness while examining asymmetry formation. Such studies could investigate which specific aspect of footedness are closer associated with handedness. For example, Kalaycioglu, Kara, and Nalcaci (2008) suggested that it is the skilled footedness that has a stronger association with handedness and thus is more informative than general foot preference.

Given the role motor asymmetry might play in overall child development, in both typical and abnormal development (Groen, Whitehouse, Badcock, & Bishop, 2013; Finch et al., 2017; Floris et al., 2013; Knaus et al., 2010; Lindell & Hudry, 2013; Preti, Sardu, & Piga, 2007; Szaflarski et al., 2012) investigation of systemic patterns in foot preference, hand preference and language asymmetry seems a promising direction for future research.

4.3 Conclusions

The goal of the study was to investigate handedness and language relation in a diverse sample of adults. Study results do not support that handedness and language asymmetry in humans are strongly related. However, analyses comparing right handers, left handers an ambidexters demonstrate existence of group level differences in varied asymmetries, including the linguistic one, between these participants. It is concluded that handedness can be an important indicator of processes in varied domains, including other types of asymmetries. It is suggested that handedness and language might not be causally related yet not be completely independent from each other, likely interacting in development. Further research is needed to decipher specific mechanisms involved in asymmetry formation in the manual, linguistic and other domains as well as their relation to different cognitive processes. Routine exclusion or left handers leads to reductionism and limits researchers’ ability to fully investigate factors involved in asymmetry formation. Additionally, it is proposed that the field of handedness and language research addresses the question of how additional factors such as gender and footedness, along with other types of asymmetries (e.g spatial cognition or face processing) interact with language and handedness formation. Such approach again would be useful for determining precise factors (from neurobiological to systemic interaction with the environment) that are involved in asymmetry formation.

Study results support the proposition that handedness and language or plastic traits which are subjected to different developmental factors. For example, factors such as the age of the second language acquisition in bilinguals, or the type of language participants acquire, might have an effect on language asymmetry. At the same time, different aspect of handedness and language apparently vary in susceptibility to environmental factors. Based on study results it can be concluded that bilingual and multilingual participants overall demonstrate predominant right ear advantage in the dichotic listening task (which tentatively suggests corresponding left-hemisphere processing for language) concordant to monolinguals. It can be concluded that the left hemisphere dominance for language in humans is quite resilient to variation in the environment including varied linguistic environment. Frequent exclusion of bilinguals from research on language asymmetry and handedness that might be considered unwarranted. It is rather proposed that samples should be diversified in a meaningful theory-driven way.

Understanding the nature of handedness and language research is incomplete without knowledge of how these two asymmetries interact in development. Importantly developmental research. Importantly developmental research should not be limited to early developmental stages but consider asymmetry formation over the lifespan. Study results demonstrate that residence of hand preference and object manipulation in adults differ from the ones previously described in children.

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Appendix A.

Language Experience and Proficiency Questionnaire (LEAP).

Last Name		First Name		Today's Date	
Age		Date of Birth		Male	Female

(1) Please list all the languages you know in order of dominance:

Language A	Language B	Language C	Language D	Language E

(2) Please list all the languages you know in order of acquisition (your native language first):

Language A	Language B	Language C	Language D	Language E

(3) Please list what percentage of the time you are currently and on average exposed to each language.

(Your percentages should add up to 100%):

	Language A	Language B	Language C	Language D	Language E
List language here					
List percentage here					

(4) When choosing to read a text available in all your languages, in what percentage of cases would you choose to read it in each of your languages?

Assume that the original was written in another language, which is unknown to you.

(Your percentages should add up to 100%):

	Language A	Language B	Language C	Language D	Language E
List language here					
List percentage here					

(5) When choosing a language to speak with a person who is equally fluent in all your languages, what percentage of time would you choose to speak each

language? Please report percent of total time.

(Your percentages should add up to 100%):

	Language A	Language B	Language C	Language D	Language E
List language here					
List percentage here					

(6) Please name the cultures with which you identify. On a scale from zero to ten, please rate the extent to which you identify with each culture. (Examples of possible cultures include Canadian, First Nations, US-American, Chinese, Jewish-Orthodox, etc.):

	Culture A	Culture B	Culture C	Culture D	Culture E
List culture here					
List a number here (1-10)					

(7) How many years of formal education do you have?____

Please check your highest education level (or the approximate Canadian equivalent to a degree obtained in another country):

Less than High School	
High School	
Professional Training	
Some College	
College	
Some Graduate	
Masters	
PhD/MD/JD	
Other	

(8) Date of moving to the Canada, if applicable:

___

If you have ever lived in another country, please provide name of country and dates of residence:

___

(9) Have you ever had the following: (Check all applicable)

a vision problem	
hearing impairment	
language disability	
learning disability	

If yes, please explain (including any corrections):

___

Language: Language X

This is my (please select: First, Second, Third, etc.) language.

All questions below refer to your knowledge of **Language X**.

(1) Age when you:

began acquiring Language X	became fluent in Language X	began reading in Language X	became fluent reading in Language X

(2) Please list the number of years and months you spent in each language environment:

	Years	Months
A country where Language X is spoken		
A family where Language X is spoken		
A school and/or working environment where Language X is spoken		

(3) On a scale from zero to ten, please select your level of proficiency in speaking, understanding, and reading Language X:

	Speaking	Understand Spoken Language	Reading
1-10			

(4) On a scale from zero to ten, please select how much the following factors contributed to you learning Language X:

Interacting with friends		Language tapes/self instruction	
Interacting with family		Watching TV	
Reading		Listening to the radio	

(5) Please rate to what extent you are currently exposed to Language X in the following contexts:

Interacting with friends		Listening to radio/music	
Interacting with family		Reading	
Watching TV		Language-lab/self-instruction	

(6) In your perception, how much of a foreign accent do you have in Language X (on a scale from 1-10, with 1 – not having any accent and 10 – having a very strong accent)?

(7) Please rate how frequently others identify you as a non-native speaker based on your accent in Language X (on a scale from 1-10, with 1 – never identifying me as a non-native speaker and 10 – as always identifying me as a non-native speaker):

Appendix B.

Waterloo Handedness Questionnaire

Revised Instructions:

Please indicate your hand preference for the following activities by circling the appropriate response. If you always (i.e. 95 % or more of the time) use one hand to perform the described activity, circle Ra or La (for right always or left always). If you usually (i.e. about 75% of the time) use one hand circle Ru or Lu as appropriate. If you use both hands equally often (i.e. you use each hand about 50% of the time), circle Eq.

Questions included in the Short Version of the Questionnaire

1	Which hand would you use to adjust the volume knob on a radio?	La	Lu	Eq	Ru	Ra
2	With which hand would you use a paintbrush to paint a wall?	La	Lu	Eq	Ru	Ra
3	With which hand would you use a spoon to eat soup?	La	Lu	Eq	Ru	Ra
4	Which hand would you use to point to something in the distance?	La	Lu	Eq	Ru	Ra
5	Which hand would you use to throw a dart?	La	Lu	Eq	Ru	Ra
6	With which hand would you use the eraser on the end of a pencil?	La	Lu	Eq	Ru	Ra
7	In which hand would you hold a walking stick?	La	Lu	Eq	Ru	Ra
8	With which hand would you use an iron to iron a shirt?	La	Lu	Eq	Ru	Ra
9	Which hand would you use to draw a picture?	La	Lu	Eq	Ru	Ra

10	In which hand would you hold a mug full of coffee?	La	Lu	Eq	Ru	Ra
11	Which hand would you use to hammer a nail?	La	Lu	Eq	Ru	Ra
12	With which hand would you use the remote control for a TV?	La	Lu	Eq	Ru	Ra
13	With which hand would you use a knife to cut bread?	La	Lu	Eq	Ru	Ra
14	With which hand would you use to turn the pages of a book?	La	Lu	Eq	Ru	Ra
15	With which hand would you use a pair of scissors to cut paper?	La	Lu	Eq	Ru	Ra
16	Which hand would you use to erase a blackboard?	La	Lu	Eq	Ru	Ra
17	With which hand would you use a pair of tweezers?	La	Lu	Eq	Ru	Ra
18	Which hand would you use to pick up a book?	La	Lu	Eq	Ru	Ra
19	Which hand would you use to carry a suitcase?	La	Lu	Eq	Ru	Ra
20	Which hand would you use to pour a cup of coffee?	La	Lu	Eq	Ru	Ra
21	With which hand would you use a computer mouse?	La	Lu	Eq	Ru	Ra
22	Which hand would you use to insert a plug into an outlet?	La	Lu	Eq	Ru	Ra
23	Which hand would you use to flip a coin?	La	Lu	Eq	Ru	Ra
24	With which hand would you use a toothbrush to brush your teeth?	La	Lu	Eq	Ru	Ra
25	Which hand would you use to throw a baseball?	La	Lu	Eq	Ru	Ra

Additional Questions Included in the Long Version of the Questionnaire

26	Which hand would you use to turn a doorknob?	La	Lu	Eq	Ru	Ra
27	Which hand would you use for writing?	La	Lu	Eq	Ru	Ra
28	Which hand would you use to pick up a piece of paper?	La	Lu	Eq	Ru	Ra
29	Which hand would you use a hand saw?	La	Lu	Eq	Ru	Ra
30	Which hand would you use to stir a liquid with a spoon?	La	Lu	Eq	Ru	Ra
31	In which hand would you hold an open umbrella?	La	Lu	Eq	Ru	Ra
32	In which hand would you hold a needle while sewing?	La	Lu	Eq	Ru	Ra
33	Which hand would you use to strike a match?	La	Lu	Eq	Ru	Ra
34	Which hand would you use to turn on a light switch?	La	Lu	Eq	Ru	Ra
35	Which hand would you use to open a drawer?	La	Lu	Eq	Ru	Ra
36	Which hand would you use to press buttons on a calculator?	La	Lu	Eq	Ru	Ra

Appendix C.

Waterloo Footedness Questionnaire

Revised Instructions: Answer each of the following questions as best you can. If you always use one foot to perform the described activity, circle Ra or La (for right always or left always). If you usually use one foot circle Ru or Lu, as appropriate. If you use both feet equally often, circle Eq. Please do not simply circle one answer for all questions, but imagine yourself performing each activity in turn, and then mark the appropriate answer. If necessary, stop and pantomime the activity.

		La	Lu	Eq	Ru	Ra
1	Which foot would you use to kick a stationary ball at a target straight in front of you	La	Lu	Eq	Ru	Ra
2	If you had to stand on one foot, which foot would it be?	La	Lu	Eq	Ru	Ra
3	Which foot would you use to smooth sand at the beach?	La	Lu	Eq	Ru	Ra
4	If you had to step up onto a chair, which foot would you place on the chair first?	La	Lu	Eq	Ru	Ra
5	Which foot would you use to stomp on a fast-moving bug?	La	Lu	Eq	Ru	Ra
6	If you were to balance on one foot on a railway track, which foot would you use?	La	Lu	Eq	Ru	Ra
7	If you wanted to pick up a marble with your toes, which foot would you use?	La	Lu	Eq	Ru	Ra
8	If you had to hop on one foot, which foot would you use?	La	Lu	Eq	Ru	Ra
9	Which foot would you use to help push a shovel into the ground?	La	Lu	Eq	Ru	Ra
10	During relaxed standing, people initially put most of their weight on one foot, leaving the other leg slightly bent. Which foot do you put most of your weight on first?	La	Lu	Eq	Ru	Ra

		Yes	No
11	Is there any reason (i.e. injury) why you have changed your foot preference for any of the above activities?		
12	Have you ever been given special training or encouragement to use a particular foot for certain activities?		
13	If you have answered YES for either question 11 or 12, please explain:		